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Research article

Air pollution and blood pressure in the elderly: evidence from a panel study in Nanjing, China

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ABSTRACT

Background: Air pollution is known to have notable negative effects on human health. Recently, the effect of air pollution on blood pressure among the elderly has attracted researchers' attention. However, the existing evidence is not consistent, given that positive, null, and negative outcomes are presented in the literature. In this study, we investigated the relationship between blood pressure (BP) and indices of air pollutants ($PM_{2.5}$, PM_{10}, and air quality index) in a specific elderly population through a panel study to address this knowledge gap.
Methods: We obtained repeated BP measurements from January 2017 to May 2019 in a panel of 619 elderly with a total of 5106 records in Nanjing, China. Data on daily indices of ambient air pollutants, including fine particulate matter with an aerodynamic diameter of $\leq$ 2.5 μ m ($PM_{2.5}$), $\leq$ 10 μ m (PM_{10}), and air quality index (AQI) of the same period were obtained. We evaluated the association between BP and average concentrations of air pollutants in the past one-week, two-week, and four-week lags before measuring the BP. The non-linear panel regression models were used with fixed- and mixed-effects to control age, gender, and temperature.
Results: In the non-linear panel fixed-effects model, the average concentration of $PM_{2.5}$ is significantly associated with systolic BP (SBP) at all lags but is only significantly correlated with diastolic BP (DBP) at a one-week lag. An interquartile range (IQR) increase of one-week average moving $PM_{2.5}$ (38.86 μg/m^3) of our sample increases the SBP and DBP by 7.68% and 6.9%, respectively. PM_{10} shows the same pattern of effect on BP as $PM_{2.5}$. AQI shows less significant associations with BP. In the non-linear mixed-effects model, the average concentrations of $PM_{2.5}$ and PM_{10} are significantly associated with SBP at all lags but have no significant effect on DBP at one- and two-week lags. AQI is only significantly associated with DBP at a one-week lag.
Conclusions: Exposures to ambient particulate matter ($PM_{2.5}$ and PM_{10}) were associated with increased BP among older people, indicating a potential link between air pollution and the high prevalence of hypertension. Air pollution is a well-recognized risk factor for future cardiovascular diseases and should be reduced to prevent hypertension among the elderly.

1. Introduction

Approximately 90% of the population worldwide lives in areas where the air quality cannot meet the recommended standards set by the World Health Organization (Olujimi et al., 2016). $PM_{2.5}$. Fine particulate matter with an aerodynamic of ≤2.5 μm is a major component of ambient air pollution and one of the serious environmental concerns worldwide, particularly in developing countries (Yusuf et al., 2004). More than one-fourth of Chinese adults have hypertension (27.9%), and the number has significantly increased over the past few decades (Wang et al., 2017). In 2013, hypertension accounted for 2.5 million deaths (28% of total deaths) and 15% of total disability-adjusted life years (Collaborators, G.B.D.R.F. et al., 2015). High blood pressure (HBP) is a potential cardiovascular disease (CVD) risk factor, which is the leading cause of death worldwide (Perumareddi 2019). In the past two decades, numerous studies have established that air pollution exposure is a potential CVD

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risk factor (Lee and Kim, 2014 and Manisalidis et al., 2020). Inhaled pollutants might cause an imbalance in the autonomic nervous system (ANS) by activating the afferent pulmonary autonomic reflexes (Giorgini et al., 2016). Chronic systemic inflammatory responses caused by air pollution exposure can impair vascular function through endothelial dysfunction, which is represented by increased arterial stiffness, vasoconstriction, and decreased flow-mediated dilation (Finch and Conklin 2016). Excessive vascular oxidative stress is a potential feature in the pathogenesis of endothelial dysfunction. Some soluble metal particles such as Zn, Fe, Cu, and Pb (Liang et al., 2020) might penetrate the bloodstream and affect vascular endothelium. The abovementioned factors will lead to increased blood pressure.

Various studies have investigated the effect of air pollution exposures on blood pressure. It has been reported that $PM_{2.5}$ is directly associated with HBP in populations of different races, areas, ages, genders, and job types (Coogan et al., 2016; Weaver et al., 2021; Zhang et al., 2018). An investigation revealed that pregnant women with excessive $PM_{2.5}$ exposure have a higher risk of descending HBP to the next generation, which is manifested when they are 3–9 years old (Zhang et al., 2018). Data from a large school-based cross-sectional study in six provinces in China showed that $PM_{2.5}$ exposure was associated with HBP in children aged 6–18 (Wang et al., 2019). A total of 88 non-smoking outdoor workers were recruited and exposed to different $PM_{2.5}$ concentrations for 4 weeks. The results showed that an increase in BP was consistently associated with an increase in $PM_{2.5}$ concentration (Santos et al., 2019). However, some studies reported no association between HBP and $PM_{2.5}$ (Mordukhovich et al., 2009; Pieters et al., 2015), or they are negatively related (Ibald-Mulli et al., 2004; Wang and Wang 2021). Given that there is inconsistency in the literature, this motivated us to use unique data to investigate the association between air pollution exposures and BP. Moreover, these existing studies on the association between BP and $PM_{2.5}$ have limitations. For example, the BP monitoring time on the same subject was short, and the measuring frequency was low. The research period of a study in Beijing, China, was from December 2011 to April 2012 which addressed the effects of high-level $PM_{2.5}$ exposure on central BP, and the measuring frequency for each individual was at most 2 (Fan et al., 2019). Although a panel study was conducted among university students in Guangzhou, China, from December 2017 to January 2018. Despite a relatively short period, they measured the weekly BP for 5 consecutive weeks (Guo et al., 2021). Consequently, BP was measured at a certain point or a few times over a short period and thus might be affected by various factors, such as mood swings and sports. Some studies adopted The annual mean value from the medical examination reports was adopted by some studies, however, it cannot rule out the drug use factor. The inconsistencies observed in the previous studies resulted in another factor, many of them are cross-sectional (aka, one-time measurements). To address these knowledge gaps, we seek to investigate the associations between the indices of air pollutants (including $PM_{2.5}$, PM_{10}, and AQI index) and the BP among the 619 Chinese elderly people via multiple BP monitoring. This investigation includes systolic and diastolic BP during a long sampling period from January 2017 to May 2019. We utilized repeated measurements on the same subject in this study.

The study was conducted in Nanjing, China. The Nanjing Municipal Government issued an environmental quality report that stated the city's mean value of $PM_{2.5}$ in 2018 was 43 $\mu m/m^3$. This means that the air was classified into the second group of "unhealthy air for sensitive groups to breathe in" according to the Chinese Air Pollution Index Standard. Moreover, this value represents the severity of air pollution in China, given that it has increased by 7.5% compared to the data in 2017 (40 $\mu m/m^3$).

2. Methods

2.1. Study population and research design

Our study population was a group of older people in Nanjing City, China, mostly aged 60 years old and above. These elderly came to multi-service centers for various ailments' consultation. The elderly multi-service center has accessed the detailed records of the medical examinations among the elderly, including systolic blood pressure (SBP, mmHg), diastolic blood pressure (DBP, mmHg), and individual data, such as age and gender. The sample period was from January 2017 to May 2019. An important feature of this data was the sample individual had multiple medical check-ups during the sample period. We were then able to perform a panel data analysis that could reveal the real effects of air pollution on BP by properly controlling the influence of time-invariant individual effects. We restricted the sample to individuals with multiple check-up records within the sample period, which left us a final unbalanced individual panel sample of 619 and a total of 5106 medical records with precise examination dates. Ethical approval was obtained from Home Care Service Center of Nanjing and Jiangsu Zhongmeng Yunzheng Information Technology Co., LTD research ethics committees, and all participants for our study provided written informed consent.

2.2. Research data source

In this analysis, blood pressure (BP) with systolic and diastolic measurements were used as the main health outcomes. Different participants' BP was measured on different dates. For medical reasons, several BP measurements were collected from the same participant on a particular date, thus using the average BP measurement. The BP measurements data were provided by the Nanjing Municipal Government and the collection time was from January 2017 to May 2019. Air pollution data for the same period were obtained from the Ministry of Environmental Protection Information Center of China (http://106.37.208.233:20035/). The central monitoring stations were used to assess the exposure to air pollution. The exposure levels of all the participants in Nanjing would be the same if their BP were measured and collected on the same date. In this study, we used $PM_{2.5}$, PM_{10}, and AQI as air pollution measurements, and their units are all in μ g/m^3. Nine corresponding variables ($PM_{2.5}$_1W, PM_{10}_1W, AQI_1W, $PM_{2.5}$_2W, PM_{10}_2W, AQI_2W, $PM_{2.5}$_4W, PM_{10}_4W, and AQI_4W) were subsequently generated. This represented the past one-week, two-week, and four-week average of $PM_{2.5}$, PM_{10}, and AQI concentrations, respectively. After studying an authoritative systematic review on the global association between ambient air pollution and BP, we found that most high-quality studies on short-term effects of air pollutants used one-week, two-week, and four-week as time lags, and thus we would follow (Yang et al., 2018). Temperature data for the same period was acquired from China Meteorological Administration (http://www.cma.gov.cn) and the corresponding temperature variables (Temperature_1W, Temperature_2W, and Temperature_4W) were constructed. The unit of temperature used is degree Celsius (°C).

2.3. Statistical analysis

By the time of the subject's BP measurements, the environmental data including air pollution and temperature were linked with the individual's health data. Non-linear panel models with fixed- and mixed-effects were used to study the effect of air pollution on BP.

First, the effect of air pollution on BP in the elderly was analyzed using a non-linear panel model with fixed effects. Natural log value was employed for the dependent and independent variables for easy econometric interpretation, this paradigm is known as the log-log model. This model can measure the non-linear relationships between the health variable of interest and the intensity of air pollution, and handle the non-normality of SBP and DBP. In the model, the dependent variable was the BP measurements with log transformation, and the independent variables included air pollutants, controlling covariates (temperature, age, and gender), and fixed effects. In our analysis, our main independent variable was focused on the average $PM_{2.5}$ concentrations in the past week(s). PM_{10} and AQI were also analyzed as important independent variables. For each air pollutant, we ran a regression on one-week, two-week, and four-week lags, respectively. Given that individuals might manifest a certain pattern of health conditions across different days of the week caused by periodic children visiting and other unobserved reasons, therefore, a weekday fixed-effect (day of the week) was included. The individual fixed effect was included in the model to account for time-invariant individual characteristics. Hence, we could compare the health conditions of the same person across varying dates with possibly distinct air pollution intensity. BP measurements, temperature, and air pollutant concentrations were treated as continuous variables, meanwhile, gender and day of the week were treated as indicator variables. The non-linear panel model with fixed effects is

$$\log(\mathrm{BP}_{i,t}) = \beta_0 + \beta_1 \log(\mathrm{Pollution}_t) + \beta_2 \log(\mathrm{Temperature}_t) + \beta_3 \log(\mathrm{Age}_{i,t}) + \theta_t + \gamma_i + \delta_i + e_{i,t}, \quad (1)$$

where $\mathrm{BP}_{i,t}$ denotes the health variable of interest (i.e., SBP or DBP) for individual i on date t; $\mathrm{Pollution}_t$ measures the intensity of air pollution on date t. We ran the regression models for different pollutants ($PM_{2.5}$, PM_{10}, and AQI) with different time lags (one-week, two-week, and four-week) separately; $\mathrm{Age}_{i,t}$ is the age for individual i on date t in years; $\mathrm{Temperature}_t$ is the temperature on date t; Weekday fixed-effects, θ_t, was included to eliminate the potential bias; Gender fixed effects, γ_i, was included to account for the difference between male and female; δ_i is the individual fixed effects, and $e_{i,t}$ is the residual error term. The standard errors were clustered at the individual level.

Given the repeated measurements, we conducted an investigation using the non-linear panel model with mixed effects to control the within-subject variances. This model allows the individual to act as his or her control over time.

The model is

$$\log(\mathrm{BP}_{i,t}) = \beta_0 + \beta_1 \log(\mathrm{Pollution}_t) + \beta_2 \log(\mathrm{Temperature}_t) + \beta_3 \log(\mathrm{Age}_{i,t}) + \theta_t + \gamma_i + \varepsilon_i + e_{i,t}, \quad (2)$$

All the variables and estimated coefficients are the same as a fixed-effect model, except for the individual effect. We included ε_i as individual random intercept for each subject in the mixed-effects model, meanwhile, we included δ_i in the fixed-effects model as the individual fixed-effects.

As for the sensitivity analysis and to make the panel data more balanced, we performed the above models on the dataset by excluding sample individuals with fewer than five examination records.

We calculated the percentage changes of effect estimates in BP variables for a 1% increase of air pollutants as β_1% (in a log-log model, the coefficient is the estimated percent change in the dependent variable for a percent change in the independent variable), and the 95% confidence intervals (CIs) ($\beta_1 \pm 1.96 \times SE$)%, where β_1 and SE were the estimated coefficient for air pollutant and its standard error, respectively.

One may raise a concern that air pollution has heterogeneous effects on individuals with different initial levels of BP. The quantile regression model allows us to account for the unobserved heterogeneity while the panel dataset allows us to include fixed effects to control for unobserved covariates (Ibald-Mulli et al., 2004). Therefore, we alternatively adopt quantile regression estimation with fixed effects to uncover a finer-grained effect of air pollution (Machado and Santos Silva, 2019). We consider individual and day-of-week fixed effects. Moreover, we consider nine quantiles running from 10% to 90%.

Statistical tests were two-sided, and p-values of $\leq$ 0.05 were considered statistically significant. Statistical analyses were performed in the R software (version 4.0.2, R Foundation for Statistical Computing, Vienna, Austria) using the "feols" function in the "fixed" package for non-linear panel models with fixed effects and the "lmer" function in "lme4" package for models with mixed effects and were performed in the STATA program (version 16.0, StataCorp, College Station, TX, USA) using the "xtqreg" package for quantile regression.

3. Results

3.1. Characteristics of the sample populations and environmental measurements

A total of 619 participants completed 5106 medical records from January 2017 to May 2019. Figure S1 (Supplementary Material) presents the geographical distribution of the sample. The graph illustrates that more individuals reside in the urban districts than in the suburbs of Nanjing, China. Figure 1 (B) plots the frequency of the medical records of our samples by week and it gradually increases over time. As discussed above, all sample individuals feature more than one medical check-up record. Figure 2 (A) presents the histograms of the number of tests per person in our sample. The participants had an average of 8.25 medical check-up records with a standard deviation of 7.29 in the same sample period. The 25^{th} quantile, the median, and the 75^{th} quantile of record numbers were 2, 5, and 13, respectively. Most sample individuals had several records less than the mean concerning a right-skewed distribution. Table 1 provides the descriptive statistics of basic demographic characteristics. The average age in our 619 sample individuals was 77.10 $\pm$ 8.07. There were 390 females, accounting for 63% of the total samples.

Table 2 shows the descriptive statistics of BP measurement, average concentrations of air pollutants, and temperature. The average SBP was 136.39 $\pm$ 20.54, which was relatively high because it almost reached the standard of hypertension (SBP $\geq$ 140 mmHg or DBP $\geq$ 70 mmHg), and the average DBP was 75.47 $\pm$ 12.58 (Lin et al., 2017). For the average concentrations of air pollutants, the average $PM_{2.5}$, PM_{10}, and AQI in one week before the scheduled measuring date were 77.58 $\pm$ 28.16, 123.21 $\pm$ 35.75, and 114.35 $\pm$ 29.13, respectively. Figure 1 (A) plots the weekly average of SBP, DBP, and $PM_{2.5}$ indices. The $PM_{2.5}$ shows a periodical pattern that achieves its peaks in winter and valleys in summer (December and January) and (July and August), respectively. We predict that this pattern is associated with the rainfall as the summer in Nanjing is the rainy season. The SBP and DBP show the same patterns with $PM_{2.5}$ as their peaks appear after $PM_{2.5}$'s peak in the summer of 2018. The distributions of the $PM_{2.5}$ index, SBP, and DBP were plotted in Figure 2 (B, C, D), respectively.

3.2. Regression results

The relationship among different time lags of air pollutant concentrations was estimated by the non-linear panel model with fixed effects and BP was shown in Table 3, **S1**, and **S2** (Supplementary Material). $PM_{2.5}$ with all the time lags was significantly and positively correlated with SBP. For every 1% increase in $PM_{2.5}$, the SBP increased by 0.0256% (95% CI, 0.0137%–0.0375%), 0.0286% (95% CI, 0.0130%–0.0442%), and 0.0435% (95% CI, 0.0178%–0.0692%) at one-week lag, two-week lag, and four-week lag, respectively. The effect of $PM_{2.5}$ on DBP had both significant and non-significant results. Particularly, for every 1% increase in the $PM_{2.5}$, the estimated percent changes showed a positive association with DBP at a one-week lag (0.0230% [95% CI, 0.0099%–0.0361%]), whereas it showed no statistical significance in association with DBP at two-week lag and four-week lag with a percentage of (0.0167% [95% CI, -0.000430%–0.0338%]) and (−0.00701% [95% CI, -0.0343%–0.0202%]), respectively. Meanwhile, the PM_{10} showed the same pattern, however, there is a slight sign of its effect on the BP compared with the $PM_{2.5}$. That is, the PM_{10} is significantly and positively correlated with SBP at all time logs. For every 1% increase in PM_{10}, SBP increased by 0.0258% (95% CI, 0.0116%–0.0400%), 0.0287% (95% CI, 0.0106%–0.0468%), and 0.0461% (95% CI, 0.0185%–0.0737%) at one-week lag, two-week lag, and four-week lag, respectively. PM_{10} is only positively associated with DBP at one-week lag (0.0247% [95% CI, 0.0085%–0.0409%]). However, AQI is only slightly positively correlated with both BPs at a one-week lag. The sensitivity analysis was shown in Table S3 (Supplementary Material), where the associations between $PM_{2.5}$ and BPs remain consistent.

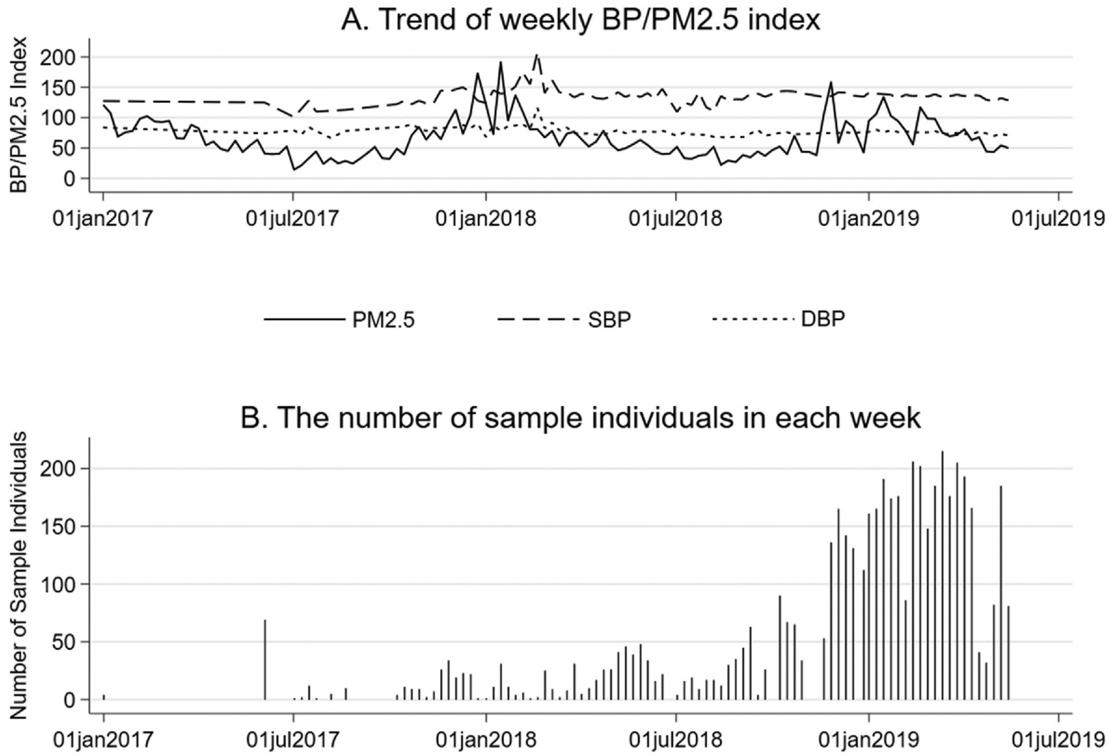

Figure 1. Air Pollution and the Sample Selection. Panel A shows the trend of weekly means of SBP, DBP, and PM 2.5 indices over the sample period, and panel B shows the number of sample individuals in each week of the sample period.

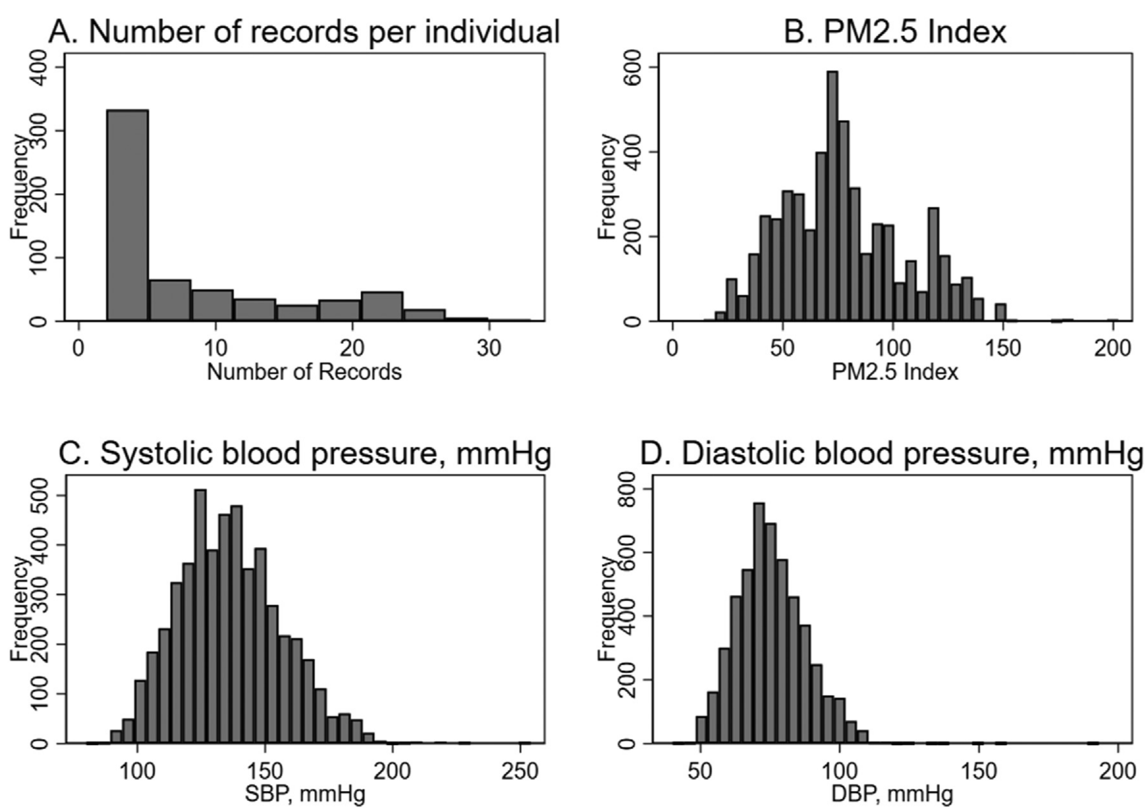

Figure 2. Histograms. Panel A presents the histograms of the number of tests per individual in our sample. The distribution of the $PM_{2.5}$ index is plotted in panel B. By contrast, the distributions of SBP and DBP are presented in panels C and D, respectively. The y-axis for the four panels is frequency, which means how many times the observation occurred in the sample. For panel A, the area of the histogram should be 5106 as the x-axis is several records per individual, while for the other panels, the value of adding up all the frequencies should be 5106.

Table 1. Descriptive statistics of basic demographical characteristics.

Characteristics	Total (N = 619)*
Age [Years], mean ± SD	77.10 ± 8.07
Female, n (%)	390 (63.00%)

* In this column, age is given an arithmetic mean and female is given the number of occurrences.

Table 2. Descriptive statistics of blood pressure, average concentrations of air pollutants, and temperature.

Variables	N	Mean	SD	P25	Median	P75
Blood pressure (mmHg)						
Systolic blood pressure	5106	136.39	20.54	122.00	135.00	149.00
Diastolic blood pressure	5106	75.47	12.58	66.00	74.00	83.00
Average concentrations of air pollutants (μ g/m^3)						
$PM_{2.5}$_1W	5106	77.58	28.16	56.00	73.86	94.86
$PM_{2.5}$_2W	5106	77.75	25.05	59.14	76.43	97.07
$PM_{2.5}$_4W	5106	77.48	21.23	58.43	82.29	92.36
PM_{10}_1W	5106	123.21	35.75	99.86	119.00	147.00
PM_{10}_2W	5106	122.71	30.03	104.50	120.79	143.57
PM_{10}_4W	5106	121.62	24.70	104.75	123.79	138.07
AQI_1W	5106	114.35	29.13	96.43	107.43	130.57
AQI_2W	5106	113.83	24.83	97.64	109.50	132.79
AQI_4W	5106	112.75	19.54	98.29	115.75	126.00
Temperature (°C)						
Temperature_1W	5106	11.63	7.76	4.21	11.21	17.93
Temperature_2W	5106	11.72	7.73	4.36	11.43	17.14
Temperature_4W	5106	11.54	7.39	4.59	10.59	17.39

Note: $PM_{2.5}$_1W, $PM_{2.5}$_2W, and $PM_{2.5}$_4W represent the average $PM_{2.5}$ concentration in the past one week, two weeks, and four weeks, and the lag meanings are the same for PM_{10}, AQI, and temperature, respectively.

Table 4, **S4,** and **S5** (Supplementary Material) present the relationship between air pollutant concentrations and BP estimated by a non-linear panel model with mixed effects. The results are consistent, and more significant findings were obtained compared to the model with fixed effects. For every 1% increase in $PM_{2.5}$, the SBP increased by 0.0257% (95% CI, 0.0149%–0.0365%), 0.0283% (95% CI, 0.0148%–0.0418%), and 0.0364% (95% CI, 0.0162%–0.0566%) at one-week lag, two-week lag, and four-week lag, respectively. Meanwhile, the DBP increased by 0.0271% (95% CI, 0.0156%–0.0386%) and 0.0252% (95% CI, 0.0108%–0.0396%) at one-week lag and two-week lag, respectively. There was no significant association between $PM_{2.5}$ and DBP only at a four-week lag. The associations between PM_{10} and SBP were significant at one-week lag, two-week lag, and four-week lag with an increase of (0.0269% [95% CI, 0.0143%–0.0395%]) (0.0299% [95% CI, 0.0140%–0.0458%]), and (0.0436% [95% CI, 0.0218%–0.0654%]), respectively. Meanwhile, the associations between PM_{10} and DBP were significant at one-week lag and two-week lag with an increase of (0.0292% [95% CI, 0.0157%–0.0427%]) and (0.0265% [95% CI, 0.0099%–0.0431%]), respectively, however, they are not significantly associated at four-week lag. AQI still had few significant associations with BP. For every 1% increase in AQI at a one-week lag, DBP would significantly increase by 0.0314% (95% CI, 0.0156%–0.0472%). In the sensitivity analysis of Table S6 (Supplementary Material), the associations between $PM_{2.5}$ and BPs remain consistent.

The coefficients in the quantile regression are presented in Figure 3. Figure 3 (A) reports the results with Log (SBP) as the dependent variable. Figure 3 (B) shows the results with Log (DBP) as the dependent variable. From the plots in Figure 3, we cannot discern a clear pattern in which the effects of air pollution appear to be different across quantiles of the distribution of the BP. Our results indicated that air pollution worsens elders' health.

4. Discussion

This study aims to investigate the associations between BP and indices of air pollutants ($PM_{2.5}$, PM_{10}, and AQI) in a longitudinal panel of 619 elderly participants from Nanjing City, China. In this study, the longitudinal design with repeated measurement contributed to a stronger statistical power in investigating the associations between air pollution exposures and BP. We found that increasing air pollutants, particularly $PM_{2.5}$, were significantly associated with the rising BP (Tables 3 and 4). Our findings are generally consistent with an existing study where a meta-analysis reported that there is a positive relationship between exposure to air pollutants and hypertension (Liang et al., 2014).

Previous studies found that an increase in $PM_{2.5}$ and PM_{10} above thresholds was associated with increased SBP, DBP, and pulse-pressure difference (Lin et al., 2017). In another study of the association of particulate number concentration, black carbon, and $PM_{2.5}$ with BP, central site particulate number concentration levels on a preceding day were significantly associated with high levels of DBP. However, most participants lived close to a highway where the levels of particulate number concentrations are elevated (Chung et al., 2015). An American study of 4121 Americans aged above 57 showed increased odds of prevalent hypertension, increased SBP, and pulse pressure when exposed to polluted air with an increased level of $PM_{2.5}$ (Honda et al., 2018). A cross-sectional study conducted in Germany and Taiwan observed that each 2.4 μg/m^3 increase in $PM_{2.5}$ was directly associated with 1.4 mmHg and 0.9 mmHg increase in SBP and DBP, respectively (Fuks et al., 2011), which was consistent with our predicted estimates. In another study,

Table 3. Results of non-linear panel fixed-effects model using $PM_{2.5}$ as pollution measure.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	Log (Systolic blood pressure)			Log (Diastolic blood pressure)		
Log ($PM_{2.5}$_1W)	**0.0256*** (0.00607)**			**0.0230*** (0.00668)**		
Log (Temperature_1W)	-0.0161*** (0.00299)			-0.0259*** (0.00299)		
Log ($PM_{2.5}$_2W)		**0.0286*** (0.00798)**			**0.0167 (0.00874)**	
Log (Temperature_2W)		-0.0153*** (0.00330)			-0.0305*** (0.00338)	
Log ($PM_{2.5}$_4W)			**0.0435*** (0.0131)**			**-0.00701 (0.0139)**
Log (Temperature_4W)			-0.0125** (0.00479)			-0.0425*** (0.00512)
Log (Age)	-0.101 (0.997)	-0.198 (0.990)	-1.09 (0.992)	-0.556 (0.994)	-0.584 (0.988)	-1.59 (0.980)
Observations	5,088	5,094	5,106	5,088	5,094	5,106
R-squared	0.438	0.438	0.436	0.467	0.469	0.468

Note: The results are presented as β_1 (SE) for the relationship between air pollutants and BP, where β_1 and *SE* were the estimated coefficient and its standard error for the air pollutant, respectively. The standard error is clustered at the individual level. ***, **, and * indicates significance at 1%, 5%, and 10%, respectively.

Table 4. Results of non-linear panel mixed-effects model using $PM_{2.5}$ as pollution measure.

	Dependent variable:					
	Log (Systolic blood pressure)			Log (Diastolic blood pressure)		
	(1)	(2)	(3)	(4)	(5)	(6)
Log ($PM_{2.5}$_1W)	**0.0257*** (0.00549)**			**0.0271*** (0.00586)**		
Log (Temperature_1W)	-0.0162*** (0.00236)			-0.0258*** (0.00253)		
Log ($PM_{2.5}$_2W)		**0.0283*** (0.00689)**			**0.0252*** (0.00734)**	
Log (Temperature_2W)		-0.0159*** (0.00275)			-0.0293*** (0.00293)	
Log ($PM_{2.5}$_4W)			**0.0364*** (0.0103)**			**0.00694 (0.0110)**
Log (Temperature_4W)			-0.0146*** (0.00407)			-0.0410*** (0.00433)
Log (Age)	0.0123 (0.0410)	0.0115 (0.0410)	0.00945 (0.0412)	-0.208*** (0.0438)	-0.207*** (0.0437)	-0.209*** (0.0436)
Observations	5088	5094	5106	5088	5094	5106
Log-Likelihood	3052	3055	3046	2718	2728	2725

Note: The results are presented as β_1 (SE) for the relationship between air pollutants and BP, where β_1 and *SE* were the estimated coefficient and its standard error for the air pollutant, respectively. The standard error is clustered at the individual level. ***, **, and * indicates significance at 1%, 5%, and 10%, respectively.

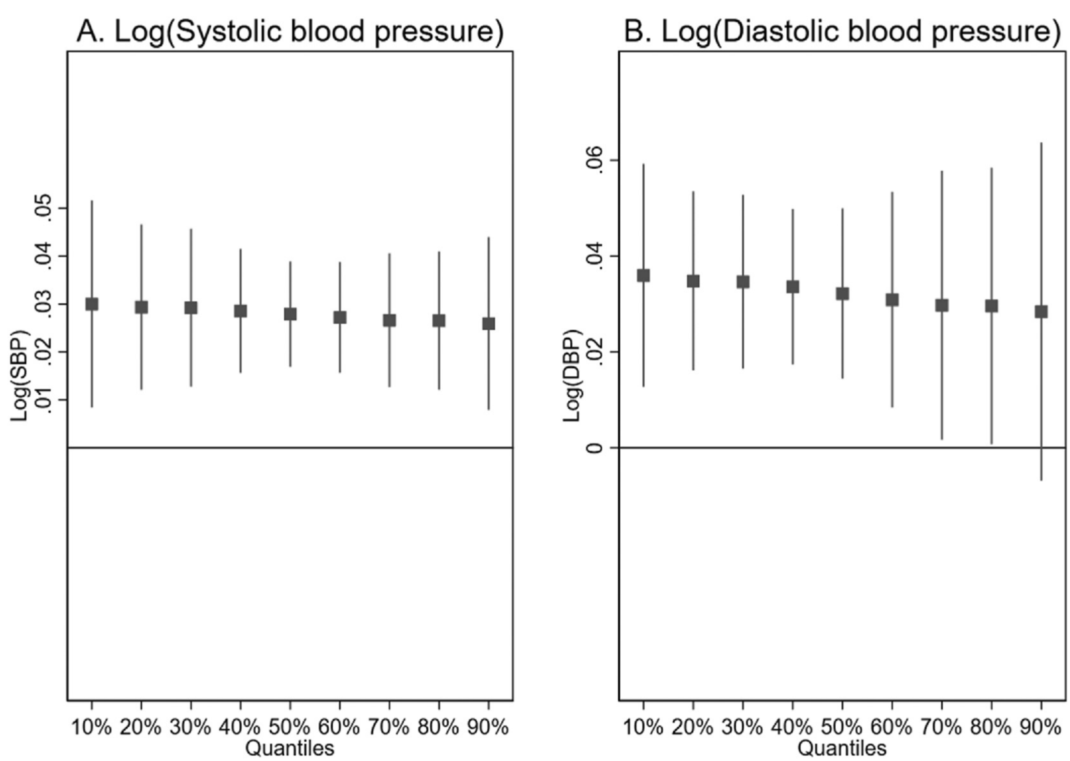

Figure 3. Coefficients in Quantile Regression Models. Panel A reports the results with Log (SBP) as the dependent variable. Panel B shows the results with Log (DBP) as the dependent variable.

traffic-related air pollution (TRAP) significantly increased both SBP and DBP. Moreover, physical activity in low-TRAP environments has stronger beneficial effects than the high-TRAP on decreasing the SBP (Weichenthal et al., 2014). Relevant experimental data at the cell biochemistry level indicate that exposure to $PM_{2.5}$ induces diastolic dysfunction by oxidative stress, NADPH oxidase, TGF-beta1, and SMAD-dependent pathways (Qin et al., 2018). In summary, evidence on the interaction between air pollution and BP in the elderly population is limited. Thus, further studies are necessary to effectively elucidate the joint effect, particularly in China with high levels of PM, and to provide insights into substantial effective strategies in preventing hypertension.

The evidence from biological experiments confirms the effect of air pollution on BP. Experimental studies have provided several biological pathways to demonstrate that breathing in pollutants may adversely affect the nervous, circulatory, and immune systems (Giorgini et al., 2016). Poor air quality caused by $PM_{2.5}$ induces multi-organ dysfunction including CVD, ANS imbalance, oxidative stress and inflammation, respiratory and lung impairment, and endocrine disorders that can consequently lead to morbidity and even death. Some interacting biological pathways are supported by an overview of the mechanistic evidence in Figure S2 (Supplementary Material).

There are some limitations to this study. First, we used the central monitoring stations, and thus the effects of air pollution are subject to the constraints posed by the availability of measurement. We only have an imperfect exposure measurement because of the time series correlations among exposure meant for individual participants with multiple records and the various individual time-activity patterns. The potential measurement errors were from the differences between individual- and population-average exposures; between population-average exposures and ambient levels at central cities; and between actual ambient levels and their measurements (Zeger et al., 2000). Second, although age, gender, and temperature have been included as control variables, some other potentially important variables were missing, such as the waistline, type of disease, and other individual characteristics like smoking and obesity, among others. Given that the study sample came from the records of the medical check-ups in the elderly multi-service center, it was not created for this research. We don't have information on other confounding factors that could be directly associated with high BP. Therefore, more relevant confounding factors should be included in future studies to improve the results further.

5. Conclusion

In conclusion, our study showed that short-term exposure to ambient PM air pollution was associated with increased BP for older people. This study aims to quantify the effect of air pollution on BP through statistical methods, providing more reliable scientific evidence. These findings support the urgent need to effectively lower air pollution and improve strategies to prevent the risk of hypertension among the elderly. China is one of the countries in Southeast Asia that is fighting $PM_{2.5}$ pollution. Various studies have shown that exposure to $PM_{2.5}$ can lead to various diseases caused by multiple organ damage, and even death and morbidity in Chinese people. In China, although the mechanisms of adverse reactions such as inflammation and oxidative stress have been found in the open environment, no research has shown which mechanism is more effective in eliminating its harmful effects. Increasing $PM_{2.5}$ exposure is a significant public health issue affecting the quality of life of Chinese people. China has a vast area where the air conditions can affect the whole world because of the mutual influence of air pollution on various nearby countries. Therefore, a new strategy should be formulated to reduce the concentration of $PM_{2.5}$ and its harmful effects on human health. Accurate evaluation and determination of the characteristics of China's $PM_{2.5}$ is a priority and needs to be strictly implemented. Finally, the results can be used as indicators and references for the Chinese local government to formulate preliminary public health, community health welfare, and environmental health control. Effective management and control of the environment and air quality will positively affect the health of a wide range of people.

Declarations

Author contribution statement

Yang-Chi-Dung Lin: Performed the experiments; Analyzed and interpreted the data; Wrote paper.

Yutong Cai: Performed the experiments; Analyzed and interpreted the data.

Hsi-Yuan Huang; Jing Li; Yun Tang; Hsiao-Chin Hong & Qiting Yan: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Donghai Liang: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Hsien-Da Huang: Conceived and designed the experiments.

Zhaoyuan Li: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

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Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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