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Short-term effects of exposure to ambient PM_1 on blood pressure in children and adolescents aged 9 to 18 years in Shandong Province, China

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HIGHLIGHTS

- Exposure to PM_1, $PM_{2.5}$ and PM_{10} at lag 0 and 1 day may affect blood pressure level.
- PM_1 has stronger association with blood pressure level than $PM_{2.5}$ and $PM_{10.}$
- Future air clean policies should cover the scope of PM_1.

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ABSTRACT

Limited evidence exists regarding the effect of exposure to ambient particle matters with aerodynamic diameter ≤1 μm (PM_1) in a short-term on blood pressure (BP) in the pediatric population. This study aims to examine the association between short-term exposure to ambient PM_1 on BP in children and adolescents. Population data were obtained from a large cross-sectional survey from 102 schools in Shandong Province, China. Daily air pollution data were collected, and individual exposure level was assigned based on coordinates of school addresses. Distributed lag non-linear models incorporated with a linear mixed model were used. A total of 35241 students aged 9–18 years were included in the study, and the mean values of PM_1, particle matters with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$), and ≤10 μm (PM_{10}) at the schools during the study period were 50.8 (SD = 7.2) μg/m^3, 75.5 (SD = 14.7) μg/m^3, and 138.9 (SD = 25.9) μg/m^3, respectively. We found that per 10 μg/m^3 increment in a cumulative exposure of PM_1 at lag 0 and lag 1 day was significantly associated with a higher systolic BP (SBP, β = 1.46 mmHg), diastolic BP (DBP, β = 1.20 mmHg, 95% CI = 0.52 to 1.88), mean arterial pressure (MAP, β = 1.28 mmHg, 95% CI = 0.61 to 1.96), and pulse pressure (PP, β = 0.65 mmHg, 95% CI = 0.14 to 1.16), after adjusting for other air pollutants and individual covariates (including sex, age, BMI, residence, month of the survey, intake of eggs, intake of milk, physical activity, and screen time). The above associations were stronger in magnitude than for $PM_{2.5}$- and PM_{10}-related associations. The associations of PM_1 with SBP, DBP, MAP, and PP were stronger among females, younger children, those overweight or obese, and those with insufficient physical activity levels. In conclusion, the susceptible window of short-term exposure to ambient PM_1, $PM_{2.5}$ and PM_{10} on BP levels for children and adolescents are lag 0 and lag 1 day, with PM_1 exhibiting a stronger association. Future interventions should be conducted to reduce the impact of PM exposure, especially PM_1, on health in children and adolescents.

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1. Introduction

Globally, hypertension is the leading risk factor for adult mortality, and it was estimated that more than 10 million deaths and 215 million disability adjusted life-years (DALYs) were attributable to elevated systolic blood pressure (SBP) in 2017 (GBD, 2017 Risk Factor Collaborators, 2018). Notably, trend analyses from multiple countries suggested that there was a clearly upward trend of the prevalence of high blood pressure (BP) in the pediatric population in recent years (Gao et al., 2021; Hardy et al., 2021). Children with high BP may suffer from severe short-term (e.g., target organ damage in childhood) and long-term consequences (e.g., stroke, coronary heart disease, and premature mortality in adulthood) (Yang et al., 2018; Liao et al., 2020). Genetics, lifestyle, diet, and the environmental factors are all considered to be important factors that are closely linked to pediatric high BP (Zhang et al., 2020; Zafarmand et al., 2020). Ambient particulate matter (PM) exposure, which can cause oxidative stress, systemic inflammation and endothelial injury, might also be a potential risk factor for elevated BP in youth (Zhu et al., 2021a).

PM is a complex mixture of solid and liquid phase particles with a variety of sizes, shapes, and chemical components (Yang et al., 2019a). In recent years, while an increasing number of observational studies have examined the association between BP levels and exposure to ambient PM among children and/or adolescents, most of them focused on $PM_{2.5}$ (particle matters with aerodynamic diameter $\leq$2.5 μm) and PM_{10} (particle matters with aerodynamic diameter $\leq$10 μm) as exposure (Zhang et al., 2020; Dong et al., 2015). A most recent meta-analysis reported that per 10 μg/m^3 increment in short-term PM_{10} exposure was associated with heightened levels of SBP ($\beta = 0.26$ mmHg, 95% CI: 0.00–0.53) and diastolic BP (DBP, $\beta = 0.32$ mmHg, 95% CI: 0.19–0.45) (Yan et al., 2021). Although further meta-analysis was not performed for short-term $PM_{2.5}$ exposure because of limited available studies (Yan et al., 2021), two separate studies reported $PM_{2.5}$ exposure to be associated with increased BP at lag 2–6 days and lag 1–6 days, respectively, indicating that short-term exposure to $PM_{2.5}$ might be a risk factor for pediatric high BP (Yang et al., 2019b; Hu et al., 2020).

PM_1 (particle matters with aerodynamic diameter $\leq$1 μm) is a dominant component of PM, with increasing evidence showing to suggest smaller size of PM fractions to have stronger adverse effects on human health (Yang et al., 2019a; Wang et al., 2020; Wu et al., 2020). Some studies have suggested that short-term exposure to PM_1 was not only related to hospital admission and mortality due to cardiovascular and respiratory diseases, but also exhibited stronger associations compared with $PM_{2.5}$ or PM_{10} exposure (Zhang et al., 2021a; Zhu et al., 2021b). To the best of our knowledge, no study available has examined the association between short-term exposure to ambient PM_1 and BP levels among children and adolescents. Thus, we aimed to examine the association of short-term exposure to ambient PM_1 on SBP, DBP, mean arterial pressure (MAP), and pulse pressure (PP) among children and adolescents. We also examined the association between $PM_{2.5}$ and PM_{10} exposure and the above four outcomes for comparing their effects with those of PM_1.

2. Methods

2.1. Study population

Population-based data were obtained from a school-based cross-sectional survey covering all 17 prefecture cities in Shandong Province, China. This survey was performed by the Department of Health and Education of the Shandong Center for Disease Control and Prevention in September and October 2014, and was used to ascertain the health status of students in Shandong (Zhang et al., 2021b). Each prefecture city in Shandong Province has several districts (urban area) and counties (rural area). Using a stratified multistage sampling method (to obtain the representative data of Shandong Province), one district and one county in each prefecture city were first randomly selected, and one primary school, one junior high school and one senior high school from each district/county was then randomly selected. For each selected school, two classes within each grade were selected randomly, and all students from these classes were then invited to participate. Informed consent was obtained from the students and their parents. This work has received approval for research ethics from the Ethics Review Committee of Public Health, Shandong University and a proof/certificate of approval is available upon request.

2.2. Measurements

A standard questionnaire, including demographic and lifestyle information, i.e., sex, birth date, intake of eggs, intake of milk, physical activity, screen time and sleep duration time, was completed by participants in grade four or above in primary schools and all participants from high schools. Questionnaire information for students under grade four was not collected because they were too young to complete the questionnaire by themselves. Then, physical examinations (including anthropometric indices and BP measurements) were conducted by trained health professionals in each school by using the same type of apparatus according to a standardized protocol.

Before height and weight measurement, participants were asked to take off their shoes and in light clothing. Then, height was measured by metal column height-measuring stand, and weight was measured by lever scale. Height values were recorded to the nearest 0.1 cm and weight values to the nearest 0.1 kg. Body mass index (BMI, kg/m^2) was calculated as weight in kilograms divided by the square of height in meters. Overweight and obesity was defined according to sex- and age-specific BMI percentile cut-offs from the National Health Commission of China (National Health Commission of China, 2018). BP was measured by professionals by mercury sphygmomanometer after each participant had rested for at least 10 min. BP was measured in a sitting position with three times on the participant's right arm with an appropriate-size cuff, and the mean value was used for data analysis. The fifth Korotkoff phase was recorded as DBP and the first as SBP. The MAP (equals to DBP plus one-third PP) and PP (equals to the difference of SBP and DBP) were calculated, and SBP, DBP, MAP, and PP were used as the outcomes of interest in this study.

2.3. Air pollution data

Daily PM_1, $PM_{2.5}$, PM_{10}, SO_2, and NO_2 datasets covering Shandong Province in the year 2014 at a spatial resolution of 0.1° ($\approx$10 km^2) are collected from the ChinaHighAirPollutants (CHAP, available at https://weijing-rs.github.io/product.html). These data were estimated based on satellite remote sensing products, atmospheric reanalysis, ground-based measurements, and model simulations by a developed space-time extremely randomized trees model (Wei et al., 2019a, 2019b, 2021a, 2021b, 2022). These predicted air pollutants are reliable compared to ground-level measurements, and the cross-validation coefficients of determination and root-mean-square error were 0.83 and 9.25 μg/m^3 for PM_1, 0.91 and 12.67 μg/m^3 for $PM_{2.5}$, 0.88 and 24.34 μg/m^3 for PM_{10}, 0.84 and 10.07 μg/m^3 for SO_2, 0.84 and 7.99 μg/m^3 for NO_2 on a daily basis (Wei et al., 2019a, 2019b, 2021a, 2021b, 2022). These datasets have been widely applied in recent epidemiological studies evaluating the impact of air pollution exposure on human health in China (Wang et al., 2021; Xu et al., 2021).

We used an online Coordinates Identification System (http://api.map.baidu.com/) to convert the school addresses into longitude and latitude coordinates, by which the daily concentrations of PM_1, $PM_{2.5}$, PM_{10}, SO_2, and NO_2 at each school were extracted. We estimated the concentrations of $PM_{1\text{-}2.5}$ by subtracting PM_1 from $PM_{2.5}$ and the concentrations of $PM_{2.5\text{-}10}$ by subtracting $PM_{2.5}$ from PM_{10} (Chen et al., 2019). Then, concentrations of these air pollutants at the day of BP measurement were assigned as exposure at lag 0 day; concentrations at the day before the day of BP measurement as exposure at lag 1 day; and so on. A maximum of lag 6 days were selected, which was consistent with previous studies (Yang et al., 2019b; Hu et al., 2020).

2.4. Data analysis

Frequency with proportions were used to describe categorical variables, and means with standard deviation (SD) or median with the first quartile (Q1) and the third quartile (Q3) were used to describe continuous variables. We tested the correlation between air pollutants and calculated Spearman correlation coefficients. To examine the associations of short-term daily exposure to PM_1, $PM_{2.5}$ and PM_{10} with SBP and DBP, a distributed lag non-linear model (DLNM) was adopted. This is because it can evaluate the nonlinear (or linear) and lagged effects of an exposure on an outcome of interest at the same time (Gasparrini et al., 2010; Gasparrini, 2014). In a DLNM, a “cross-basis” function is introduced which combines two functions: one models the exposure-response (E-R) relationship curve and the other one models the lag-response (L-R) relationship curve, simultaneously (Gasparrini et al., 2010; Gasparrini, 2014). To get an optimal E-R curve, linear, natural cubic spline (NCS) and quadratic B-spline were used to fit the E-R relationship one by one, and degrees of freedom (df) from 3 to 6 were attempted for the two spline functions. For L-R curve, a NCS with knots equally spaced at lag intervals was selected empirically, because of its flexibility and the requirement for parsimony (Gasparrini, 2014). For models with each combination of E-R and L-R relationships, we selected the one with the minimum Akaike Information Criterion (AIC), indicating the model had both the optimal E-R and L-R relationships simultaneously (Gasparrini et al., 2010; Gasparrini, 2014).

Two or more “cross-basis” functions can be simultaneously incorporated in one separate DLNM, which allowed us to isolate the independent effect of exposure to one specific air pollutant on the outcomes of interest after adjusting for other pollutants (Gasparrini et al., 2010; Gasparrini, 2014). Therefore, to account for the confounding effects of other PM fractions and air pollutants: “cross-basis” functions for $PM_{1\text{-}10}$, SO_2, and NO_2 were additionally included in the DLNMs when we examined the association between PM_1 and the outcomes of interest; “cross-basis” functions for $PM_{2.5\text{-}10}$, SO_2, and NO_2 were additionally included in the DLNMs when we examined the association between $PM_{2.5}$ and the outcomes of interest; “cross-basis” functions for SO_2, and NO_2 were additionally included in the DLNMs when we examined the association between PM_{10} and the outcomes of interest. The optimal models were selected based on the minimum AICs.

We applied DLNMs with a linear mixed model, and the effect estimate was described as regression coefficient (β) with its 95% confidence interval (CI), which was calculated for a per 10 $\mu g/m^3$ increment in exposure level. School and prefecture city were considered as random effects in the above models. Covariates adjusted in the above models included sex, age, BMI, residence, month of the survey, intake of eggs, intake of milk, physical activity, and screen time. Variables regarding intake of eggs and of milk were included as covariates because they were considered as proxies for household socioeconomic level (Vilela et al., 2020; Kang et al., 2022). In this study, a linear function depicting the E-R curve and a NCS function (df = 3) depicting the L-R curve were proved to be optimal for all air pollutants. The cumulative effects of exposure to PM on lag 0 and lag 1 day were calculated, because our preliminary analyses showed that these two days were the potential susceptible window.

Sensitivity analyses were conducted. First, daily mean temperature data during the survey period were downloaded from the China Meteorological Data Sharing Service System (http://data.cma.cn/), and a “cross-basis” function for temperature were additionally included in the DLNMs to adjusted for the confounding effect of temperature. Second, Gross Domestic Product (GDP) per capita data were downloaded from the Data Center for Resources and Environmental Sciences (www.resdc.cn). Then, we further adjusted for GDP per capita of local district/county as a covariate in the DLNMs. Third, one recent study showed that higher greenness around schools may lower BP level among children (Luo et al., 2022). Thus, we estimated the greenness levels within 500 m of each school using normalized difference vegetation index (NDVI) according to that study (Luo et al., 2022), and then we adjusted for this variable as a covariate in the DLNMs. Data on NDVI were downloaded at http://earthexplorer.usgs.gov with a 30 m × 30 m resolution. We further performed several subgroup analyses based on gender (males and females), age group (aged <12 years and ≥12 years), weight status (normal weight and overweight/obesity), and physical activity (<1 h/day and ≥1 h/day).

We also examined the association of exposure to PM_1, $PM_{2.5}$ and PM_{10} with high BP using the national BP references for Chinese children and adolescents (Dong et al., 2017), and the 2017 American Academy of Pediatrics (AAP) BP guideline reference (Flynn et al., 2017). For both references, high BP was defined as SBP/DBP ≥95th percentile by sex, age, and height, or ≥130/80 mm Hg.

All analyses were conducted using R version 4.0.3 (The R Project for Statistical Computing, Vienna, Austria). The 95% CIs were adjusted for multiple comparisons using the Bonferroni correction (Wei et al., 2019c). A two-sided *P*-value < 0.05 was considered statistically significant.

3. Results

A total of 44630 students aged 7–18 years from 102 schools were included in the original survey, and 9095 students in grade one to grade three were excluded because their demographic and lifestyle data were not collected by the questionnaire. After further excluding 294 students with missing data, 35241 students aged 9–18 years were finally included in this study. Geographic locations of the 102 schools are presented in Fig. 1. The distributions of PM_1, $PM_{2.5}$, PM_{10}, $PM_{1\text{-}10}$ and $PM_{2.5\text{-}10}$ annual mean concentrations for the 102 schools across the year 2014 are shown in Fig. 2. The median (Q1, Q3) values of PM_1, $PM_{2.5}$, PM_{10}, $PM_{1\text{-}10}$ and $PM_{2.5\text{-}10}$ at the schools during the study period were 52.4 $\mu g/m^3$ (46.0, 56.5), 80.8 $\mu g/m^3$ (67.1, 85.5), 147.2 $\mu g/m^3$ (132.3, 153.5), 91.9 $\mu g/m^3$ (77.1, 101.6), and 65.8 $\mu g/m^3$ (53.8, 69.6), and the mean values of them were 50.8 (SD = 7.2) $\mu g/m^3$, 75.5 (SD = 14.7) $\mu g/m^3$, 138.9 (SD = 25.9) $\mu g/m^3$, 88.0 (SD = 22.4) $\mu g/m^3$, and 63.4 (SD = 13.9) $\mu g/m^3$, respectively. Table S1 shows the Spearman correlation relationships among PM fractions. $PM_{2.5}$ was negatively correlated with $PM_{2.5\text{-}10}$, whereas other PM fractions were positively correlated with each other. The characteristics of the included participants are shown in Table 1. Briefly, the mean age and BMI of the participants were 13.5 years and 20.1 kg/m^2, respectively. Mean SBP, DBP, MAP, and PP levels were 111.5 (SD: 13.4) mmHg, 70.3 (SD: 9.3) mmHg, 84.1 (SD: 9.6) mmHg, and 41.2 (SD: 10.6) mmHg, respectively.

Fig. S1 shows the unadjusted association and Fig. 3 shows the adjusted association of a per 10 $\mu g/m^3$ increment in PM_1, $PM_{2.5}$ and PM_{10} exposure with SBP, DBP, MAP, and PP at each lag day. At lag 0 and lag 1 day, a per 10 $\mu g/m^3$ increment in PM_1 was positively associated with an increment in SBP (β = 0.98 mmHg, 95% CI = 0.35 to 1.61, and β

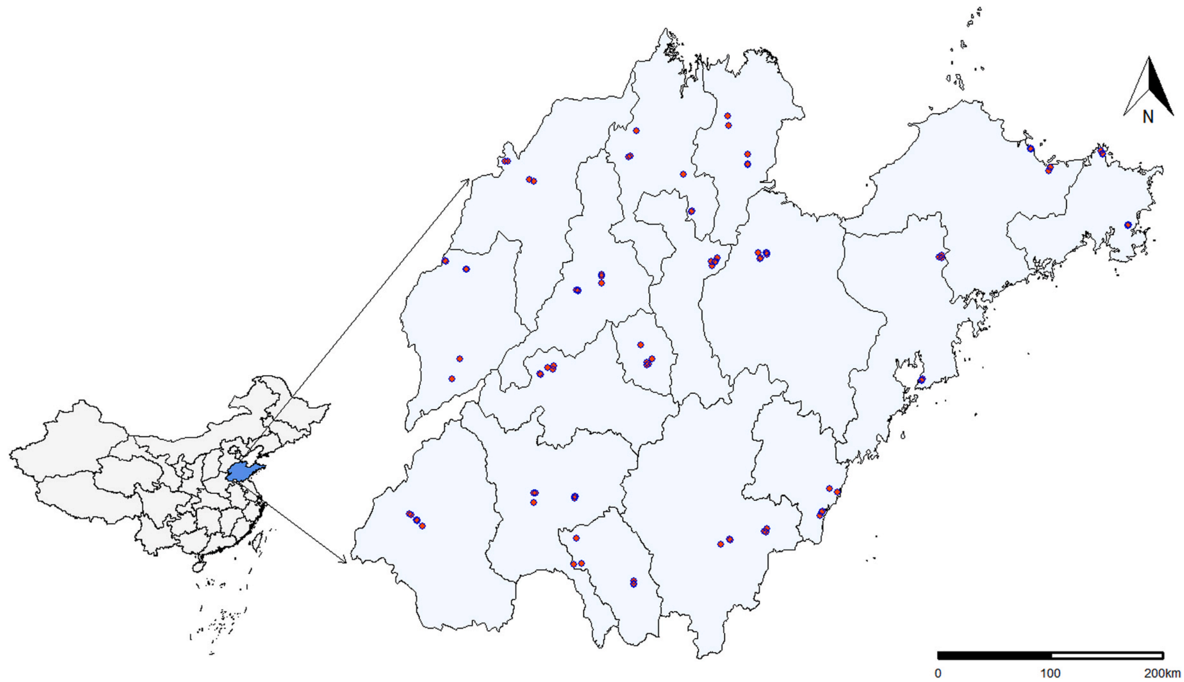

Fig. 1. Location of Shandong Province in China. *Note*: the 102 included schools are indicated by red circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

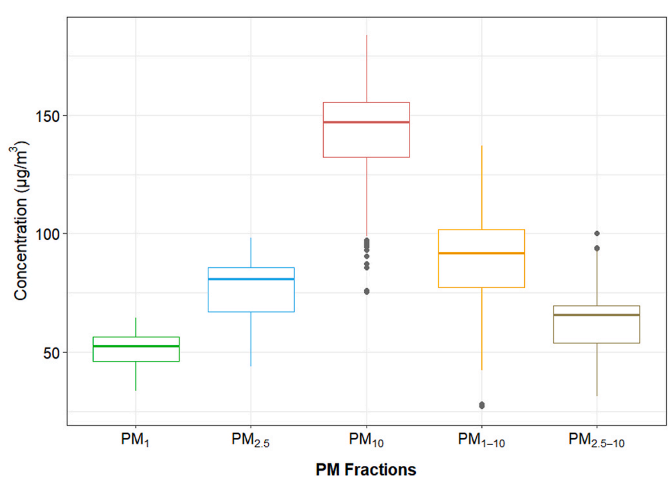

Fig. 2. The distributions of PM_1, $PM_{2.5}$, PM_{10}, $PM_{1\text{-}10}$ and $PM_{2.5\text{-}10}$ annual mean concentrations at the 102 schools across the year 2014.

= 0.48 mmHg, 95% CI = 0.13 to 0.83, respectively), DBP (β = 0.72 mmHg, 95% CI = 0.25 to 1.18, and β = 0.48 mmHg, 95% CI = 0.23 to 0.74, respectively), MAP (β = 0.80 mmHg, 95% CI = 0.34 to 1.26, and β = 0.48 mmHg, 95% CI = 0.23 to 0.74, respectively), and PP (β = 0.47 mmHg, 95% CI = 0.13 to 0.81, and β = 0.18 mmHg, 95% CI = −0.03 to 0.39, respectively) after adjusting for $PM_{1\text{-}10}$, SO_2 and NO_2 exposure and other covariates. At lag 0 and lag 1 day, a per 10 μg/m^3 increment in $PM_{2.5}$ and PM_{10} was also positively associated with a higher SBP, DBP, MAP, and PP after adjusting for covariates, respectively. A per 10 μg/m^3 increment in a cumulative exposure of PM_1, $PM_{2.5}$, and PM_{10} at lag 0 and lag 1 day was significantly associated with a higher SBP (β = 1.46 mmHg, 95% CI = 0.54 to 2.37, β = 0.92 mmHg, 95% CI = 0.10 to 1.75, and β = 0.73 mmHg, 95% CI = 0.27 to 1.19, respectively), DBP (β = 1.20 mmHg, 95% CI = 0.52 to 1.88, β = 0.77 mmHg, 95% CI = 0.16 to 1.39, and β = 0.60 mmHg, 95% CI = 0.26 to 0.94, respectively), MAP (β = 1.28 mmHg, 95% CI = 0.61 to 1.96, β = 0.81 mmHg, 95% CI = 0.21 to 1.42, and β = 0.64 mmHg, 95% CI = 0.31 to 0.98, respectively), PP (β = 0.65 mmHg, 95% CI = 0.14 to 1.16, β = 0.49 mmHg, 95% CI = 0.10 to 0.87, and β = 0.15 mmHg, 95% CI = 0.05 to 0.26, respectively), after adjusting for covariates. Fig. S2 shows the adjusted associations of $PM_{1\text{-}10}$ and $PM_{2.5\text{-}10}$ exposure with SBP, DBP, MAP, and PP, with no significant association.

Table 1
Characteristics of study participants.

Characteristics	Total (n = 35241)	Male (n = 17716)	Female (n = 17525)
Residence			
Urban	17262 (49.0)	8665 (48.9)	8597 (49.1)
Rural	17979 (51.0)	9051 (51.1)	8928 (50.9)
Age (years)	13.5 ± 2.8	13.4 ± 2.8	13.4 ± 2.8
BMI (kg/m^2)	20.1 ± 3.7	20.4 ± 3.9	19.6 ± 3.4
Intake of eggs			
<7 times/week	28210 (80.0)	13796 (77.9)	14414 (82.2)
≥7 times/week	7031 (20.0)	3920 (22.1)	3111 (17.8)
Intake of milk			
<7 times/week	21362 (60.6)	10294 (58.1)	11068 (63.2)
≥7 times/week	13879 (39.4)	7422 (41.9)	6457 (36.8)
Physical activity			
<1 h/day	23985 (68.1)	11689 (66.0)	12296 (70.2)
≥1 h/day	11256 (31.9)	6027 (34.0)	5229 (29.8)
Screen time			
<1 h/day	29401 (83.4)	14348 (81.0)	15053 (85.9)
≥1 h/day	5840 (16.6)	3368 (19.0)	2472 (14.1)
Sleep duration time			
<8 h/day	20190 (57.3)	10011 (56.5)	10179 (58.1)
≥8 h/day	15051 (42.7)	7705 (43.5)	7346 (41.9)
SBP (mmHg)	111.5 ± 13.4	114.0 ± 13.9	109.0 ± 12.4
DBP (mmHg)	70.3 ± 9.3	70.7 ± 9.6	69.9 ± 8.9
MAP (mmHg)	84.1 ± 9.6	85.2 ± 9.9	83.0 ± 9.2
PP (mmHg)	41.2 ± 10.6	43.3 ± 11.1	39.1 ± 9.6

Mean (standard deviation) and number (percentage) are presented for continuous and categorical variables, respectively.
Abbreviations: BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; PP, pulse pressure.

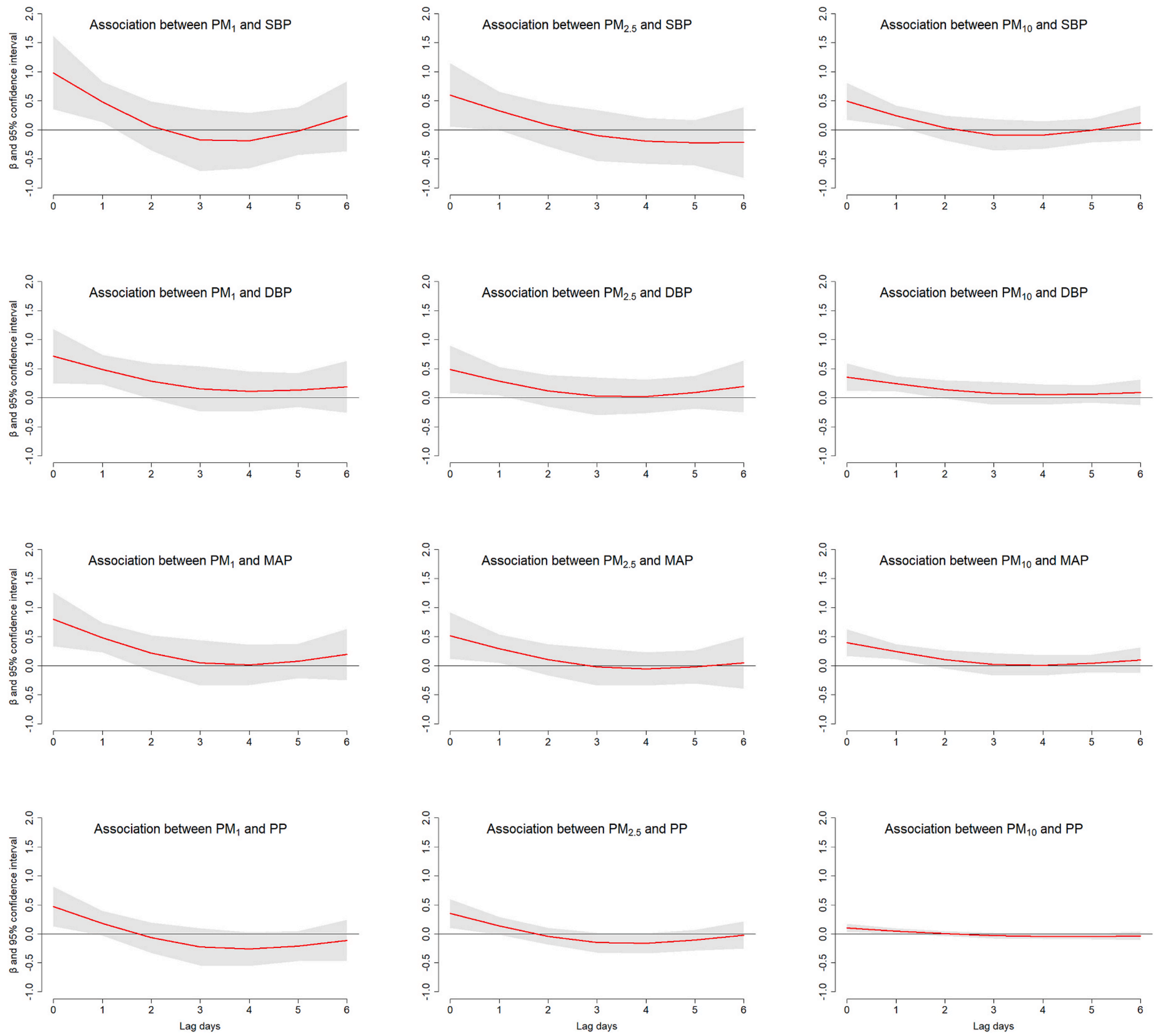

Fig. 3. The adjusted associations of per 10 μg/m^3 increment in PM_1, $PM_{2.5}$ and PM_{10} exposure with systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), and pulse pressure (PP) at lag 0–6 day.

Sensitivity analyses showed that additional adjustment for temperature (Fig. S3), local GDP per capita (Fig. S4), and greenness surrounding schools (Fig. S5) showed consistent findings with the main results. Results of subgroup analysis for PM_1 exposure are presented in Figs. S6–S9. We found that the associations of PM_1 with SBP, DBP, MAP, and PP were stronger among females, younger children (aged less than 12 years), those with overweight or obesity, and those with insufficient physical activity (less than 1 h/day), compared with their counterparts. Fig. S10 shows that there were no significant associations of exposure to PM_1, $PM_{2.5}$ or PM_{10} with high BP, regardless of the different definitions used for identifying high BP in this population.

4. Discussion

Among a large representative sample of Chinese children and adolescents, we found higher exposure to ambient PM fractions at lag 0 and lag 1 day was associated with increased levels of SBP, DBP, MAP, and PP, with PM_1 generally showing stronger association with SBP, DBP, MAP, and PP than $PM_{2.5}$ and PM_{10}. Our findings have important public health implications, highlighting that future air clean policies should cover the scope of PM_1 and relevant interventions should be conducted to reduce the impact of ambient PM exposure on health in children and adolescents.

Studies on long-term air pollution exposure have suggested that human BP levels might be more susceptible to PM_1 exposure than $PM_{2.5}$ and PM_{10} exposure. Using three- and one-year average concentrations, respectively, to denote long-term PM exposure, a study among 24845 Chinese adults from 33 communities and another study among 1.2 million adult couples from a Chinese national birth cohort found significant positive associations of BP levels with PM_1 and $PM_{2.5}$ exposure, with the magnitude of PM_1-BP association larger than $PM_{2.5}$-BP association (Yang et al., 2019a; Wang et al., 2020). To our knowledge, only Wu et al. have examined the effects of long-term exposure to PM_1 on BP levels among children and adolescents, and the authors found similar results with ours, which showed that a per 10-μg/m^3 increment in exposure to PM_1 and $PM_{2.5}$ during the past four year was associated with a 2.56 mmHg (95% CI: 1.47, 3.65) and 2.40 mmHg (95% CI: 1.17, 3.62), respectively, increase in SBP (Wu et al., 2020). Taken together, our findings and those from others suggest that PMs of smaller size might be more important for adverse health effects than PMs of larger size. Therefore, we suggest that it is necessary to adjust the air clean policy and alert the public to pay attention to ambient PM_1 since there is no environment standard on PM_1 concertation globally, although the WHO has recently updated their global air quality guideline on daily $PM_{2.5}$ and PM_{10} levels in September 2021 (World Health Organization, 2021).

We found that PM_1, $PM_{2.5}$ or PM_{10} exposure at lag 0–1 days were positively associated with BP levels, which was similar with a study suggesting $PM_{0.2}$ and $PM_{0.5}$ exposure at lag 7–24 h were associated with increased SBP in 88 healthy young adults (Guo et al., 2021). However, our findings are not consistent with two previous studies which suggested that lag 2–6 days or lag 1–6 days, respectively, was the susceptible window for $PM_{2.5}$ exposure in the pediatric population (Yang et al., 2019b; Hu et al., 2020). The discrepancies may be due to difference in methodology of estimating PM exposure, variations in PM constituents among geographical regions, and analytic models. It is worth noting that we applied DLNM in our study which is characterized by isolating the independent effect of an exposure at a certain time point while adjusting for exposures at all other time points (Bello et al., 2017). However, other studies generally regarded exposures at each lag day separately, which might ignore the confounding effect of adjacent days. Of note, we observed that the association between high BP and short-term exposure to PM fractions was not significant, regardless of the different BP references used in this population. By contrast, Wu et al. reported that each 10-$\mu g/m^3$ increment in exposure to PM_1 and $PM_{2.5}$ during the past four year was associated with a 61% (OR = 1.61, 95% CI: 1.18 to 2.18) and 55% (OR = 1.55, 95% CI: 1.11 to 2.16) higher risk for high BP in children (Wu et al., 2020). For the different findings between the study by Wu et al. and our study, we speculate that short-term exposure to PM may cause acute but small rise in BP levels, and only after a sufficient long period of cumulative exposure, the children and adolescents may have increased risk of developing high BP.

The biological mechanisms underlying BP alteration and short-term exposure to PM remain unclear. However, several potential pathways have been speculated. First, BP variability is partly determined by the sympathovagal balance of cardiovascular regulation (Guo et al., 2021). The nerve endings and receptors in the airways may be stimulated by inhaled particles, leading to an imbalance of the autonomic nervous system and further arterial vasoconstriction (Wu et al., 2020). Second, systemic inflammation and oxidative stress triggered by PM may also accelerate vasoconstriction, further affecting hemodynamic responses (Zhu et al., 2021a). Third, smaller particles have a higher surface area to mass ratio, thus their greater surface area facilitates the adsorption of toxic substance (Yang et al., 2019a). In addition, particles with smaller diameter, such as PM_1, may deposit into the smaller branches of the respiratory tree and even pass through the air-blood barrier and subsequently enter the circulatory system (Orona et al., 2019). The above pathways may help explain the relatively stronger associations we observed of smaller PM fractions and the acute rise in BP levels in response to short-term PM exposure.

Girls seemed to be more susceptible to PM-induced BP effects. This is in line with findings from two studies, and this gender-specific PM effect might be attributed to variation of hormonal levels and metabolic status between genders (Dong et al., 2015; Yang et al., 2019b). We observed that younger children were more susceptible to PM_1 exposure than adolescents. Wu et al. also found a similar age-depended pattern (Wu et al., 2020). Compared with their older counterparts, younger children have higher rates of cellular mitosis because of their vigorous growth and organ development (Wu et al., 2020). In addition, less developed lungs combined with immature metabolic pathways may further amplify their vulnerability to PM exposure (Wu et al., 2020). The associations of PM_1 exposure with SBP, DBP, and MAP were consistently larger for overweight/obese children than normal-weight children. Accumulating evidence suggests that obesity is associated with enlarged hypertrophied adipocytes and variations in secretion of free fatty acids as well as adipokines, and all of which could lead to vascular inflammation and oxidative stress (Kochumon et al., 2021). Therefore, PM exposure in concert with overweight and obesity might cause a synergistic effect on BP levels. We observed stronger PM_1-DBP, PM_1-MAP, and PM_1-PP associations in participants with insufficient physical activity (<1 h/day) than in those with sufficient physical activity (≥1 h/day). This might be because physical activity could mitigate some inflammatory responses. A murine study also showed that 10-weeks of exercise training could avoid increases in proinflammatory cytokines (IL-23 and IL-12p40) (Olivo et al., 2021).

Our findings add to the growing literature evaluating the role of exposure to PM fractions on human BP levels. To our knowledge, no previous study has examined the relationship between short-term exposure to PM_1 and BP levels in children and adolescents. Survey data used in this study were collected from a province with severe PM pollution in China, adding more epidemiological evidence to the understanding of the short-term effects of exposure to PM fractions on BP levels. Although the observed association between PM fractions and BP levels was relatively small, there is evidence that even a 1–2 mmHg population-wide reduction in SBP can reduce the hypertension prevalence by 10% in children, and a decrease of 2 mmHg in SBP can lower mortality from stroke by 10% in adults (Ingelfinger, 2004; Jafar et al., 2010). Considering the severe PM pollution and the huge amount of population in China, it is crucial to protect the pediatric population against PM related health burden.

Several limitations should be noted. First, we used air pollutant concentrations at schools as the individual exposure level because residential address was not collected in the survey. In addition, we used air pollutant data generated from aggregated datasets rather than personal measurements. Although these datasets have relatively high accuracy, measurement errors of personal exposure were unavoidable. However, previous studies suggest that this kind of error is non-differential and might underestimate observed effects (Chen et al., 2019). Second, the absence of data on some factors known to influence BP levels, such as household income and coal use, family history of hypertension, parental education, active and passive smoking, and medication use, might bias our results. However, adjustment for most of the abovementioned variables had little influence on the association between PM fractions and BP levels in a previous study (Wu et al., 2020). Third, data on smaller size and specific constituents of particles were unavailable in this study, which did not allow us to fully determine the toxicity of the particle mixture or to account for the adverse effects on BP levels associated with PM fractions or their constituents. For example, a positive association between elevated BP in adults and ultrafine particles (PM < 0.1 μm) and some specific constituents of $PM_{2.5}$ (e.g., elemental carbon, organic carbon, ammonium and nitrate) has been shown (Lin et al., 2017, 2021).

5. Conclusion

In conclusion, the susceptible window for short-term exposure to ambient PM_1, $PM_{2.5}$ and PM_{10} on BP levels among children and adolescents are lag 0 and lag 1 day, with PM_1 exposure exhibiting a stronger association. Future air clean policies should cover the scope of PM_1 and further raise public attention to PM_1. The impact of population interventions, such as the wearing of masks and use of air purifiers, should be conducted to determine any benefit in reducing the impact of ambient PM exposure to BP levels among children and adolescents.

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CRediT authorship contribution statement

Han Wu: Formal analysis, Methodology, Visualization, Writing – original draft. **Yingxiu Zhang:** Investigation, Resources, Data curation, Writing – review & editing. **Min Zhao:** Formal analysis, Validation, Writing – original draft. **Wenhui Liu:** Software, Writing – review & editing. **Costan G. Magnussen:** Methodology, Writing – review & editing. **Jing Wei:** Methodology, Resources, Data curation, Writing – review & editing. **Bo Xi:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2022.119180.

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