Environmental Science and Pollution Research (2022) 29:71665–71675
https://doi.org/10.1007/s11356-022-20842-6

RESEARCH ARTICLE

Association between short-term exposure to ambient PM_1 and $PM_{2.5}$ and forced vital capacity in Chinese children and adolescents

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Received: 3 January 2022 / Accepted: 11 May 2022 / Published online: 23 May 2022

Abstract

This study aims to examine the association between short-term exposure to ambient PM_1, $PM_{1\text{-}2.5}$, and $PM_{2.5}$ and forced vital capacity (FVC). Population data were obtained from a school-based cross-sectional survey in Shandong in 2014. Distributed lag non-linear models were used to examine the association between exposure to PM_1, $PM_{1–2.5}$, and $PM_{2.5}$ and FVC at the day of FVC measurement and the previous 6 days (lag 0 to 6 days). A total of 35,334 students aged 9 to 18 years were included in the study, and the mean exposure concentrations of ambient PM_1, $PM_{1–2.5}$, and $PM_{2.5}$ for them were 47.4 (standard deviation [SD] = 21.3) μg/m^3, 32.8 (SD = 32.2) μg/m^3, and 80.1 (SD = 47.7) μg/m^3, respectively. An inter-quartile range (IQR, 24 μg/m^3) increment in exposure to PM_1 was significantly associated with a lower FVC at lag 0 and lag 1 day (β = − 80 mL, 95% CI = − 119, − 42, and β = − 37 mL, 95% CI = − 59, − 16, respectively), and an IQR (54 μg/m^3) increment in exposure to $PM_{2.5}$ was significantly associated with a lower FVC at lag 0 and lag 1 day (β = − 57 mL, 95% CI = − 89, − 18, and β = − 34 mL, 95% CI = − 56, − 12, respectively) after adjustment for gender, age, body mass index category, residence, month of the survey, intake of eggs, intake of milk, physical activity, and screen time. No significant associations were observed for $PM_{1–2.5}$. The inverse associations of PM_1 and $PM_{2.5}$ with FVC were larger in males, younger children, those overweight or obese, and those with insufficient physical activity levels. Short-term exposure to ambient PM_1 and $PM_{2.5}$ was associated with decreased FVC, and PM_1 may be the primary fraction of $PM_{2.5}$ causing the adverse pulmonary effects. Our findings emphasize the need to address ambient PM, especially PM_1, pollution for affecting pulmonary health in children and adolescents.

Keywords Particulate matter · PM_1 · $PM_{2.5}$ · Forced vital capacity · Children · China

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Responsible Editor: Lotfi Aleya

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Introduction

Chronic respiratory diseases pose a major public health problem globally, with an estimated 7.6 million deaths in 2019 by chronic pulmonary disease (COPD), lower respiratory infections, and trachea, bronchus, and lung cancers, and chronic respiratory diseases accounted for 13.7% of all deaths worldwide (World Health Organization 2020b, 2020a). For decades, a growing amount of evidence linked ambient particle matters with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) exposure to morbidity and mortality for these respiratory diseases (Losacco and Perillo 2018). It was estimated that the number of global COPD and lung cancer deaths attributable to exposure to ambient $PM_{2.5}$ was 0.31 and 7.02 million, and the number of disability-adjusted life years (DALYs) of them attributable to that was 0.70 and 15.41 million, respectively (World Health Organization 2020b, 2020a).

Children and adolescents are considered to be particularly susceptible to particulate matter (PM)-related respiratory system impairment because of their immature immune system, developing lungs, and higher volume of air inhalation per kilogram of body weight compared with adults (Tasmin et al. 2019). Increasing evidence suggests that exposure to ambient PM is associated with various detrimental health outcomes (e.g., obesity, hypertension, metabolic syndrome, visual impairment, pneumonia, and reduced renal function) in the pediatric population (Ban et al. 2021; Li et al. 2021b; Wang et al. 2021b; Wu et al. 2020; Yang et al. 2021; Zhang et al. 2021c). Previous studies mainly focused on the effect of exposure to PM on the lung function, which is a significant predictor for future pulmonary morbidity and mortality (Bui et al. 2017; Wong et al. 2016), and most of these studies consistently reported that both short- and long-term exposure to $PM_{2.5}$ or particle matters with aerodynamic diameter ≤ 10 μm (PM_{10}) were associated with a decreased lung function (Chen et al. 2018; Fuertes et al. 2015; Gehring et al. 2013; Hwang et al. 2015; Li et al. 2020; Rice et al. 2016; Tasmin et al. 2019; Wong et al. 2016; Wu et al. 2021).

PM_1 (particle matters with aerodynamic diameter ≤ 1 μm) is the dominant component of PM, and substantial research revealed that smaller sizes of PM fractions are more harmful to child health (Wang et al. 2021b; Wu et al. 2020; Zhang et al. 2021c). However, the majority of published PM_1-related studies has focused on the effect of long-term exposure on lung function (Chen et al. 2018; Tasmin et al. 2019; Wu et al. 2021), and the evidence on the relation between short-term exposure to PM_1 and lung function in the pediatric population is limited. The forced vital capacity (FVC) is known as a common indicator of lung function, measuring the total volume exhaled after a maximum inspiration. It is related to all-cause mortality in the general population (Collaro et al. 2021; Gaffney et al. 2021) and can predict it better than body mass index (BMI) or systolic blood pressure (Gupta and Strachan 2017). Many studies showed significant links between FVC and cardiovascular diseases and cardiovascular risk factors (e.g., obesity, hypertension, and diabetes) (Jacobs et al. 2012; Laurendi et al. 2015; Wang et al. 2018). In addition, FVC is more associated with exposure to ambient PM when compared to other indicators for lung function such as forced expiratory volume in one second (FEV_1) among children (Frye et al. 2003; Svendsen et al. 2012). The aim of this study was to examine the association between short-term exposure to ambient PM_1 and FVC among children and adolescents in Shandong province of China.

Methods

Study population

Data were obtained from a school-based cross-sectional survey in the Shandong province, and this survey was a part of the Chinese National Survey on Students' Constitution and Health (CNSSCH) which was initially designed to assess physical fitness, growth, and nutritional status of Chinese children and adolescents (Dong et al. 2019; Song et al. 2019). The CNSSCH covered all 17 prefectures of the Shandong province and was carried out in September and October in 2014 with a multistage stratified cluster sampling method (Zhang et al. 2021b). Briefly, one district (representing an urban area) and one county (representing a rural area) were first randomly selected from each prefecture, and three schools (i.e., primary, junior high, and senior high schools) were further randomly selected from each district/county to form a sample pool of school students aged 7–18 years. Within each school, two classes in each grade were randomly selected, from which all students were invited to participate in the study. Informed consent was obtained from both the participants and their parents or guardians. Ethical approval was obtained from the Ethics Review Committee of Public Health, Shandong University.

Measurements

A standard questionnaire, collecting demographic, dietary, and lifestyle information, was handed out to all students in grade four or above in primary schools and to all students in high schools. Questionnaire-based information for students under grade four was not collected, because they were considered to be too young to be able to satisfactorily complete the questionnaire. FVC and anthropometry were then measured by trained technicians in each survey site along a standardized protocol. All participants were in apparently good health, free from overt diseases and deformities.

FVC was measured with an electronic spirometer which was calibrated before use. Students were asked to take forced expiratory measurement twice in a comfortable standing position after having been instructed by the technicians and were asked to have a rest between the two measurements. The maximum value of the two measurements was recorded in milliliter (mL). Height without shoes was measured to the nearest 0.1 cm. Weight was measured using lever scales to the nearest 0.1 kg in light clothing. BMI was calculated as weight divided by the square of height (kg/m^2). Cut-off values for identifying overweight and obesity were based on sex- and age-specific BMI references from the National Health Commission of China (National Health Commission of China 2018).

Air pollution data

Daily ambient PM_1, $PM_{2.5}$, SO_2, and NO_2 are measured in the Shandong province in at a spatial resolution of 0.1° (≈10 km^2) and data were available from the ChinaHighAirPollutants (CHAP) dataset (https://weijing-rs.github.io/product.html). SO_2 and NO_2 data were also collected because they were regarded as potential confounders which should be adjusted for in analytic models. Air pollutant data were estimated from ground-based measurements, satellite remote sensing products, atmospheric reanalysis, and model simulations using the developed space–time extremely randomized trees (STET) model (Wei et al. 2020, 2019a, 2022, 2021). These predicted levels of air pollutants are reliable compared to ground-level measurements with a cross-validation coefficient of determination (CV-R^2) of 0.83, 0.91, 0.84, and 0.84 for PM_1, $PM_{2.5}$, SO_2, and NO_2 on a daily basis, respectively (Wei et al. 2020, 2019a, 2022, 2021). These datasets have been widely applied in recent epidemiological studies evaluating the impact of air pollution exposure on human health in China (Ge et al. 2021; Wang et al. 2021a; Xu et al. 2021; Zhang et al. 2021a).

School geographical location was converted into longitude and latitude coordinates based on an online Coordinates Identification System (http://api.map.baidu.com/lbsapi/getpoint/index.html), and daily concentrations of ambient PM_1, $PM_{2.5}$, SO_2, and NO_2 at each school were generated according to these coordinates. We estimated the concentrations of $PM_{1–2.5}$ by subtracting PM_1 from $PM_{2.5}$ (Chen et al. 2019). The concentration of the ambient air pollutants on the day of the FVC measurement was assigned as having a lag time interval of 0 day; concentration on the day before the day of FVC measurement was assigned as having a lag time of 1 day between exposure to air pollution and FVC measurement; and so on. We considered a maximum lag time of 6 days, which was consistent with previous studies (Hu et al. 2020; Yang et al. 2019).

Data analysis

Means with standard deviation (SD) were calculated for continuous variables and proportions for categorical variables. Median values with the first quartile (Q1) and the third quartile (Q3) values were used to describe the distribution of air pollutants.

Distributed lag non-linear models (DLNMs) were used to examine the associations between daily PM_1, $PM_{1–2.5}$, and $PM_{2.5}$ exposure and FVC. DLNMs are suitable for exploring short-term sequential exposures on an outcome of interest, since these modeling techniques can simultaneously estimate the nonlinear (or linear) and lagged time interval relationship between an exposure and an outcome of interest (Gasparrini 2014; Gasparrini et al. 2010). The core structure of a DLNM is the "cross-basis" function, which integrates two separate functions. The first function estimates the exposure–response (E-R) association and the second function estimates the lag-response (L-R) association (Gasparrini 2014; Gasparrini et al. 2010). A natural cubic spline with a degree of freedom (*df*) of 3 was used to model the L-R association because of its flexibility and the requirement for parsimony when a short lag period between exposure and outcome is expected (Gasparrini 2014; Gasparrini et al. 2010). We also considered linear, quadratic B-spline, and natural cubic spline models to describe the E-R association, and *df*s ranging from 3 to 6 were alternated to test for an optimal fit of the latter two functions, (Gasparrini 2014; Gasparrini et al. 2010). The minimum Akaike information criterion (AIC) was used to select the optimal function to model the E-R association (Gasparrini 2014; Gasparrini et al. 2010).

We first built three unadjusted DLNMs by only including the "cross-basis" function for PM_1, $PM_{1–2.5}$, and $PM_{2.5}$ without adjusting for other variables. We then added "cross-basis" functions for SO_2, NO_2, and individual covariates to build adjusted DLNM models. In addition, the "cross-basis" function for $PM_{1–2.5}$ was included in the adjusted DLNM for PM_1 and the "cross-basis" function for PM_1 was included in the adjusted DLNM for $PM_{1–2.5}$, to account for their confounding effects. In the adjusted DLNMs, individual covariates were gender, age, BMI category (normal weight, overweight, and obesity), residence, month of the survey, intake of eggs, intake of milk, physical activity, and screen time, and they were all assigned fixed effects. Variables regarding intake of eggs and of milk were included as covariates because they were considered as proxies for household socioeconomic level (Kang et al. 2022; Vilela et al. 2020). The optimal "cross-basis" functions for SO_2 and NO_2 were selected also based on the minimum AIC. As a result, linear functions for E-R association were used for all air pollutants in the analysis. The effect estimates were obtained from linear mixed models, in which school and prefecture were considered as random effects. The effect estimates were expressed as regression coefficients (β) with 95% confidence intervals (CI). For comparison of the effect estimates among PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ exposure, βs were calculated for a difference in exposure corresponding to the inter-quartile range (IQR) in exposure levels of PM_1, $PM_{1-2.5}$, and $PM_{2.5}$, respectively. In addition, our preliminary analyses showed that the lag 0 and lag 1 day was the potential susceptible window. Hence, the cumulative effects of exposure to PM on lag 0 and lag 1 day were then calculated.

We performed several sensitivity analyses to account for potential confounding variables. First, to control for the confounding effect of temperature on child FVC, the mean temperature on the day of FVC measurement was additionally adjusted. Local daily temperature data during the survey period were collected from the China Meteorological Data Sharing Service System (http://data.cma.cn/). Second, to control for the influence of local economic level on our results, gross domestic product (GDP) per capita for each district/county was additionally adjusted as a covariate. The GDP per capita for the Shandong province of the year 2015 were extracted from the Data Center for Resources and Environmental Sciences (www.resdc.cn). Although this dataset was built for year 2015, we assumed that this economic indicator for years 2014 and 2015 was highly correlated and using this 1-year lag dataset only had minimal influence. Third, we assigned to each student a surrogate for long-term exposure to PM of the mean PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ concentrations between Jan 1st, 2014, to the day of FVC measurement to control for the influence of long-term exposure to PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ on the observed short-term PM-FVC association.

We also conducted several subgroup analyses stratified by sex, age group (aged $\leq$ 12 years and > 12 years), weight status (normal weight and overweight/obesity), and physical activity (< 1 h/day and $\geq$ 1 h/day). The 95% CIs were adjusted for multiple comparisons using the Bonferroni correction (Wei et al. 2019b). All analyses were conducted in R version 4.0.3 (The R Project for Statistical Computing, Vienna, Austria). The two-sided *P*-value of < 0.05 was considered to have statistically significance.

Results

There were 44,630 students aged 7 to 18 years from 102 schools in the original survey, and 9095 students under grade four were excluded due to the absence of questionnaire data. A total of 35,334 students aged 9 to 18 years were finally included in this study after excluding 201 students with missing data. Geographic locations of the 17 prefectures in Shandong province and the included 102 schools are presented in Fig. 1.

Table 1 shows the characteristics of the included participants. Of the included 35,334 participants, the average age, BMI, and FVC were 13.5 years (SD = 2.8 years), 20.1 kg/m^2 (SD = 3.7 kg/m^2), and 2646 mL (SD = 1059 mL), respectively. The proportions of males and females were both 50.0%, and 51.0% (*n* = 18,018) of the participants were from rural region. The median (Q1, Q3) exposure concentrations of ambient PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ for all participants were 42.0 (33.0, 57.0) μg/m^3, 27.7 (11.0, 48.0) μg/m^3, and 70.0 (47.0, 101.0) μg/m^3, and the corresponding IQR were 24 μg/m^3, 37 μg/m^3, and 54 μg/m^3, respectively. The mean exposure concentrations of ambient PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ for all participants were 47.4 (SD = 21.3) μg/m^3, 32.8 (SD = 32.2) μg/m^3, and 80.1 (SD = 47.7) μg/m^3, respectively.

Figure 2 shows the unadjusted and adjusted associations between per IQR increment in exposures to PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ and FVC at each lag day. In unadjusted models, per IQR increment in PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ was significantly associated with a decrease in FVC at lag 0–2 day, lag 0 day, and lag 0–1 day, respectively. In adjusted models, the increment of per IQR (24 μg/m^3) for PM_1 was significantly associated with a lower FVC at lag 0 and lag 1 day (β = − 80 mL, 95% CI = − 119, − 42, and β = − 37 mL, 95% CI = − 59, − 16, respectively) after adjusting for $PM_{1-2.5}$, SO_2, NO_2 exposure, and individual covariates. Per IQR (54 μg/m^3) increment in $PM_{2.5}$ was significantly associated with a lower FVC at lag 0 and lag 1 day (β = − 53 mL, 95% CI = − 89, − 18, and β = − 34 mL, 95% CI = − 56, − 12, respectively) after adjusting for SO_2, NO_2, and individual covariates. The decrease of FVC of cumulative exposure to per IQR increase in PM_1 and $PM_{2.5}$ at lag 0 and lag 1 days were 118 mL (95% CI = − 174, − 62) and 87 mL (95% CI = − 141, − 33), respectively. There was no significant association between $PM_{1-2.5}$ exposure and FVC at lag 0 to lag 6 days. Figure S1 shows the adjusted associations between SO_2 and NO_2 exposure, respectively, and FVC after adjusting for PM_1 and $PM_{1-2.5}$ exposure and individual covariates, with no significant associations observed.

As shown in Figure S2, S3, and S4, the three sensitivity analyses showed that additional adjustment for temperature, local GDP per capita, and long-term exposure were consistent with the main results. Results of subgroup analyses are presented in Figure S5, S6, S7, and S8. We found that the associations of PM_1 and $PM_{2.5}$ exposures, respectively, with FVC were stronger in magnitude among males, younger children (aged less than 12 years), those with overweight or obesity, and those with insufficient physical activity (less than 1 h/day).

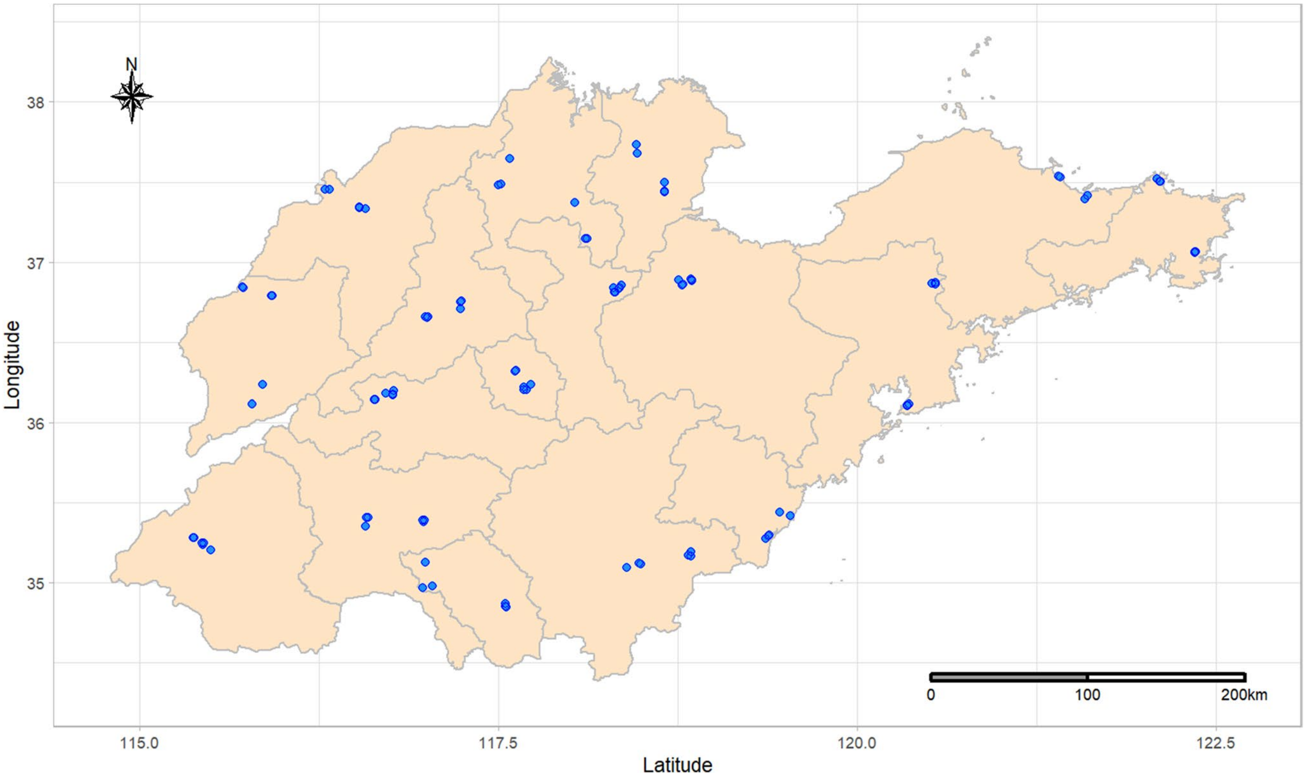

Fig. 1 Geographic location of the 17 prefectures in the Shandong province. The included 102 schools are indicated by blue dots

Discussion

This study is among the first to assess the association between short-term exposure to ambient PM_1, $PM_{1-2.5}$, and $PM_{2.5}$ and FVC based on a large sample size in children and adolescents. We found that short-term exposure to ambient PM_1 and $PM_{2.5}$ was associated with reduced FVC in children and adolescents, and the association with PM_1 was stronger than that with $PM_{2.5}$, but no significant association between $PM_{1-2.5}$. Findings from our study indicate that smaller particles may play a greater role than larger particles in the associations with FVC. Furthermore, the association was larger for male, younger or overweight children, and those with insufficient physical activity.

Previous studies regarding ambient PM and lung function in children focused on the short-term effects of exposure to $PM_{2.5}$ on using peak expiratory flow (PEF) and forced expiratory volume within 1 s (FEV_1) but had fairly small sample sizes (generally no larger than 500) (Chen et al. 2018; Tasmin et al. 2019; Wu et al. 2021). Two longitudinal studies from China showed that exposure to $PM_{2.5}$ was associated with decreased FVC and FEV_1 at lag 0 to 2 days (Chen et al. 2018; Wu et al. 2021). Another study in 315 Bangladeshi children found a reduced PEF at lag 1–2 day and reduced FEV_1 at lag 1 day with $PM_{2.5}$ (Tasmin et al. 2019). Our findings are consistent, although not identical, with these other studies since we observed a significant $PM_{2.5}$-FVC association only at lag 0 and lag 1 day.

With respect to PM_1, most previous studies examined the long-term association with PM_1. For example, several studies in China, which used 4-year mean PM concentrations to assess long-term exposure, found a long-term impact of PM_1 and $PM_{2.5}$ on the lung function (Xing et al. 2020; Yang et al. 2020; Zhang et al. 2019). Only one study has examined the effect of short-term exposure to PM_1 on the lung function in children (Zwozdziak et al. 2016). This study, which included 141 children aged 13–14 years, reported that the association between PM and FVC and PEF was larger for $PM_{2.5}$ than PM_1, which contrasts with our findings. Discrepancies of results between studies may relate to difference in methods used for estimating air pollutant exposure (averaging the measurements from monitoring sites or integrated data from multiple environmental sources), variations in the composition of particulate matter constituents across geographical regions, difference in statistical power (sample sizes), and analytic models.

A number of biological mechanisms may underlie the detrimental impact of particulate matter on pulmonary function. In particular, one pathophysiological pathway underlying the PM-FVC association might be the onset of airway inflammatory response while acute exposure to PM

Table 1 Main characteristics of participants in this study

Characteristics	Total ($n = 35{,}334$)	Male ($n = 17{,}777$)	Female ($n = 17{,}557$)
Residence	☐	☐	☐
Urban	17,316 (49.0)	8705 (49.0)	8611 (49.0)
Rural	18,018 (51.0)	9072 (51.0)	8946 (51.0)
Age (years)	13.4 ± 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
BMI category			
Normal weight	26,938 (76.2)	12,544 (70.6)	14,394 (82.0)
Overweight	4973 (14.1)	3049 (17.2)	1924 (11.0)
Obesity	3423 (9.7)	2184 (12.2)	1239 (7.0)
Intake of eggs			
< 7 times/week	28,286 (80.1)	13,849 (77.9)	14,437 (82.2)
≥ 7 times/week	7048 (19.9)	3928 (22.1)	3120 (17.8)
Intake of milk			
< 7 times/week	21,415 (60.6)	10,325 (58.1)	11,090 (63.2)
≥ 7 times/week	13,919 (39.4)	7452 (41.9)	6467 (36.8)
Physical activity			
< 1 h/day	24,041 (68.0)	11,724 (66.0)	12,317 (70.2)
≥ 1 h/day	11,293 (32.0)	6053 (34.0)	5240 (29.8)
Screen time			
< 1 h/day	29,477 (83.4)	14,396 (81.0)	15,081 (85.9)
≥ 1 h/day	5857 (16.6)	3381 (19.0)	2476 (14.1)
FVC (mL)	2646 ± 1059	3046 ± 1169	2241 ± 740

Mean (standard deviation) and number (percentage) are presented for continuous and categorical variables, respectively

Abbreviations: *BMI*, body mass index; *FVC*, forced vital capacity

even in a very short period (Paunescu et al. 2019). Several longitudinal panel studies in both the pediatric and adult population found a short-term impact of PM_1 or $PM_{2.5}$ and lung function that was accountable to elevated fractional exhaled nitric oxide, which is a biomarker of airway inflammation (Chen et al. 2021; Sun et al. 2021; Wang et al. 2021c; Wu et al. 2021). In addition to the inflammation caused by inhaled PM in the alveolar ducts and the alveolus, PM can trigger endothelial and oxidative stress which can lead to pulmonary dysfunction (Losacco and Perillo 2018). No significant association between short-term exposure to ambient $PM_{1-2.5}$ and FVC was observed in this study, and previous studies also found that PM_1 rather than $PM_{1-2.5}$ contributed to $PM_{2.5}$-induced hospital admission or mortality of respiratory diseases (e.g., COPD and pneumonia), which was consistent with our findings (Zhang et al. 2020; Zhu et al. 2021). These as well as our findings suggest that smaller PM fractions may play an important role in determining the toxicity attributable to ambient PM. Smaller PM fractions can reach the lungs deeper than larger ones, and they have larger surface area to volume ratio and higher level of adsorbed or condensed toxic compounds per unit mass (Caggiano et al. 2019). Thus, smaller PM fractions have a larger potential to induce detrimental biological interactions with pulmonary tissues (Mei et al. 2018).

The association between PM and lung function was larger in boys than girls, and this finding was in accordance with a previous study. Yang et al. reported that per IQR increase in long-term exposure to PM_1 was associated with more decrease in FVC (− 163.2 vs. − 148.1 mL) and FEV1 (− 119.4 vs. − 116.4 mL) among boys than girls (Yang et al. 2020). Schultz et al. found similar larger association among boys, although they used PM_{10} as the exposure variable (Schultz et al. 2012). This sex difference may be related to the larger surface area of alveoli in males than females at any given age; thus, more particulate matter would deposit in their lungs (Carey et al. 2007). We also observed a larger association of PM_1 with lung function in younger children. This may relate to rapid growth and organ development in early life with the respiratory and metabolic system not being yet fully developed (Chen et al. 2018; Li et al. 2021a). Thus, the less developed lungs accompanied with the immature metabolic pathways may pose them at a higher risk to PM exposure (Wu et al. 2020).

The PM_1-FVC and $PM_{2.5}$-FVC associations were consistently larger in magnitude for overweight/obese children than for normal-weight children at lag 0 and 1 day. This is

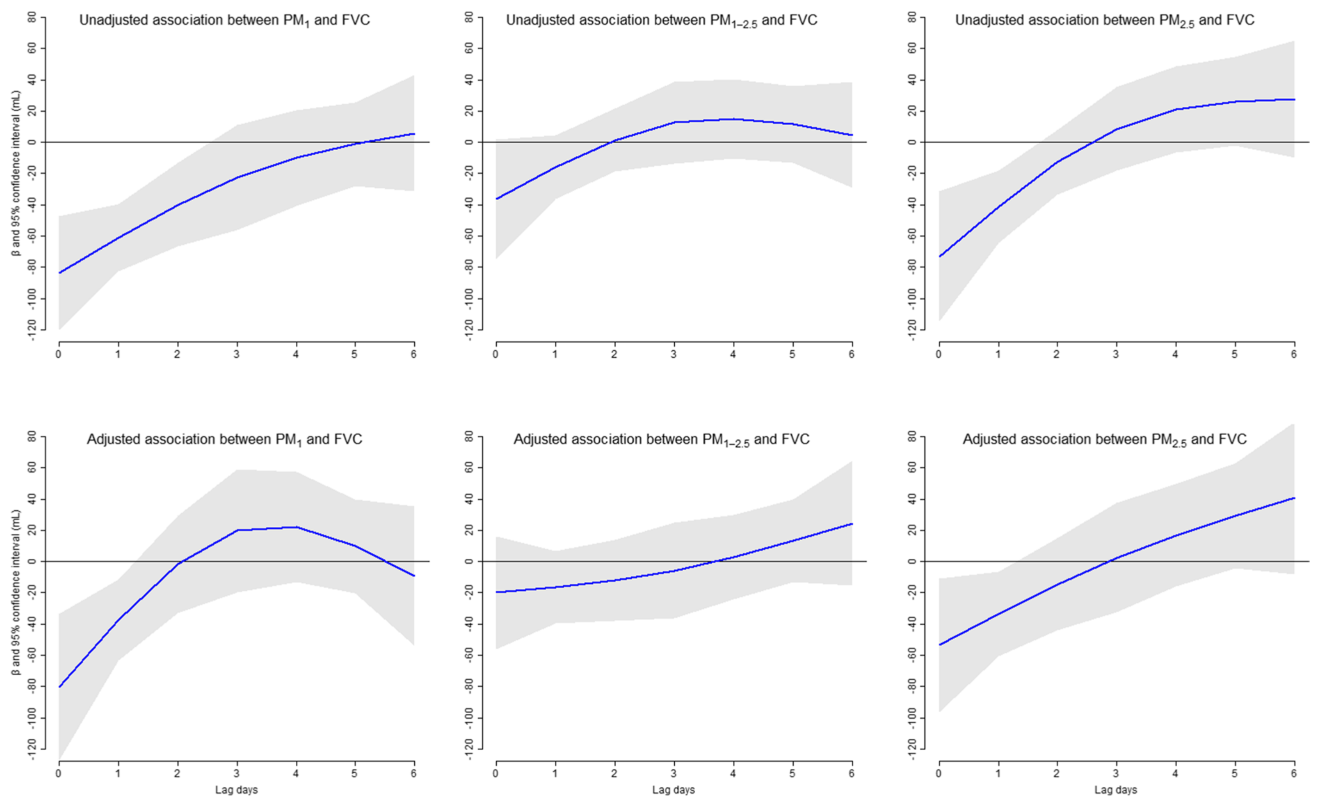

Fig. 2 The unadjusted and adjusted association between per inter-quartile range increment in PM$_1$, PM$_{1-2.5}$, and PM$_{2.5}$ exposure and forced vital capacity (FVC) at lag 0 to 6 day

consistent with a study in 6740 children from seven Chinese cities that found a graded relationship between long-term exposure to PM$_1$ and PM$_{2.5}$ and FVC among normal weight, overweight, and obese children (Xing et al. 2020). Adipokines (e.g., adiponectin and leptin) generated by adipose tissue are mediators of inflammatory response, and proinflammatory cytokines (such as IL-1b, IL-6, and TNF-a) produced by adipocytes are also involved in inflammation and oxidative stress (Endalifer and Diress 2020, Kochumon et al. 2021, Wiebe et al. 2021). This may be a pathway through the association of PM with lung function that can be larger in overweight vs. normal weight children. We also found that a stronger association between PM and lung function in children with low physical activity (<1 vs. ≥ 1 h/day), which is possibly because some inflammatory responses can be reduced via physical activity. This is evidenced by a latest murine study indicating that 10 weeks of exercise training could reduce the release of some proinflammatory cytokines (IL-23 and IL-12p40) (Olivo et al. 2021).

Our study has several strengths. First, we included a large number of participants ($n = 35{,}334$) from all prefectures in Shandong province, and the range of daily PM$_1$ and PM$_{2.5}$ concentrations (ranging from 1 to 90 μg/m^3 and 1 to 376 μg/m^3, respectively) during the study period is much wider than those in previous studies. This strength might lower the risk of finding spurious association because of a small sample size under a scenario of modest level of exposure. Second, the statistical model used in this study (DLNM) has the advantage of allowing to identify the independent effect of an exposure at a certain point of time while adjusting for other exposures at other time points (Bello et al. 2017). By contrast, most previous studies regarded exposures at each lag day separately, which might bias their results due to neglecting the confounding effect of exposure at adjacent days. Hence, this study provided solid evidence on the association between short-term exposure to PM$_1$ and PM$_{2.5}$ and decreased lung function.

Several limitations of this study should also be noted. First, we considered PM exposure concentrations based on school location with no consideration of residential or mobility information of the children. However, children in China attend the nearest available school, along a policy published by the Chinese government to control housing prices and avoid education inequity (Wen et al. 2017). In addition, the distances between children's home and schools are generally less than 2 km in Shandong province (The Central People's Government of the PRC. 2012). Therefore, PM level at school may be a valid surrogate for individual PM exposure. Second, we lacked data on several factors that could have an effect on lung function, such as exposure to tobacco smoke (including at home), household-source PM pollution (e.g., charcoal wood or fuel used for cooking or heating), information on house status (e.g., isolation from ambient air pollution, exposure to PM from vehicles from nearby roads or factories, aeration to evacuate household PM), presence of pets at home, and history of asthma or other respiratory diseases. Of note, household PM pollution may be rather low in the considered region as most households do not use coal for heating or cooking, because a "coal to gas" policy, which stipulated households to use natural gas instead of coal, has been implemented in China in the year 2013 (Liu et al. 2020). However, previous studies revealed that additional adjustment for the abovementioned variables only had slight influence on the estimated long-term PM_1-FVC and $PM_{2.5}$-FVC associations (Yang et al. 2020). Third, previous studies showed that children with asthma were more susceptible to PM exposure (Hu et al. 2017; Tasmin et al. 2019). While data on asthma history were not available in this study, the relatively low prevalence of asthma in the Chinese pediatric population ($<3\%$) would likely not have a major effect on our findings (Shu et al. 2020). Fourth, the absence of data on smaller size and specific constituents of particles did not allow us to further explore the pulmonary toxicity of the particle mixtures. For instance, a recent study showed that decreased FVC was associated with ultrafine particles (PM < 0.1 μm) and some PM constituents (e.g., elemental carbon, organic carbon, NO_3^-, and NH_4^+) during lag 0–72 h (Li et al. 2021a). Fifth, previous studies showed that long-term exposure to PM was associated with other spirometric parameters such as FEV_1 and peak expiratory flow, but these parameters were not collected in our survey (Xing et al. 2020). Thus, we were not able to test the association between short-term exposure to PM and other spirometric parameters. Sixth, our study only addresses short-term exposure to PM but does not consider the background impact of overall PM levels on the lung function resulting from long-term exposure. However, our daily PM_1 dataset was built only since Jan 1st, 2014, and we were unable to expand this dataset for an earlier period because most ground monitoring stations for PM_1 across China were not built until 2014. Therefore, we had to use these limited data to partly account for the influence of long-term exposure to PM on the observed short-term PM-FVC association in one of the sensitivity analyses.

Conclusions

Our results indicate that short-term exposure to ambient PM_1 and $PM_{2.5}$ was associated with decreased FVC, and PM_1 may be the primary fraction of $PM_{2.5}$ causing the adverse pulmonary effects in children and adolescents. This study added to the very limited literature on acute pulmonary effects of ambient PM_1 exposure among children and adolescents. These data further emphasize the need for clean air policies aimed at reducing ambient air pollution and chronic respiratory diseases.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-20842-6.

Author contribution HW: formal analysis, methodology, visualization, writing—original draft. YZ: investigation, resources, data curation, writing—review and editing. JW: methodology, resources, data curation, writing—review and editing. PB: methodology, writing—review. MZ: formal analysis, validation, writing—original draft. WL: software, writing—review and editing. BX: conceptualization, supervision, funding acquisition, writing—review and editing.

Funding 1. National Important Project of the Ministry of Science and Technology in China (2017YFC1501404); 2. Innovation Team of "Climbing" Program of Shandong University, and the Youth Team of Humanistic and Social Science of Shandong University (20820IFYT1902).

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Ethical approval was obtained from the Ethics Review Committee of Public Health, Shandong University (LL20211204). Informed consent was obtained from both the participants and their parents or guardians.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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