Environmental Science and Pollution Research (2021) 28:65140–65149
https://doi.org/10.1007/s11356-021-15246-x

RESEARCH ARTICLE

Short-term effects of real-time individual fine particulate matter exposure on lung function: a panel study in Zhuhai, China

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Received: 25 March 2021 / Accepted: 28 June 2021 / Published online: 6 July 2021

Abstract

Fine particulate matter ($PM_{2.5}$) is still the primary air pollutant in most Chinese cities and its adverse effects on lung function have been widely reported. However, short-term effects of individual exposure to $PM_{2.5}$ on pulmonary expiration flow indices remain largely unknown. In this study, we examined the short-term effects of real-time individual exposure to $PM_{2.5}$ on lung function in a panel of 115 healthy adults. We measured individual real-time $PM_{2.5}$ exposure and lung function. Environmental $PM_{2.5}$ concentrations in the same period were collected from the nearest monitoring station. Generalized linear model was used to assess the effects of individual $PM_{2.5}$ exposure on lung function after adjusting for potential confounders. Individual $PM_{2.5}$ exposure ranged from 18.5 to 42.4 μg/m^3 with fluctuations over time and ambient $PM_{2.5}$ concentrations presented a moderate trend of fluctuation at the same day. Except forced expiratory volume in 1 s (FEV_1) decline related to 2-h moving average $PM_{2.5}$ exposure, no significant associations between individual $PM_{2.5}$ exposure and other volume indices including forced vital capacity (FVC) and FEV_1/FVC ratio were observed. The adverse effects of individual $PM_{2.5}$ exposure on pulmonary expiration flow indices including peak expiratory flow (PEF), maximal mid-expiratory flow (MMF) and forced expiratory flow at 50%, and 75% of vital capacity ($FEF_{50\%}$ and $FEF_{75\%}$) were observed to be strongest at 2 moving average hours and could last for 24 h. Stratified analysis showed greater and longer effects among participants who were aged over 40 years, males, or smokers. These findings suggested that individual $PM_{2.5}$ exposure was significantly associated with altered lung function, especially with pulmonary expiration flow indices decline, which was strongest at 2 moving average hours and could last for 24 h.

Keywords $PM_{2.5}$ · Individual exposure · Short-term effects · Adults · Lung function · Pulmonary expiration flow

Introduction

Particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) is a major pollutant in most cities in China and has been linked with various adverse health effects, especially direct damage to the respiratory system. Increasing evidences suggest that $PM_{2.5}$ exposure is associated with impaired lung function and respiratory diseases. Each 10 μg/m^3 increase in daily $PM_{2.5}$ was associated with a 3.1% increase in chronic obstruction pulmonary disease (COPD) hospitalizations and a 2.5% increase in COPD mortality (Li et al. 2016). Long-term $PM_{2.5}$ exposure has also been reported to be associated with increased risk of COPD (Guo et al. 2018).

Lung function, tested by spirometry, is a commonly used method for evaluating respiratory system condition in clinical practice (Liou and Kanner 2009). Lung function indices include a set of parameters to evaluate the status of the respiratory system, airflow, and oxygen supply in different airways. Among these indices, forced vital capacity (FVC), forced expiratory volume in 1 s (FEV_1) and FEV_1/FVC ratio are the most common parameters to reflect the development of lung capacity and large airway resistance; peak expiratory flow (PEF) is used to reflect the strength of the respiratory muscles and large airway obstruction; maximal mid-expiratory flow

Responsible Editor: Lotfi Aleya

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(MMF) and instantaneous forced expiratory flow when X% of the FVC has been expired ($FEF_{x\%}$) are used to measure small airway function (Graham et al. 2019; Xu et al. 2018). Currently, cumulative literatures have suggested that expiratory flow indicators are more sensitive than those volume indicators in identifying early pulmonary impairment or response to potential harmful exposure (Huang et al. 2019; Simon et al. 2010). However, the acute effect of $PM_{2.5}$ exposure on expiratory flow indicators is still unclear.

In addition, several epidemiological studies have confirmed the association between long-term exposure to $PM_{2.5}$ and declined lung function while the relationship between short-term exposure and lung function alteration was still inconsistent (Rice et al. 2015, 2016). A study conducted in four Chinese cities revealed that daily and 2-day moving average $PM_{2.5}$ exposure were associated with decreased FVC and FEV_1 (Chen et al. 2018). Wang et al. found the adverse effects on FEV_1 and FEV_1/FVC occurred within 3–6 h of $PM_{2.5}$ exposure in an observational study (Wang et al. 2017). Nevertheless, no significant associations between short-term $PM_{2.5}$ exposure and FVC, FEV_1 or PEF were found in the studies in four European cities and in Japan (De Hartog et al. 2010; Ng et al. 2019). Among above researches, $PM_{2.5}$ concentrations came from local ambient air monitoring stations and did not take indoor $PM_{2.5}$ exposure produced from cigarette smoking or cooking into account. The study by Singh et al. demonstrated that personal $PM_{2.5}$ exposure was varied by more than 20%, compared with indoor or outdoor fixed-site monitoring via a modeling approach after taking the impact of population activity pattern into consideration (Singh et al. 2019). Therefore, individual measurement of exposure level with higher degree of accuracy is needed to provide the evidence on the effects of air pollution on lung function.

We convened a panel of healthy urban adults to carry out present study, using an individual sampler to measure 24 h of $PM_{2.5}$ exposure for each participant. Lung function indices including volume and expiratory flow indicators were measured before and after individual real-time $PM_{2.5}$ determination. The objective of this study was to investigate the short-term effects of real-time $PM_{2.5}$ exposure on lung function parameters among healthy adults.

Materials and methods

Study participants and design

During April 2018, healthy urban adults were recruited in Zhuhai, which is a coastal city in southern China. We excluded those with respiratory system diseases or severe cardiovascular diseases, and excluded those with infectious diseases or inflammation in last 1 month. A total of 115 participants were recruited and measurements of 24-h $PM_{2.5}$ exposure were completed. Before exposure assessment, a face-to-face interview and a physical examination were conducted for each participant by trained professional to collect information on demographics, socioeconomics, living habits, anthropometrics, diseases, medical care, and biochemical indexes of urine and blood. Lung function test was performed before and after exposure assessment.

In the current study, body mass index (BMI) was calculated as weight (kg) divided by height (m) squared. Cigarette smoking was defined as smoking at least one cigarette per day for over 6 months and smokers included current smokers and former smokers while nonsmokers were those never smoking before. Alcohol consumption was defined as drinking at least once per week for over 6 months and drinkers included current drinkers and former drinkers while non-drinkers were those never drinking before.

The study was approved by the Medical Ethics Committee of the School of Public Health, Tongji Medical College, Huazhong University of Science and Technology. All participants have given written informed consent for participation before the study began.

Lung function test

Spirometry was performed by specialists using electronic spirometers (Chestgraph HI-101, CHEST Ltd., Tokyo, Japan). All participants were required in the sitting position with a nose clip and to execute three acceptable curves after at least 5 min normal breath in accordance with the American Thoracic Society (ATS) guideline (1995), and the best one was chosen for analyzes. Lung function parameters include (1) volume indicators: FVC, FEV_1, and FEV_1/FVC; (2) expiratory rate indicator of large airway: PEF; and (3) expiratory rate indicators of small airway: MMF, $FEF_{50\%}$, and $FEF_{75\%}$.

Exposure assessment

The real-time individual $PM_{2.5}$ exposure was recorded by portable monitoring device BBair (Shanghai Yuanrui Environmental Protection Technology Co., Ltd, Shanghai, China), which was calibrated by MicroPEM (v3.2 MicroPEM, RTI, USA) every week. The frequency of recording concentration of $PM_{2.5}$ was set in every 15 min and hourly concentration was calculated by the average of 4 recordings. Data of $PM_{2.5}$ concentration was uploaded to the cloud and just downloaded at the end of measurement. Data of temperature and relative humidity were also collected through above processes.

Each participant carried the BBair on the shoulder approximately 8 a.m. on the first day, keeping sampler port at the height of breathing zone with air inlet port facing out. Before starting to monitor, participants were informed of performing their regular activities during the next 24-h study period, bringing the sampler with them all the time and putting the device nearby when sleeping, taking a shower and during strenuous physical activities. Simultaneously, correct way of wearing the device was demonstrated for each participant in order to avoid mis-operation and achieve accurate exposure assessment.

In addition, hourly ambient $PM_{2.5}$ concentration data of the nearest air quality monitoring station at the same day was gathered from platform of the national real-time air quality monitoring operated by China National Environmental Monitoring Center.

Statistical analysis

Before statistical analysis, personal $PM_{2.5}$ exposure concentration, ambient $PM_{2.5}$ concentration at the same day and corresponding lung function were matched. The moving average $PM_{2.5}$ exposure was calculated by average concentration of $PM_{2.5}$ during 24 h before lung function test while taking the time point of lung function test as 0 h of exposure measurement. For example, 2-h moving average exposure was calculated as the average concentration of 0–2 h exposure prior to lung function test. The first 12 h after wearing monitoring device was identified as daytime and the following 12 h was nighttime. Manne-Whitney U-test was used to compare lung function parameters and $PM_{2.5}$ concentrations of daily average, daytime, and nighttime among male and female.

Correlations among basic characteristics of participants, levels of $PM_{2.5}$ exposure, meteorological factor, and changes of lung function were estimated by Pearson correlation and Point-biserial correlation. Associations between short-term exposure to $PM_{2.5}$ and lung function were assessed using generalized linear model (GLM). Age (years), gender (male/female), height (cm), weight (kg), and smoking status (smoker/nonsmoker) were adjusted in all models. The effect estimates were presented as changes of lung function parameters before and after $PM_{2.5}$ monitoring and its 95% confidence intervals (CIs) with each 10 μg/m^3 increase in $PM_{2.5}$ concentration.

Stratification analyzes were conducted to assess effect modification by age (<40y and ≥40y), gender (male and female) and smoking status (smoker and nonsmoker). In addition, sensitivity analyzes were performed in the associations between moving average $PM_{2.5}$ exposure and expiratory flow indicators by incorporating lifestyle factors (drinking status, cooking meals at home) and meteorological factors (daily mean temperature and relative humidity) into the model individually or simultaneously, respectively. All analyzes were performed by using SAS version 9.4 (SAS Institute). All statistic tests were 2-sided and its significant level was defined as $P < 0.05$.

Results

Study participants

As presented in Table 1, study participants consisted of 49 males and 66 females with an average age of 40.9 years and a mean BMI of 22.4 kg/m^2. The percentage of current and ever smoker, drinker, and cooking meals at home were 18.3%, 13.0%, and 39.1%, respectively. Most indices of lung function were significantly higher in males than that in females ($P < 0.001$), while only FEV_1/FVC was higher in females but with no significance ($P = 0.54$).

Individual and environmental $PM_{2.5}$ exposure

Daily individual $PM_{2.5}$ concentration was 29.8 μg/m^3, and average $PM_{2.5}$ concentrations of daytime and nighttime were 28.3 μg/m^3 and 31.2 μg/m^3, respectively. The average $PM_{2.5}$ concentration of male participants (35.7 μg/m^3) was higher than that of female participants (25.4 μg/m^3), the same as daytime and nighttime $PM_{2.5}$ concentrations (all $P < 0.05$, shown in Table 1).

Changes in individual and environmental $PM_{2.5}$ concentrations within 1 day during study period are shown in Fig. 1. Individual $PM_{2.5}$ exposure ranged from 18.5 to 42.4 μg/m^3 with fluctuations over time while ambient $PM_{2.5}$ concentrations from fixed-site monitors presented a moderate trend of fluctuation. We observed that individual $PM_{2.5}$ concentrations were relatively high during meal periods, i.e., from 12:00 to 14:00 at noon and from 18:00 to 22:00 in the afternoon. In addition, compared to environmental $PM_{2.5}$, individual $PM_{2.5}$ concentrations were higher at most time points.

Association between individual PM2.5 exposure and lung function change

The negative correlations between $PM_{2.5}$ exposure and pulmonary expiration rate indicators was weak to moderate (all $P < 0.001$, shown in Table S1). After adjusting for potential confounders, we observed significant association between individual $PM_{2.5}$ exposure (a 10 μg/m^3 increase in moving average hours concentration) and lung function indices changes (Fig. 2). Among volume indicators, significant decline in FEV_1 may be due to 2-h moving average $PM_{2.5}$ exposure. Since 2-h individual $PM_{2.5}$ exposure, pulmonary expiration rate indicators including PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$ were significantly decreased, and the effects lasted for 24 h. Each 10 μg/m^3 increase in 2-h moving average $PM_{2.5}$ concentration was associated with 314.5 mL/s (95% CI: 153.9, 475.0), 285.5 mL/s (196.3, 374.8), 298.3 mL/s (195.3, 401.2), and 133.4 mL/s (72.5, 194.4) decreases in PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$, respectively (all $P < 0.05$). Each 10 μg/m^3 increase in 24-h moving average $PM_{2.5}$

Table 1 Basic characteristics, lung function, and individual $PM_{2.5}$ concentrations of participants

Characteristics	Total N=115	Male N=49	Female N=66
Age, years, Mean (SD)	40.9(16.9)	38.4(16.9)	42.8(16.8)
Height, cm, Mean (SD)	163.1(9.1)	171.9(6.7)	157.4(5.8)
Weight, kg, Mean (SD)	59.6(9.7)	64.7(7.8)	55.7(9.1)
BMI, kg/m^2, Mean (SD)	22.4(3.7)	22.3(3.3)	22.6(4.0)
Smoking status, N (%)			
yes [a]	21(18.3)	21(42.9)	0(0)
no	94(81.7)	28(57.1)	66(100)
Drinking status, N (%)			
yes [a]	15(13.0)	10(20.4)	5(7.6)
no	100(87.0)	39(79.6)	61(92.4)
Cooking meals at home, N (%)			
yes	45(39.1)	11(22.4)	34(51.5)
no	70(60.9)	38(77.6)	32(48.5)
Lung function [b], Mean (SD)			
FVC**, mL	3309.4(1490.0)	4062.6(910.2)	2750.9(457.9)
FEV_1**, mL	2741.5(1160.0)	3339.0(861.2)	2297.9(515.6)
FEV_1/FVC, %	82.5(10.3)	81.9(97.7)	82.9(81.7)
PEF**, mL/s	6710.0(2122.6)	8149.2(1978.1)	5641.7(1513.8)
MMF**, mL/s	2999.5(1302.8)	3617.8(1442.3)	2540.5(966.3)
$FEF_{50\%}$**, mL/s	3598.4(1466.4)	4311.0(1628.6)	3069.2(1070.3)
$FEF_{75\%}$**, mL/s	1444.2(1200.0)	1802.2(1027.2)	1178.3(615.2)
$PM_{2.5}$, μg/m^3, Mean (SD)			
Daily*	29.8(20.0)	35.7(28.1)	25.4(8.5)
Daytime*	28.3(18.8)	32.4(26.1)	25.2(9.6)
Nighttime*	31.2(25.8)	38.7(35.7)	25.5(12.3)
Meteorological factors, Mean (SD)			
Temp, °C	25.90(1.32)	25.84(1.20)	25.94(1.41)
RH, %	78.22(8.20)	79.06(8.10)	77.60(8.29)

Abbreviations: *FVC*, forced vital capacity; FEV_1, forced expiratory volume in 1 s; *PEF*, peak expiratory flow; *MMF*, maximal mid-expiratory flow; $FEF_{50\%}$, forced expiratory flow at 50% of FVC; $FEF_{75\%}$, forced expiratory flow at 75% of FVC; *Temp*, temperature; *RH*, Relative humidity; *SD*, standard deviation

* The significance for difference between male and female $^*P < 0.05$, $^{**}P < 0.001$

[a] Including current and former smokers/drinkers

[b] Detection of lung function before exposure monitoring

exposure was associated with 182.7 mL/s (91.8, 273.3), 144.1 mL/s (91.3, 197.0), 145.8 mL/s (84.9, 206.8), and 70.2 mL/s (35.0, 105.3) declines in PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$, respectively (all $P < 0.05$).

Stratified analysis

We further evaluated the relationship between $PM_{2.5}$ exposure and lung function indices through stratified analyzes by age, gender, and smoking status (Fig. 3). The $PM_{2.5}$ exposure had significant stronger and longer effects on expiratory rate indicators (PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$) among elder adults (40 years old), males, and smokers. The associations of $PM_{2.5}$ exposure with expiratory rate indicators were not observed among those younger than 40 years old. Interestingly, we noticed that increased 2-h and 4-h moving average $PM_{2.5}$ exposure were associated with FEV_1 decline in nonsmokers and females, and with FVC in nonsmokers.

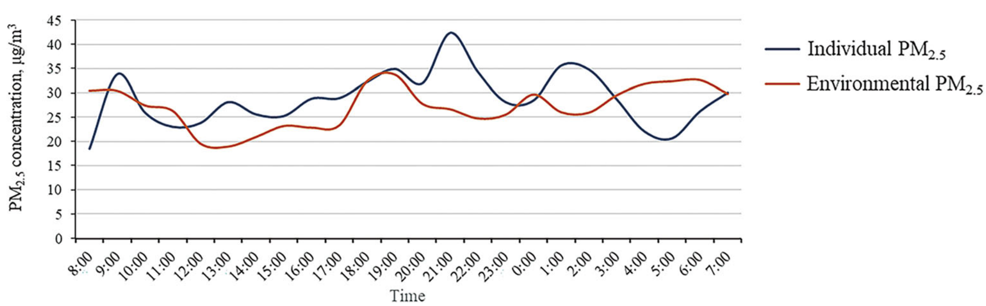

Fig. 1 Individual and environmental $PM_{2.5}$ concentrations within 1 day during study period

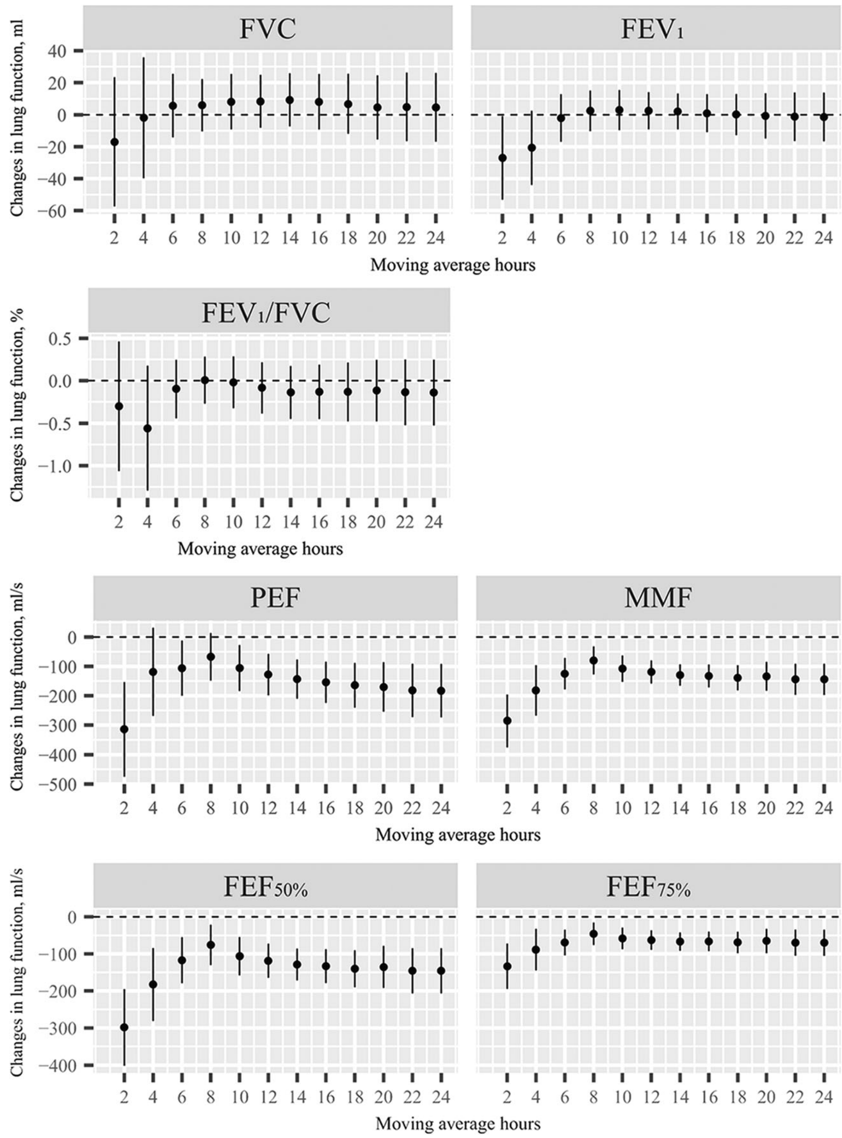

Fig. 2 Estimated changes in lung function associated with a 10 μg/m³ increase in moving average hours of individual $PM_{2.5}$ exposure. Models adjusted for age (continuous variable), gender (male/female), height (continuous variable), weight (continuous variable), and smoking statues (smoker/nonsmoker). Abbreviations: FVC, forced vital capacity; FEV_1, forced expiratory volume in 1 s; PEF, peak expiratory flow; MMF, maximal mid-expiratory flow; $FEF_{50\%}$, forced expiratory flow at 50% of FVC; $FEF_{75\%}$, forced expiratory flow at 75% of FVC

Sensitivity analysis

Figure 4 shows the results of sensitivity analyzes. When including lifestyle factors (drinking status, cooking meals at home) and meteorological factors (daily mean temperature and relative humidity) into the model individually or simultaneously, similar exposure-response patterns with the main model were observed, indicating that our results were relatively robust.

Discussion

In this study, we observed that short-term exposure to $PM_{2.5}$ was significantly associated with decreased lung function, especially pulmonary expiration flow indicators including PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$. Such adverse effects were stronger among participants who were aged over 40 years old, males, and smokers.

We noted that personal $PM_{2.5}$ exposure showed continuous fluctuations over time due to daily activities, especially a regular increase during mealtime, whereas ambient $PM_{2.5}$ maintained a relatively moderate trend. More importantly, in most periods, the concentrations of individual $PM_{2.5}$ exposure were higher than environmental data from fixed monitoring station, which is consistent with several previous studies (Curto et al. 2019; Lai et al. 2019; Ren et al. 2019). Several reasons may contribute to such differences. Firstly, compared with outdoors, participants spend approximately 80% or even more of their time indoors where has been confirmed with higher air pollution concentrations on account of the presence of existing pollutant sources such as smoking, fuel combustion, and movement of people (Abt et al. 2000; Adgate et al. 2003; Leech et al. 2002). Besides, fixed monitoring stations should

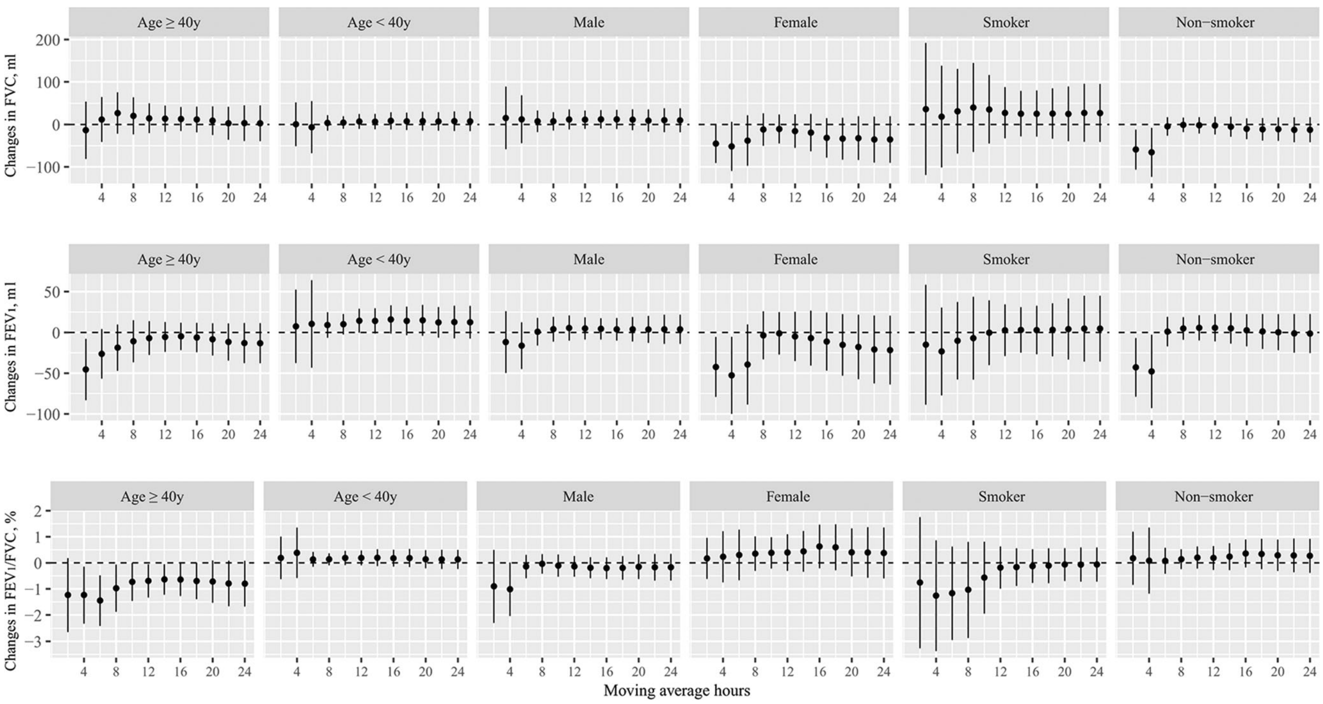

Fig. 3 Estimated changes in lung function associated with a 10 μg/m^3 increase in moving average hours of individual $PM_{2.5}$ exposure in different groups. Models adjusted for age (continuous variable), gender (male/female), height (continuous variable), weight (continuous variable), and smoking statues (smoker/nonsmoker). Abbreviations: FVC, forced vital capacity; FEV_1, forced expiratory volume in 1 s; PEF, peak expiratory flow; MMF, maximal mid-expiratory flow; $FEF_{50\%}$, forced expiratory flow at 50% of FVC; $FEF_{75\%}$, forced expiratory flow at 75% of FVC

be far away from direct pollutant sources including traffic pollution, industrial emission, and the burning of fossil fuel, in accordance with technical specifications published by China National Environmental Monitoring Center. Thus, data from fixed monitoring station cannot reflect precise exposure of individual. We also observed that $PM_{2.5}$ concentrations of men were higher at night than those during the day, which is consistent with previous studies in China (Ren et al. 2019), America (Adgate et al. 2003), and Italy (Siciliano et al. 2018). Possible explanations are cigarette smoking and high indoor $PM_{2.5}$ levels at night. The most of night activities were indoors where with high $PM_{2.5}$ concentrations (Adgate et al. 2003; Steinle et al. 2015). In addition, $PM_{2.5}$ difference between day and night was smaller among female may due to better ventilation habits and none of the female participants smoked.

Declined expiratory flow indices including PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$ were observed to be associated with short-term $PM_{2.5}$ exposure, suggesting that expiratory flow indicators were possibly more sensitive to $PM_{2.5}$ than volume indicators during the short-term exposure period. Similarly, two other panel studies among healthy adults conducted in Wuhan and Beijing also found that decreased PEF was associated with acute $PM_{2.5}$ exposure (Wu et al. 2014; Zhang et al. 2015). But one observational study among adult asthmatics and one longitudinal study of healthy children didn't observe such significant association (Chen et al. 2018; Ng et al. 2019). PEF is an indicator of respiratory muscle and airway obstruction and the result depends on strength (Xu et al. 2018). Vulnerable populations such as children or asthmatic patients cannot perform well in the measurement of this index, and the changes are not obvious after being affected by $PM_{2.5}$. MMF, $FEF_{50\%}$, and $FEF_{75\%}$ are used to evaluate small airway function and few studies assessed the adverse effects of $PM_{2.5}$ exposure on these indices. The results of present study suggested that expiratory flow indexes were not only sensitive to $PM_{2.5}$ exposure, but the flow reduction could last for 24 h. More attention should be paid on adverse effects of $PM_{2.5}$ exposure on small airway.

Most previous studies mainly focused on the short-term adverse effects of daily $PM_{2.5}$ exposure but neglected hourly exposure effects (Chen et al. 2018; Ng et al. 2019; Xu et al. 2018; Zhang et al. 2015). In this study, we observed that risk on lung function decline occurred in the early stage of exposure and relatively alleviated with time. One possible biological mechanism underlying the observed association could be the occurrence of airway inflammatory response which has been proved to be one of the pathogenesis of lung diseases (MacNee 2001) while acute exposure to $PM_{2.5}$ even in a very short period. A longitudinal panel study conducted in healthy adults (Shi et al. 2016) supported this hypothesis and found the association between short-term exposure to $PM_{2.5}$ (0-6 h) and

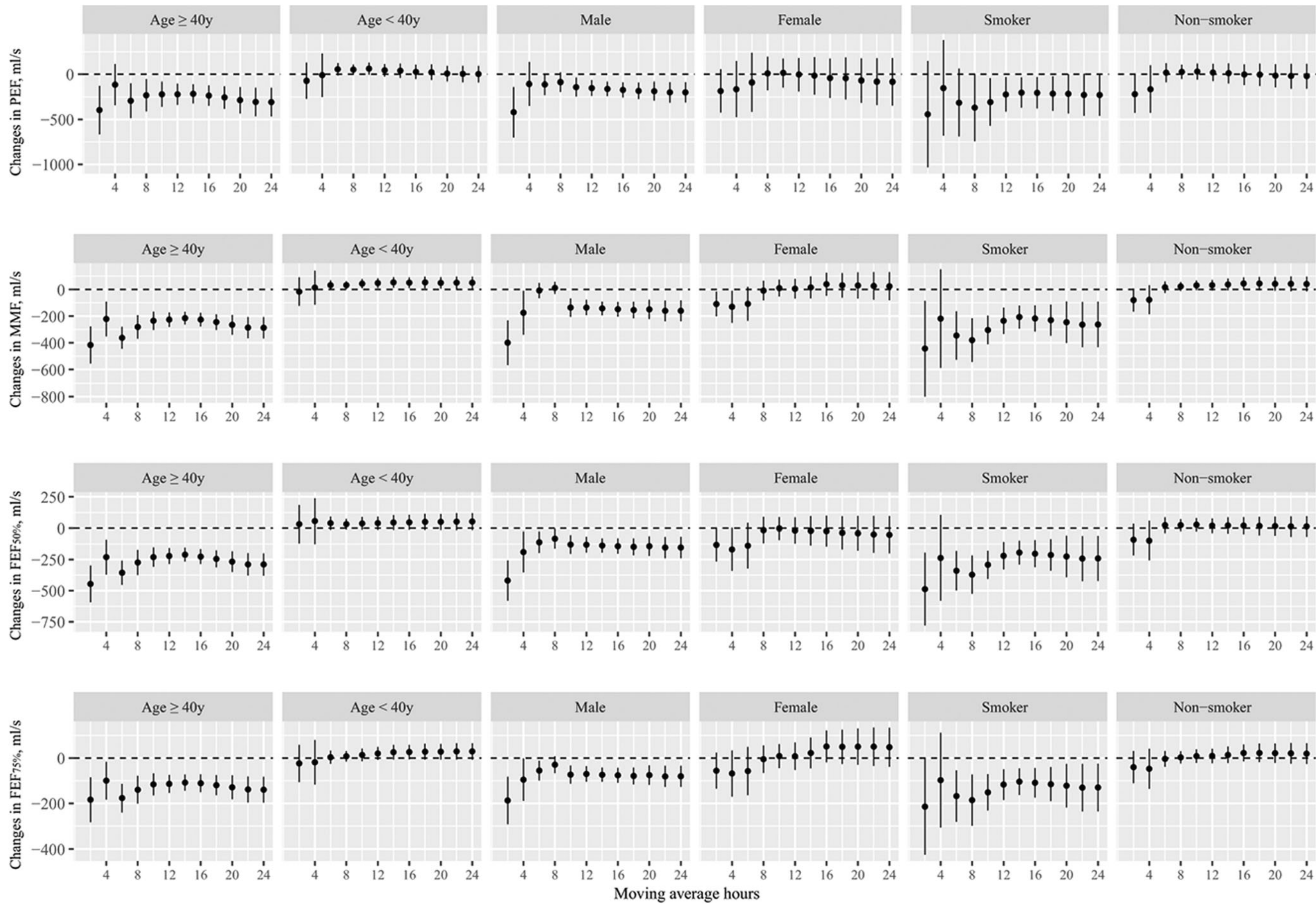

Fig. 3 (continued)

increased Fractional exhaled nitric oxide (FeNO) level, which is a well-established biomarker of airway inflammation (Haccuria et al. 2014). More studies are needed in the future to provide evidence on the acute effects of $PM_{2.5}$ exposure on altered lung function and illustrate specific exposure-response pattern.

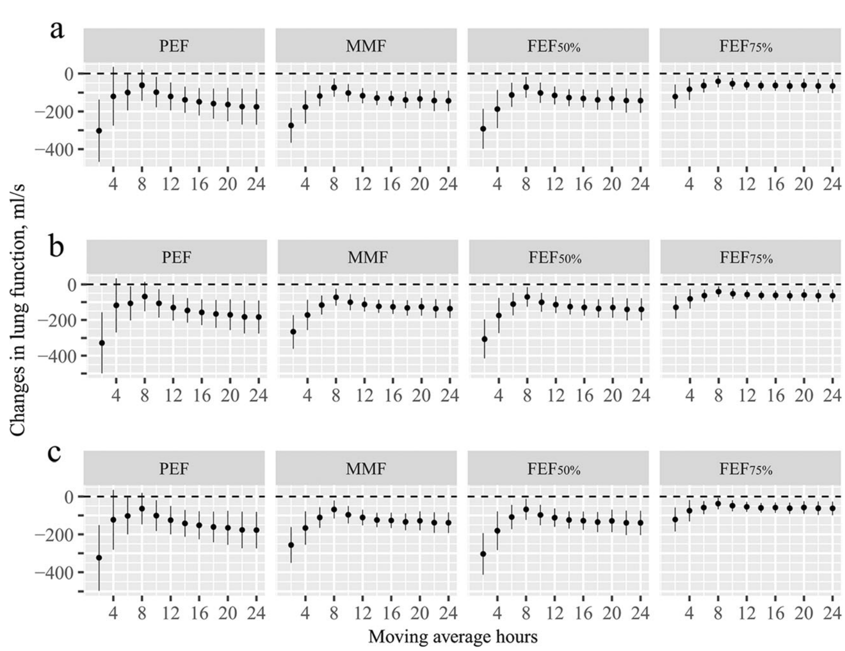

Fig. 4 Results of sensitivity analyzes with adjusted models to evaluate the association between moving average $PM_{2.5}$ exposure and lung function. Based on the main model adjusted for age (continuous variable), gender (male/female), height (continuous variable), weight (continuous variable), and smoking statues (smoker/nonsmoker), model **a** included drinking status (drinker/nondrinker), cooking meals at home (yes/no), model **b** included daily mean temperature and relative humidity, and model **c** included all confounders at the same time. Abbreviations: PEF, peak expiratory flow; MMF, maximal mid-expiratory flow; $FEF_{50\%}$, forced expiratory flow at 50% of FVC; $FEF_{75\%}$, forced expiratory flow at 75% of FVC

In our study, the adverse effects of $PM_{2.5}$ exposure on expiratory flow indices were stronger and lasted longer in the participants who were aged over 40 years, males, and smokers. Previous studies have revealed possible mechanisms for $PM_{2.5}$ exposure-related lung function reduction, which including inflammatory response and oxidative stress (Feng et al. 2021; Huang et al. 2012; Moller and Loft 2010; Mu et al. 2021). Meanwhile, epidemiological investigations have reported a higher level of oxidative stress and inflammation among elder people, smokers, and males (Barreiro et al. 2010; Goldberg and Dixit 2015; Rea et al. 2018; Sculley and Langley-Evans 2003). Similarly, physical activity could induce acute oxidative stress and males usually exercise more intensively and longer than females, which may strengthen the adverse effect of $PM_{2.5}$ exposure on lung function (Bloomer 2008).

We observed an association of 2-h moving average $PM_{2.5}$ exposure and FEV_1 reduction, and didn't find any association between short-term exposure to $PM_{2.5}$ and FVC or FEV_1/FVC in present study. Previous studies have reported inconsistent effects of $PM_{2.5}$ exposure on FVC, FEV_1. and FEV_1/FVC. Edginton et al. performed a meta-analysis by including 8 studies of healthy adults from different regions and found that a 10 μg/m^3 increase in short-term $PM_{2.5}$ exposure was associated with 7.1 mL (2.3, 11.8) decrease in FEV_1 (Edginton et al. 2019). A Chinese multicity study also reported that daily and two-day average $PM_{2.5}$ exposure were significantly associated with decrements in FVC and FEV_1, with a high level of $PM_{2.5}$ concentration (mean of 102.6 μg/m^3) (Chen et al. 2018). Nevertheless, Wu et al. found that $PM_{2.5}$ was positively associated with FVC and FEV_1 at 1-day, 2-day, and 3-day moving average time and negative associations were observed at longer moving days till 14 days (Wu et al. 2013). Besides, Baccarelli et al. followed two panels, 60 office workers and 60 trunk drivers, and did not find a significant association between $PM_{2.5}$ exposure and FVC or FEV_1 (Baccarelli et al. 2014). Different research results may be related to $PM_{2.5}$ level, age, and physical condition of the participants.

Our study has several strengths. First, we evaluated individual $PM_{2.5}$ exposure by applying a wearable device for every participant and thus accurate exposure measurement could be achieved. Second, we measured indicators of expiratory flow to search for sensitive index responding to $PM_{2.5}$ exposure. Based on accurate measurements of exposure and more lung function indices, our study provided some novel evidence on the relationship of short-term exposure to $PM_{2.5}$ and altered lung function.

Nevertheless, there are some limitations in our study. First, we did not take consecutive measurements to assess the cumulative effect of more than 24 h but focused on the adverse effect of $PM_{2.5}$ on lung function within 1 day. Second, the sample size was relatively small, however, it made realizable to measure $PM_{2.5}$ exposure at the individual level. Besides, the sample size in present study was sufficient to assess the relationship between $PM_{2.5}$ exposure and lung function estimated by SAS (PROC POWER) program. Lastly, this study was conducted in Zhuhai, a coastal city of China, and multicenter studies with the same framework are needed in the future.

Conclusions

In summary, our study findings support the hypothesis of the short-term adverse effects of $PM_{2.5}$ exposure on lung function and significantly decreased expiratory flow indices (including PEF, MMF, $FEF_{50\%}$, and $FEF_{75\%}$) started from 2-h moving average exposure and lasted for 24 h. Moreover, the adverse effects on expiratory flow indices were stronger and longer among participants who were aged over 40 years, males, and smokers. These findings may help to clarify specific exposure-response pattern within 1 day and emphasize the needs to take measures such as using air purification equipment, prohibiting indoor smoking, adopting clean energy (electricity or natural gas) as heating or cooking fuel, and using ventilation facilities in the kitchen to reduce $PM_{2.5}$ exposure for preventing potential lung impairment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-15246-x.

Acknowledgements We thank all participants involved in the present study.

Availability of data and materials The datasets generated and analyzed in the present study are not publicly available due to privacy concerns, but reasonable requests to access the data can be sent to corresponding author.

Authors' contributions W.C. was responsible for the design of the present study, obtaining funding, reviewed the manuscript, and assisted with manuscript revision. Z.Y. conducted data collection, performed the statistical analyzes, drafted, and revised the manuscript. Z.Y., B.W., G.M., Y.Z., W.Q., S.Y., X.W., Z.Z., and W.C. contributed to the data acquisition, manuscript revision, and final version approval.

Funding This study was funded by the Key Program of the National Natural Science Foundation of China (grant number: 91543207) and the Major Research Program of the National Natural Science Foundation of China (grant number: 91843302).

Declarations

Ethics approval and consent to participate The study was approved by the Medical Ethics Committee of the School of Public Health, Tongji Medical College, Huazhong University of Science and Technology. All participants have given written informed consent for participation before the study began.

Consent for publication Not applicable.

Competing interests The authors declare no competing of interests.

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