RESPIRATORY EFFECTS OF TRAFFIC-RELATED AIR POLLUTANT EXPOSURE DURING SHORT-TERM CYCLING AMONG HEALTHY ADULTS IN THREE CHINESE CITIES

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by
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ABSTRACT

Cycling to work has been promoted as a green commute in many countries because of its reduced congestion relative to that of cars and its reduced environmental impact on air pollution. However, cyclists might be exposed to higher air pollution, causing adverse health effects. The aim of this thesis was to assess the impact of air pollution exposure on lung function while cycling in traffic. Twenty-five healthy adults in total cycled on a specified route in each of three Chinese cities during four periods of a day. Lung function, real-time particulate matter concentration, and ambient concentration of other pollutants were measured. Mixed-effect models were applied to estimate the impact of short-term air pollution exposure on participants' lung function during cycling. The results indicated that cyclists' exposure to fine particles was significantly associated with reduced lung function. Fine particles compared to other pollutants are more harmful to cyclists' respiratory health.

BIOGRAPHICAL SKETCH

Lejian (Leo) He is currently pursuing an Master of Science in the Transportation Systems Engineering Program at Cornell University. In June 2017, he graduated from Sun Yat-Sen University with a Bachelor of Science degree in Atmospheric Sciences, with a focus in urban infrastructure and environment.

During the last two years of undergraduate, Leo published two papers in two research journals: Science of the Total Environment and Environmental Pollution. The two papers investigated the impact of urban geometry and transportation infrastructure such as viaduct and noise barriers on the air pollutant dispersion and community health. After graduation, Leo continued to pursue research in urban environment and health in Prof. Oliver Gao’s group at Cornell University. His research focuses on sustainable urban transportation systems from the perspective of health and environment: evaluation, optimization, and policy implications. Leo is skilled in statistical modeling, computational fluid dynamics modeling, transportation emission modeling, and health impact modeling.

Outside of academics, Leo is actively involved in university activities. Leo has served as Secretary and Symposium Chair of the Graduate Student Association of the Department of Civil and Environmental Engineering at Cornell since September 2018. Leo was also a tenor in Angelic Voices Chorus and an aerobic gymnastics athlete at Sun Yat-Sen University. He enjoys skiing, running and hiking during spare time.

To my loved ones.

ACKNOWLEDGMENTS

I sincerely thank all the participants who made our experiment in China possible, and particularly the following individuals for their generous help in the recruitment, data collection, and team training: Dr. Huiyong Li from Shanghai Jiao Tong University, Mr. Wazi Wang from Chang’an University, and Ms. Yinping Luo from Sun Yat-Sen University.

I also acknowledge the fact that the data collected does not reflect the whole population nor every road condition. The results only apply to the participants during the experiment periods.

I sincerely appreciate the help and instructions from my committee chair Prof. Oliver Gao, my peer Dr. Mohammad Tayarani, Dr. Shuai Pan, and Cornell Statistical Consulting Unit.

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PREFACE

This thesis focuses on the impact of short-term exposure to traffic-related air pollution during cycling on cyclists' respiratory health. Cycling has been promoted as "Green Commute" in many countries since it is believed to reduce the vehicle emission and increase commuters' physical activity. However, cyclists can be exposed to higher pollutant concentration for its closer proximity to mobile emission sources relative to other commuting modes. Cyclists might inhale more pollutants since their breathing rates increase when they cycle. Furthermore, most previous studies that didn't find significant adverse respiratory effects of cycling were conducted in developed countries where air pollution level was relatively lower than developing countries such as China. Hence, it is of great interest to investigate this topic in the setting of heavily polluted urban areas.

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August 2021

CHAPTER 1

INTRODUCTION

1.1 Research Background

Cycling as a green commuting mode has been promoted in many countries because of the reduction in ambient air pollution and subsequent health benefits (Chavarrias, Carlos-Vivas, & Pérez-Gómez, 2018; Grabow et al., 2012; Jarrett et al., 2012; Maizlish et al., 2013). The rise in use of shared bicycles in recent years has even made cycling one of the top choices for urban commuting in densely populated cities in China (iResearch, 2017). However, cyclists are exposed to an increased level of air pollution because of their close proximity to vehicle emissions, while they have higher minute ventilation that causes increased inhaled doses of traffic-related air pollutants such as fine particulate matter (PM), nitrogen oxides (NO_x), and carbon monoxide (CO) (Bleux et al., 2010; de Nazelle et al., 2012; Good et al., 2016; Ragettli et al., 2013; Thai, McKendry, & Brauer, 2008; Yu et al., 2012). Exposure to traffic-related air pollution is known to be associated with respiratory and cardiovascular diseases (Atkinson et al., 2016; Beelen et al., 2008; Brønnum-Hansen et al., 2018; Brunekreef et al., 2009; Hoek, Brunekreef, Goldbohm, Fischer, & Van Den Brandt, 2002).

1.2 Literature Review

Many cohort and experimental studies examined the association between outdoor air pollution and pulmonary function, a key indicator of respiratory health, in children and adults. Increased exposures to particles with aerodynamic diameter ≤ 10 μm (PM_{10}), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) have been reported to be negatively associated with forced expiratory volume in 1 sec (FEV_1) (Forbes et al., 2009). Similar negative associations were found between lung function measurements (FEV_1 and forced vital capacity FVC) and other air pollutants such as ozone (O_3) (Rice et al., 2013). PM and NO_2 can also have significant negative effects on lung function growth in children (Gauderman et al., 2000; Schultz et al., 2012).

Nevertheless, there is limited and inconsistent evidence of respiratory effects of short-term air pollution exposure during cycling. Several studies demonstrated negative impacts of traffic-related air pollution exposure on the lung function of cyclists. Park, Gilbreath, & Barakatt (2017) found significant associations between increased levels of ultrafine particulate matter (UFPM) and decrements in lung function measurements FEV_1 and FVC. Measures of lung function FEV_1 and forced expiratory flow at 25–75% of vital capacity ($FEF_{25–75\%}$) were found to decrease after inhalation of fine (≤ 2.5 μm in aerodynamic diameter) particulate matter ($PM_{2.5}$) and ultrafine (≤ 0.1 μm in aerodynamic diameter) particles (UFP) (Rundell et al., 2008). However, other studies didn’t observe strong or consistent relationships between traffic-related air pollution and acute changes in lung function measures (Jarjour et al., 2013; Weichenthal et al., 2011). Strak et al. (2010) even found mostly positive associations between air pollution during cycling and lung function change immediately after cycling.

1.3 Research Goal

Given that the relationships between short-term air pollution exposure and acute changes in lung function among cyclists remain unclear, I led a study in three Chinese cities to examine the associations between traffic-related air pollution and changes in cyclists' lung function during short-term cycling. Most previous similar studies were conducted in the US or Europe, where the air pollution level was relatively low compared to that in developing countries such as China. Therefore, I aimed to investigate the associations between short-term exposure to air pollution and lung function change among cyclists in regions of high air pollution and to assess differences in the impact of cities with different air pollution levels on cyclists' respiratory response.

CHAPTER 2

METHODOLOGY

2.1 Participants and Study Design

Twenty-five healthy non-smoking adults in total were recruited to participate in the experiment, which was conducted in January 2019 in three Chinese cities: Shanghai, Guangzhou, and Xi’An. Exposure sessions included weekdays and weekends. Rainy days were excluded. Subjects of age 19–38 with no history of pulmonary or cardiovascular disease were chosen. Participants were asked to take the same routes and modes of transportation to and from the study site for each exposure session. In each city, different subjects cycled on the same route in four periods of a day: morning rush hours (8:00–10:00), noon hours (12:00–14:00), afternoon rush hours (17:00–19:00), and evening hours (20:00–22:00). Subjects were assigned randomly to the time periods, and no subject cycled more than once a day. The study was conducted in the three cities simultaneously. In each city, no subject participated in more than one session a day. Routes in the three cities were of approximately equal length (~2.8 km).

2.2 Lung Function Measurements

Before cycling, participants used a portable spirometer (Contec SP10, China) to measure their baseline lung function, including forced vital capacity (FVC), FEV_1, the FEV_1/FVC ratio in percentage ($FEV_1\%$), peak expiratory flow (PEF), and forced expiratory flow over the middle half of FVC ($FEF_{25–75\%}$). Follow-up pulmonary measurements were performed immediately after cycling. Participants rested in a sitting position post cycling—and, after their first cycling session, completed a questionnaire to provide their demographic information and medical history.

2.3 Exposure Measurements

In order to measure the real-time PM (PM_1, $PM_{2.5}$, PM_{10}) and particle number count (PNC) throughout each exposure session, a light scattering and filter sampling sensor was used (GRIMM 11-A, GRIMM Labortechnik GmbH & Co. KG, Germany). The equipment was mounted at the front of bikes to measure real-time air pollution. Ambient NO_2, SO_2, O_3, and CO concentrations, as well as meteorological data, were taken from the stationary sites of the China National Environmental Monitoring Centre which were nearest to the routes during that specific hour. The mean concentrations of PM and other pollutants and the 99th percentile PNC for small particles (diameter ≤ 1 μm) in each exposure session were used in the statistical analyses to represent the PM level of that trip. We also calculated the personal pollutant intake in each exposure session as follows:

$$\text{Personal pollutant intake} = \dot{V}_E * \text{Trip duration} * \text{Pollutant concentration}$$

The minute ventilation $\dot{V}_E$ of each subject was estimated by the following predictive model (Campos et al., 2015):

$$\dot{V}_E = e^{0.58+0.025HR}$$

The heart rates (HR) of participants were measured by a portable device during one cycling trip. The mean heart rate of each participant was then used to estimate mean minute ventilations $\dot{V}_E$, and ultimately pollutant intakes, in each exposure session. Both air pollutant exposures and personal pollutant intakes were considered in the analysis of their associations with subjects' respiratory responses in this study.

2.4 Statistical Analysis

Any trip for which either exposure or health measurements were missing was excluded from the analysis. Exposure data, including pollutant concentrations and pollutant intakes for each trip, were summarized as means and transformed to IQRs. Correlations between pollutants were also examined via Pearson correlation coefficients.

The associations between traffic-related air pollutant exposure and cyclists' respiratory responses were examined via city-pair comparative analysis and pollutant-specific exposure–response analysis. A paired difference test was used to compare the lung function pre and post exposure, and an unpaired two-sample test (the t-test for normally distributed variables, and the Wilcoxon test for non-normally distributed variables) was performed for the comparison of exposure and health measures between cities. The normality of variables was examined by the Shapiro–Wilk test. Significance was considered at $p < 0.05$.

Linear mixed-effect models were constructed for the exposure–response analysis, where random intercepts of subjects were used to account for the correlation between measurements from the same individual. The percentage change in lung function measurements from the pre-exposure baseline value was used as the response variable in the analysis later. All models were adjusted with additional covariates, including age, sex, body mass index (BMI), ambient temperature and relative humidity, day of the week (weekday vs weekend), and time period (morning, noon, afternoon, or evening). Single-pollutant models were constructed for all air pollutants in the exposure–response analysis. All analyses were done using R (R Core Team, 2018).

CHAPTER 3

RESULTS

3.1 Participants

The twenty-five participants in this study contributed a total of 120 effective observations that excluded missing exposure or health outcome data. Table 1 summarizes the descriptive characteristics of the participants. Forty-eight percent of the participants were female, and 52% were male. The age of the participants ranged from 19 to 38, with a mean age of 24.72. According to the standard weight status categories associated with BMI ranges provided by the United States Centers for Disease Control and Prevention (U.S. CDC), the majority of participants had a normal BMI, ranging from 18.5 to 24.9 kg/m^2 (weight in kilograms divided by square of height in meters), while five participants were underweight ($BMI < 18.5$) and one participant was obese ($BMI \geq 30$). None of the participants was a smoker or had ever smoked. No participant reported having asthma, while only three of them reported having allergies, including allergies to Demodex and metals. The average duration of the 120 effective observations was 18.31 minutes. Note that trip durations vary among different participants as they had different cycling speed in different microenvironments. Trip durations were included in the models to test the stability of the results.

Table 1 Descriptive characteristics of participants

Characteristics	
Sex: Number (%)	
Male	13 (52%)
Female	12 (48%)
Age: Mean (Range)	24.72 (19–38)
Height (m): Mean (Range)	1.671 (1.54–1.83)
BMI (kg/m^2): Mean (Range)	21.24 (17.29–33.20)
Trip duration (min): Mean (Range)	18.26 (10.4–28.3)
Smoker	0 (0%)
Asthma	0 (0%)
With allergies	3 (12%)

3.2 Pollutant Exposure and Intake

3.2.1 Real-time Particulate Matter

As anticipated, Xi'An had the highest mean concentration of PM_{10}, $PM_{2.5}$, and PM_1 among the three cities (Fig. 1a). Xi'An is located in northern China where the wintertime daily mass concentrations of $PM_{2.5}$ in many cities are typically one or two orders of magnitude higher than those in urban areas of the United States (Zhang et al., 2012; Zhang and Cao, 2015). The high level of PM concentration in this region during wintertime is due to adverse meteorological conditions (synoptic weather patterns), high traffic emission, and residential coal combustion related to cooking and winter heating.

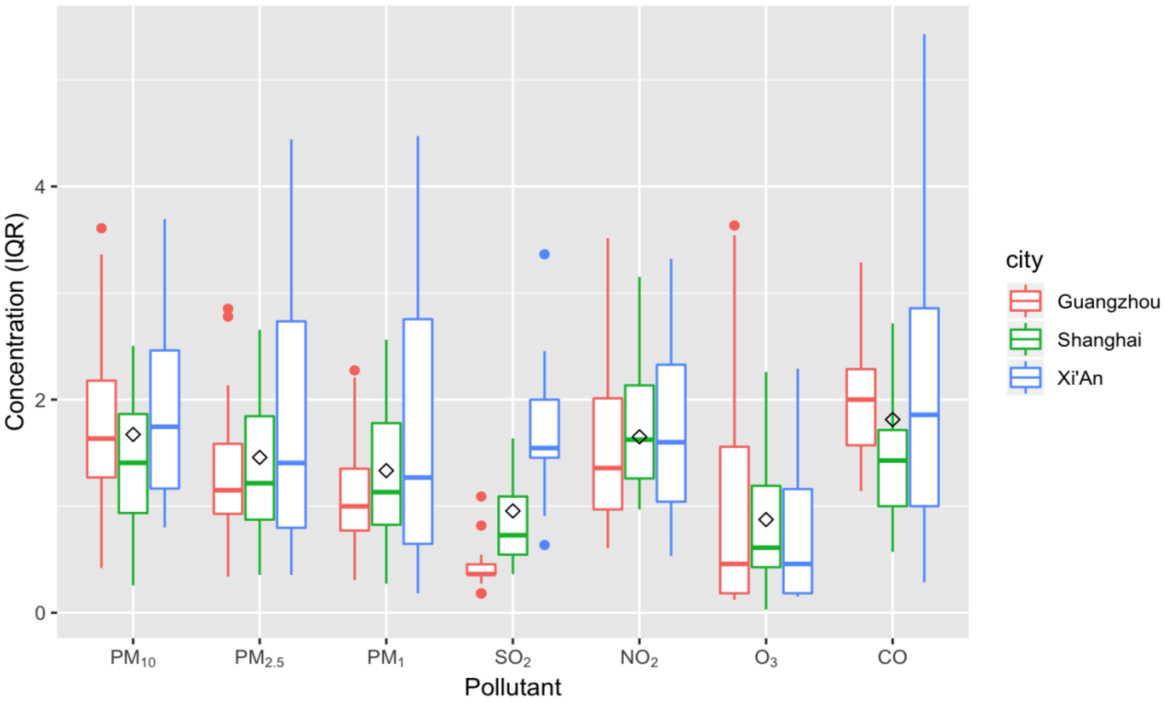
Participants in Xi'An had significantly higher exposure to PM_{10} and $PM_{2.5}$ than those in Shanghai ($p = 0.027$ and 0.034, respectively) and significantly higher exposure to PM_1 than those in Guangzhou ($p = 0.019$). Xi'An also had the highest 99th percentile of PNC for fine particles with a diameter ≤ 0.3 μm (Fig. 1c). Shanghai had the significantly lowest levels of coarse particle concentrations (PM_{10}) among the three cities while slightly higher fine particle concentrations than Guangzhou. Guangzhou had the lowest levels of fine particle concentrations relative to Xi'An and Shanghai.

3.2.2 Ambient Air Pollution

The mean concentration of SO_2 in Xi'An was 4.4 and 2.24 times as high as that in Guangzhou and Shanghai, respectively. Shanghai had the lowest level of CO, compared to Guangzhou ($p < 0.001$) and Xi'An ($p = 0.008$). The NO_2 concentration levels in Guangzhou were lower than Xi'An and Shanghai while the O_3 levels were the highest among the three cities. The differences in the NO_2 and O_3 concentrations among the three cities were not significant.

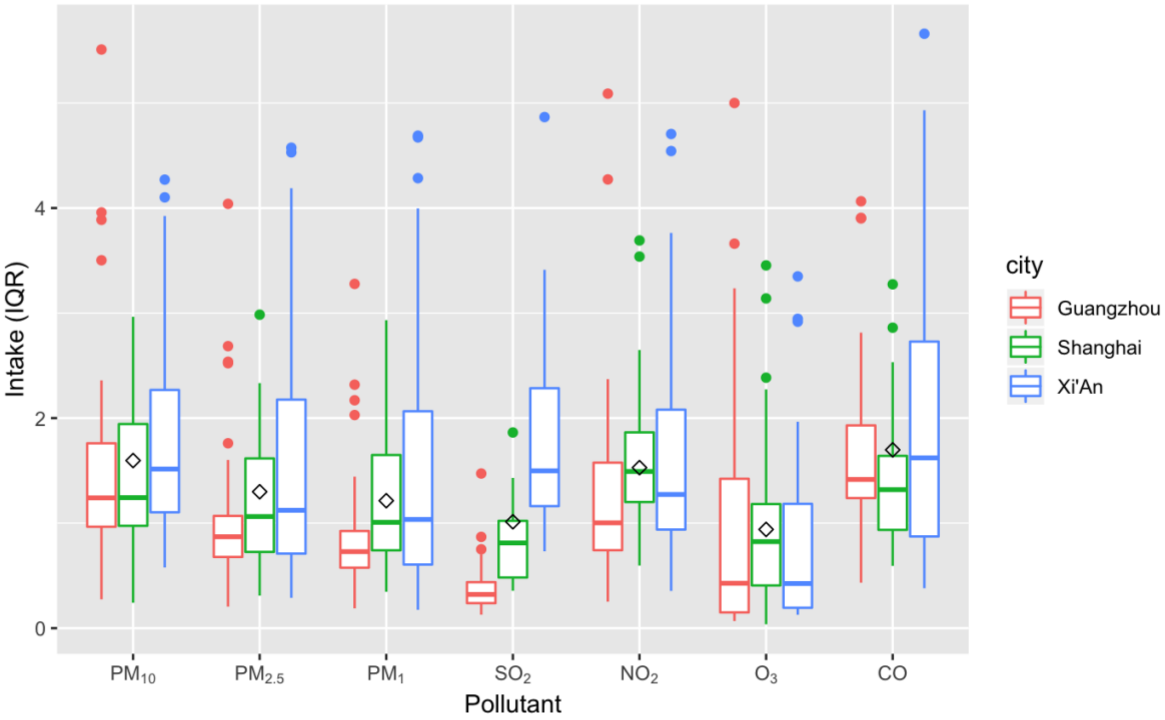
3.2.3 Pollutant Intake

As shown in Fig. 1b, the distribution of participants' mean pollutant intake was similar to the distribution of the mean pollutant concentration, except that subjects in Guangzhou had the lowest mean pollutant intake of $PM_{2.5}$, compared to Xi'An ($p = 0.012$) and Shanghai ($p = 0.148$). Not surprisingly, there existed strong correlations between PM_1, $PM_{2.5}$, and PM_{10} ($r = 0.81$–0.99). Correlations between PM and other air pollutants were low to moderate. The strongest correlation was observed between $PM_{2.5}$ and CO ($r = 0.82$). Complete results of the comparison tests of air pollutant exposures and air pollutant intakes, as well as pollutant correlations, are provided in Tables A1–A3 of the Supplementary Appendix.



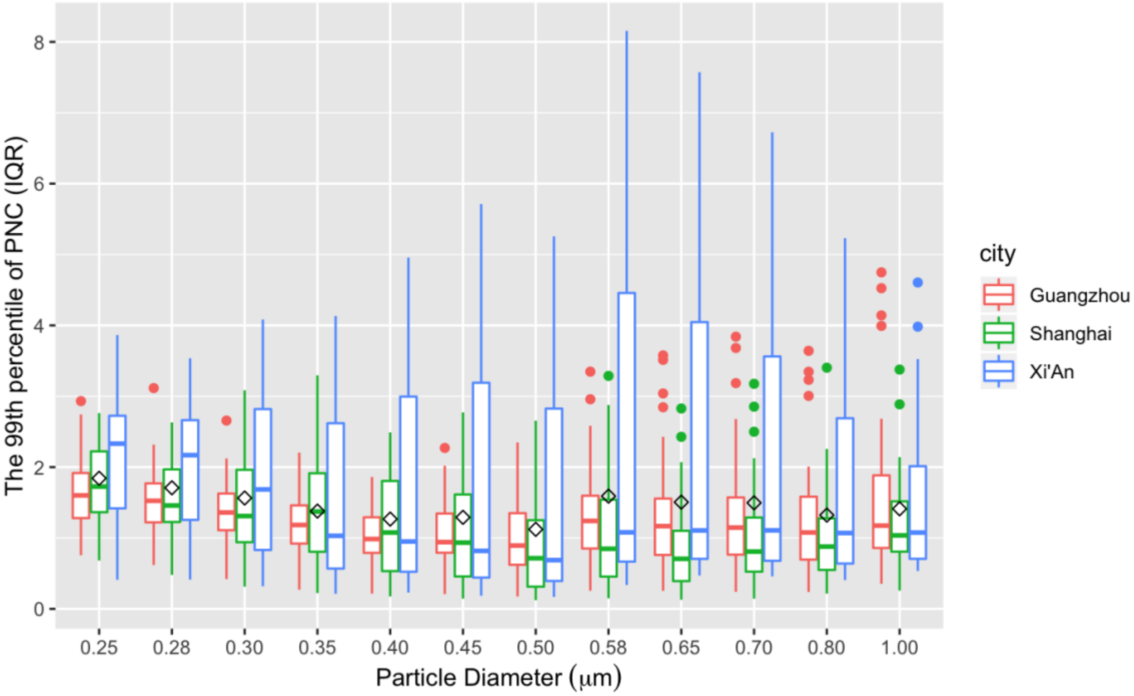
Concentration (IQR)
0
2
4
PM10
PM2.5
PM1
SO2
NO2
O3
CO
Pollutant
city
Guangzhou
Shanghai
Xi'An

(a)



Intake (IQR)
0
2
4
PM10
PM2.5
PM1
SO2
NO2
O3
CO
Pollutant
city
Guangzhou
Shanghai
Xi'An

(b)



(c)

Fig. 1 Distribution (IQR) of (a) mean pollutant concentration, (b) pollutant intake, and (c) 99th percentile of PNC in each trip for Shanghai, Guangzhou, and Xi'An. Boxes include values between the 25th and 75th percentiles, thick horizontal lines in each box indicate median values, thin horizontal lines indicate values within 1.5 IQR of the nearest quartile, dots indicate outliers, and diamonds indicate the average of pooled mean concentration or pollutant intake for each trip. IQR for each pollutant (concentration; pollutant intake): PM_{10} (71.63 μg/m^3; 40.34 μg), $PM_{2.5}$ (46.64 μg/m^3; 27.22 μg), PM_1 (35.17 μg/m^3; 22.27 μg), SO_2 (11 μg/m^3; 5.39 μg), NO_2 (42 μg/m^3; 25.55 μg), O_3 (36 μg/m^3; 17.22 μg), CO (0.7 mg/m^3; 0.37 mg), $PNC_{0.25}$ (129386/l), $PNC_{0.28}$ (134626/l), $PNC_{0.30}$ (122748/l), $PNC_{0.35}$ (113827/l), $PNC_{0.40}$ (64222/l), $PNC_{0.45}$ (31474/l), $PNC_{0.50}$ (37236/l), $PNC_{0.58}$ (11112/l), $PNC_{0.65}$ (5046/l), $PNC_{0.70}$ (4516/l), $PNC_{0.80}$ (2731/l), $PNC_{1.00}$ (1745/l).

3.3 Lung Function

Participants were required to measure their lung function before and after each trip (Table 2). The percentage changes in FVC, FEV_1, $FEV_1\%$, PEF, and $FEF_{25–75\%}$ are presented in Fig. 2. The average baseline spirometry values (pre-trip) were normal compared to the nationwide reference values for Chinese (Jian et al., 2017). Overall, there were significant changes (post-cycling compared to pre-cycling) in FVC and FEV_1 for the participants in the three cities ($p < 0.001$). The average FVC and FEV_1 decreased by 160 mL and 265 mL, respectively. There were no significant differences in $FEV_1\%$, PEF, or $FEF_{25–75\%}$ among the participants before and after cycling.

Table 2 Comparison of lung function measurements immediately before and after cycling

		N	Pre-trip	Post-trip	Change	p-value
FVC (L)	Pooled	120	3.62 (1.10)	3.46 (1.13)	-0.16 (0.67)	< 0.001
	Guangzhou	40	3.46 (0.91)	3.34 (0.75)	-0.12 (0.54)	0.088
	Shanghai	40	4.01 (0.72)	4.02 (1.17)	0.02 (0.89)	0.878
	Xi'An	40	3.40 (1.45)	3.03 (1.21)	-0.37 (0.46)	< 0.001
FEV_1 (L)	Pooled	120	3.33 (1.04)	3.07 (0.98)	-0.27 (0.76)	< 0.001
	Guangzhou	40	3.39 (0.80)	3.27 (0.67)	-0.12 (0.52)	0.059
	Shanghai	40	3.31 (0.85)	2.96 (1.01)	-0.35 (1.14)	0.021
	Xi'An	40	3.30 (1.39)	2.97 (1.18)	-0.33 (0.43)	< 0.001
$FEV_1\%$	Pooled	120	0.92 (0.15)	0.90 (0.19)	-0.02 (0.16)	0.353
	Guangzhou	40	0.99 (0.04)	0.99 (0.05)	0.00 (0.02)	0.921
	Shanghai	40	0.83 (0.18)	0.75 (0.22)	-0.08 (0.27)	0.029
	Xi'An	40	0.95 (0.16)	0.96 (0.16)	0.01 (0.07)	0.245
PEF (L/s)	Pooled	120	10.18 (4.21)	9.83 (4.11)	-0.35 (1.50)	0.054
	Guangzhou	40	10.89 (2.68)	10.84 (2.82)	-0.05 (1.16)	0.825
	Shanghai	40	10.35 (4.38)	9.84 (4.75)	-0.50 (1.62)	0.121
	Xi'An	40	9.30 (5.15)	8.80 (4.48)	-0.49 (1.67)	0.090
$FEF_{25–75\%}$ (L/s)	Pooled	120	4.86 (1.91)	4.79 (1.95)	-0.07 (0.83)	0.343
	Guangzhou	40	5.08 (1.30)	5.05 (1.29)	-0.02 (0.79)	0.907
	Shanghai	40	4.88 (1.71)	4.70 (2.18)	-0.18 (0.66)	0.114
	Xi'An	40	4.63 (2.30)	4.61 (2.19)	-0.02 (1.01)	0.952

The major contribution to the reduction in FVC came from Xi'An, where the mean FVC of the participants declined by 370 mL. This change differed significantly from those in Guangzhou ($p = 0.003$) and Shanghai ($p = 0.001$). For FEV_1, the participants in Shanghai and Xi'An had an average decrease of 348 mL and 333 mL, respectively ($p = 0.021$ and $p < 0.001$). The reductions in FEV_1 were significantly greater among the participants in Xi'An than among those in Guangzhou ($p = 0.006$). Results of the comparison tests of changes in lung function measures are provided in Table A4 of the Supplementary Appendix.

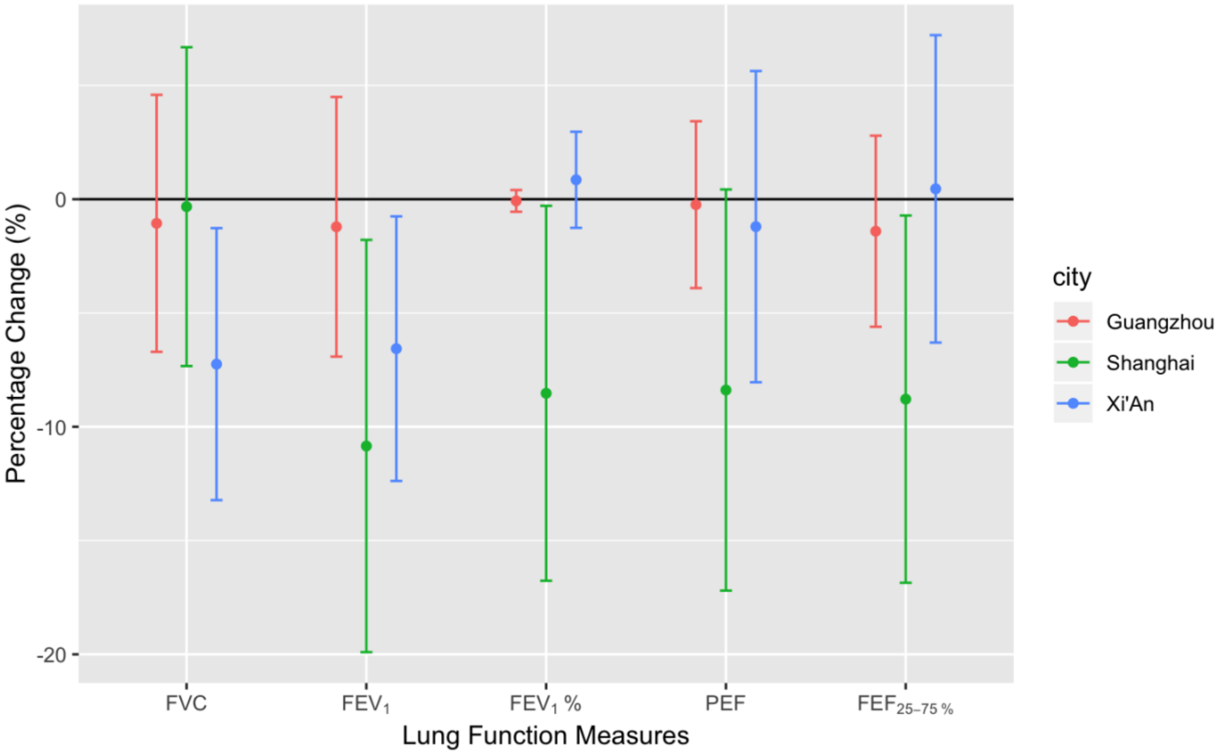


Fig. 2 Percentage change from baseline lung function measures for the three cities

3.4 Associations between Air Pollution Exposures and Pulmonary Responses

3.4.1 FVC and FEV_1

There existed significant inverse relationships between exposure to fine particles ($PM_{2.5}$ and PM_1) and FVC (Fig. 3a). With an IQR increase in $PM_{2.5}$ and PM_1 during a trip, cyclists' FVC decreased by 5.57% (95% CI, –10.35%, –0.80%, p = 0.022) and 5.60% (95% CI, –10.38%, –0.83%, p = 0.021). Exposure to coarse particles (PM_{10}) was also negatively associated with FVC, though not statistically significant, with a coefficient of –4.92% (95% CI, –10.14%, 0.31%, p = 0.065). The significant negative associations between fine particulate matter exposures and FVC stayed stable after further adjusted with trip duration.

There was a significant negative association between CO and FVC during short-term cycling, with a reduction of 5.78% (95% CI, –10.44%, –1.11%, p = 0.015) in FVC per IQR increase in CO. SO_2 and NO_2 exposures were also associated with reduced FVC (p = 0.089 and p = 0.063, respectively), while O_3 had a weak positive association with FVC (p = 0.296).

Both fine- and coarse-particle exposures were also negatively associated with FEV_1, though less pronounced. There were weaker negative associations between SO_2, NO_2, and CO exposures and FEV_1 compared to FVC. There was no association between O_3 exposures and FEV_1.

3.4.2 Other Lung Function Measures

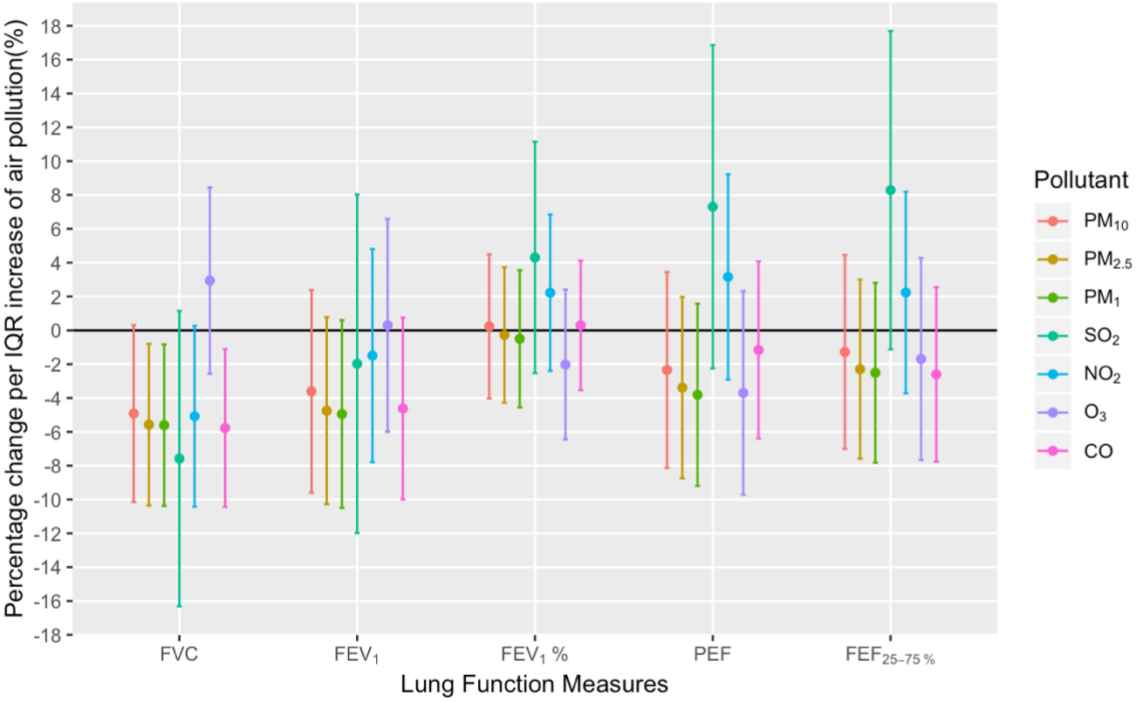
The associations between air pollutant exposures and PEF had patterns similar to those with $FEF_{25–75\%}$: PM, O_3, and CO concentrations were inversely related to PEF and

$FEF_{25–75\%}$, while SO_2 and NO_2 concentrations were directly related to these two measures. There were no associations between air pollutant exposures and $FEV_1\%$—except for SO_2, which had a weak positive impact on $FEV_1\%$.

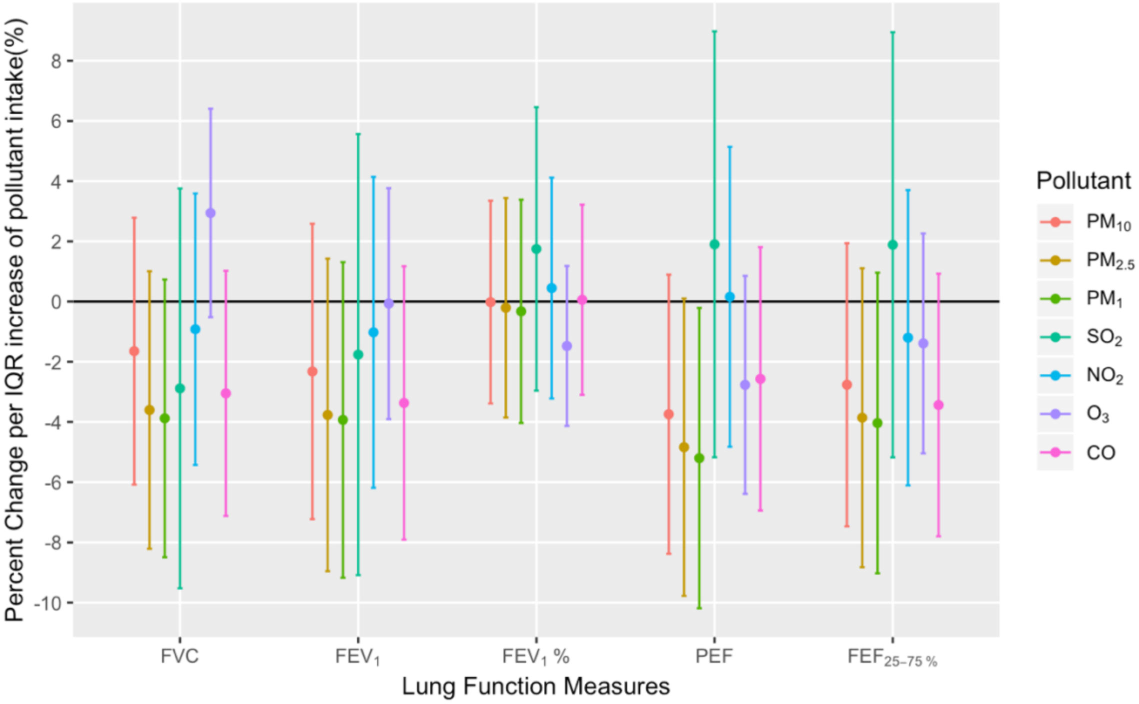
In general, PM and CO exposures had consistent negative associations with lung function and significant reductions in FVC and FEV_1. SO_2 and NO_2 were also negatively associated with FVC and FEV_1, but less pronounced, and they even had weak positive effects on PEF and $FEF_{25–75\%}$. Ozone exposures had an inconsistent weak or absent impact on cyclists' lung function. As illustrated in Fig. 3b, associations of cyclists' pollutant intakes with lung function measures were similar to those of air pollutant exposures, though mostly not statistically significant.

3.4.3 PM Particle Size and Lung Function

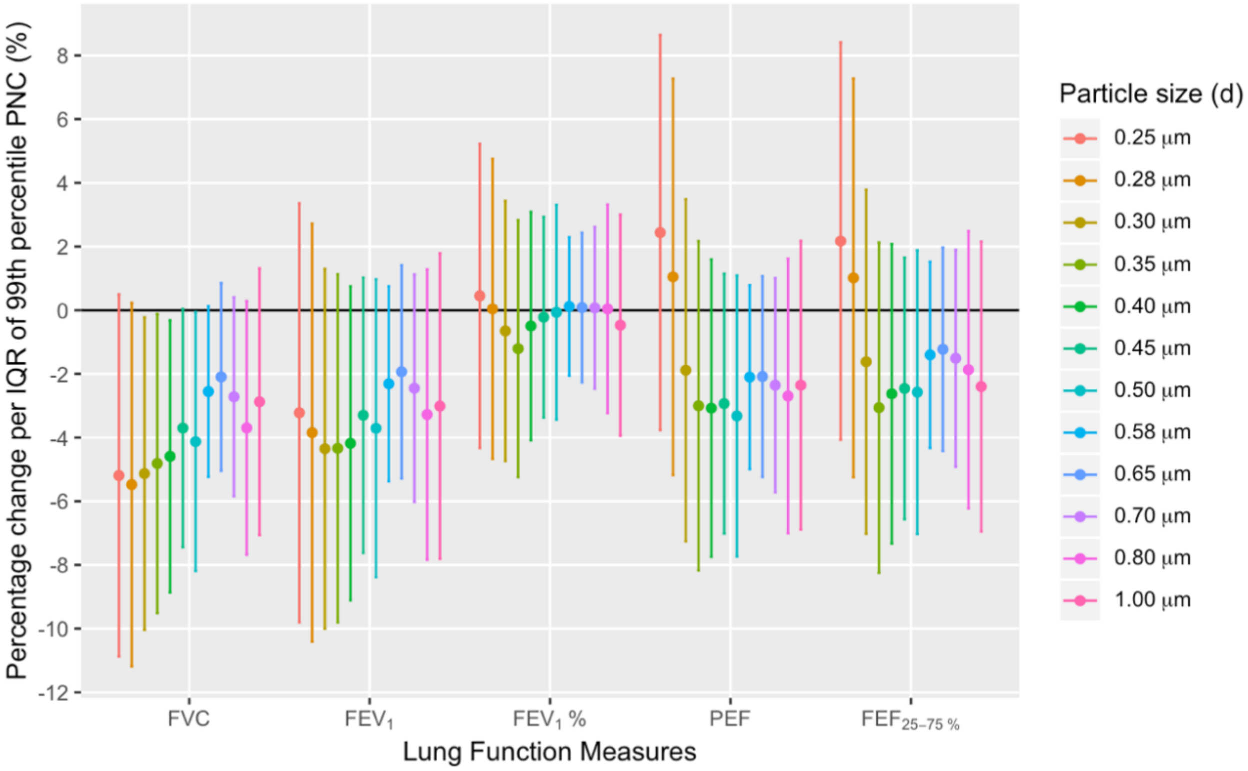
There were also significant negative associations between the 99th percentile of PNC for particles with a diameter of 0.30–0.50 μm and FVC. The negative associations with FVC became smaller and less prominent as the particle size increased. No significant associations were found between the 99th percentile of PNC and other lung function measures. Tables A5 and A6 in the Supplementary Appendix summarize the coefficients and p values for associations between each pollutant and the lung function measures, and Table A7 provides statistics on temperature and relative humidity in the three cities during the experiment.


Percentage change per IQR increase of air pollution(%)
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
FVC
FEV_1
FEV_1 %
PEF
$FEF_{25-75\,\%}$
Lung Function Measures
Pollutant
PM_{10}
$PM_{2.5}$
PM_1
SO_2
NO_2
O_3
CO

(a)


Percent Change per IQR increase of pollutant intake(%)
8
6
4
2
0
-2
-4
-6
-8
-10
FVC
FEV_1
FEV_1 %
PEF
$FEF_{25-75\,\%}$
Lung Function Measures
Pollutant
PM_{10}
$PM_{2.5}$
PM_1
SO_2
NO_2
O_3
CO

(b)



(c)

Fig. 3 Point estimates and 95% CI of the percentage change in lung function measure per IQR increase in (a) air pollutant exposure, (b) pollutant intake, and (c) 99th percentile PNC for fine particles of different sizes (0.25–1.00 µm).

CHAPTER 4

DISCUSSION

4.1 Summary and Discussions

In this well-controlled real-world study of healthy young adults cycling in three Chinese cities with different air pollution levels, I examined the pulmonary effects of short-term exposure to air pollution during cycling. The findings suggest that participants in Xi'An, with the highest levels of air pollution for most criteria pollutants except O_3, had a significantly larger reduction in FVC than those in Guangzhou and Shanghai. Moreover, participants in Xi'An and Shanghai had significant reductions in FEV_1 after short-term cycling, whereas there was no significant change in FEV_1 from baseline for participants in Guangzhou, suggesting that cycling in environments with high levels of air pollution could reduce lung function (FVC and FEV_1). No consistent significant changes from baseline after short-term cycling were found for other lung function measures, including FEV_1%, PEF, and $FEF_{25–75\%}$. The study added to the limited existing evidence of inconsistent results of the pulmonary effects of exposure to air pollution during cycling, especially in heavily polluted real-world environments. This study extended the current body of research to real situations of urban active commuting in developing countries faced with severe traffic-related environmental health problems and stressed the importance of assessing the environmental health impact when promoting active commuting such as bike sharing in these regions.

In previous studies, there was no consistent evidence of reduced lung function (FVC and FEV_1) shortly after cycling or other active commuting such as walking or running. Park, Gilbreath, & Barakatt (2017) observed significant associations between increased levels of UFPM concentrations and decrements in lung function measurements (FVC and FEV_1), which is consistent with this study. A study conducted in the United States found that FEV_1 and $FEF_{25–75\%}$ decreased significantly after a 30-min exercise in a high PM_1 environment (252290 ± 77529 particles per cm^3) (Rundell et al., 2008). In an Oxford street study, significant reduction was found in the predicted FVC and FEV_1 of subjects with asthma immediately after a two-hour walk on a busy street (McCreanor et al., 2007). However, a few studies found no significant change in lung function after cycling or walking. Jarjour et al. (2013) found no significant changes in lung function in healthy non-asthmatic subjects after cycling on high-traffic ($PM_{2.5}$: 4.88 $\mu g/m^3$) or low-traffic ($PM_{2.5}$: 4.53 $\mu g/m^3$) routes. Kubesch et al. (2015) even found PA-associated increases in FVC, FEV_1, and $FEF_{25–75\%}$ irrespective of the traffic-related air pollution exposure levels. The findings of this study suggest that FVC and FEV_1 significantly decreased in Xi'An, whereas there were no significant changes of lung function in Guangzhou. The inconsistency of lung function change after active commuting in previous studies could be explained by the various traffic-related air pollution (TRAP) levels in different cities. The significantly reduced FEV_1 in Xi'An is consistent with the finding of Rundell et al. (2008), and Xi'An had a PM_1 concentration level comparable to that in their study. However, the studies that found no significant change in lung function had lower TRAP exposure levels even at their high-concentration sites ($PM_{2.5}$: 4.88–82 $\mu g/m^3$ vs 86.56 $\mu g/m^3$ in Xi'An). In addition, susceptible groups such as subjects with asthma or COPD had higher reductions in lung function than healthy adults even though they were exposed to relatively low air pollution (Sinharay et al., 2018).

In the pooled mixed-effect analysis, I found significant negative associations between fine particle exposures (PM2.5, PM1, and PNC for particles with diameter 0.30–0.50 μm) and FVC. The negative associations between PNC and FVC became weaker as the particle size increased, indicating that finer particles are more harmful than coarse particles to lung function in short-term cycling. This is in agreement with the results of previous studies (Rundell et al., 2008; Sinharay et al., 2018; McCreanor et al., 2007). Exposures to fine particles were significantly associated with declines in lung function such as FEV_1 among college-aged subjects after running along or near busy highways (Rundell et al., 2008). For subjects with asthma or COPD, there were significant associations between ultrafine particles and reduced lung function (FEV_1 and FVC) (Sinharay et al., 2018; McCreanor et al., 2007). A negative association was observed, though not statistically significant, between coarse particles (PM_{10}) and lung function, which is consistent with the results of a study in Spain (Matt, Cole-Hunter, Donaire-Gonzalez, & Kubesch, 2016). They found that reductions in lung function (FVC and FEV_1) were significantly associated with particles with a diameter between 2.5 and 10 μm. In addition to experimental studies, the results of this study are also consistent with the cohort studies indicating associations between long-term exposure to fine particulate air pollution and cardiovascular disease and mortality (Laden, Schwartz, Speizer, & Dockery, 1998; Pope et al., 2002; Thurston et al., 2016). For other pollutants, including NO_2, SO_2, and O_3, no significant associations were observed with lung function changes after short-term cycling. Previous studies reported inconsistent effects of NO_2 on lung function. According to Sinharay et al. (2018), exposure to NO_2 in particpants with COPD was associated with reduced FVC and FEV_1, while Matt, Cole-Hunter, Donaire-Gonzalez, and Kubesch (2016) observed a negative impact of NO_2 on PEF and FEV_1%. Overall, this study and a few previous studies demonstrated a negative impact of exposure to particulate pollutants, especially fine particles, on lung function during active commuting or physical exercise. This adverse effect was enhanced in highly polluted environments or among vulnerable populations such as asthmatic and COPD patients.

This study is unique for its experiment locations. Most previous similar studies were conducted in developed countries that have relatively low levels of air pollution, even at their high-pollution sites. By contrast, the sites in this study, especially Xi'An, had a high PM concentration. Moreover, I was more interested in the respiratory effects of cycling as a commuting mode than in cycling for physical exercise or entertainment, hence I designed the study routes, cycling duration, and commuting time to better represent the daily commuting of most cyclists in China: People usually cycle for short distances or to connect between subway or bus stops and their destination (first mile/last mile). I didn't include routes with different traffic intensities in the same city; instead, I investigated the respiratory effect in different cities with different air pollution levels on urban cyclists in a regular commuting setting in China.

4.2 Limitations

This study also has a few limitations. First of all, this was an on-road experiments with a lot of complicated conditions. There might exist some unexpected errors in the experiment data that we did not realize. Furthermore, I didn’t include resting participants as a control group; therefore, I was unable to distinguish the short-term effects of physical activity (PA) on lung function or their interaction with TRAP exposures. PA was found to improve lung function in commuting (Kubesch et al., 2015; Matt, Cole-Hunter, Donaire-Gonzalez, and Kubesch, 2016). There is substantial evidence that PA attenuates the negative effects of PM exposures on upper and lower respiratory airways (Matt, Cole-Hunter, Donaire-Gonzalez, and Kubesch, 2016). Thus, further investigation of the interaction between PA and TRAP exposures during active commuting is needed in the future. Moreover, the effects of different participants cannot be excluded completely, though random effects were included in the mixed-effect models. There were also unexpected factors that contributed to the lung function changes in cycling. I didn’t include pre-experiment exposures, such as indoor exposures, in the models. Lastly, only real-time PM data during each trip was collected. For other air pollutants and weather conditions, I used the ambient levels at the nearest site of the China National Environmental Monitoring Centre during that specific hour. This may have caused discrepancies in the respiratory effects of other air pollutants.

4.3 Conclusions, Recommendations, and Future Research

To conclude, this study suggests that cycling in a highly polluted environment, even for a short period of time, has detrimental effects on lung function in healthy adults. Higher exposure to fine particles was significantly associated with reduced lung function. It is recommended that urban dwellers avoid long-distance active commuting, such as cycling, in heavily polluted areas or during times of high traffic congestion. Particulate-filtering facepiece respirators, such as N95 masks, are recommended when cycling in highly polluted environments or on days when pollution levels are high. It is also recommended that the environmental and health effects of active commuting be evaluated by local governments, especially for cities with high levels of air pollution, such as Xi’An, in promoting “green commuting” bike-sharing systems. Companies are suggested to notify users, through their apps, of the potential adverse health effects of cycling on days with high levels of air pollution. A comprehensive assessment of the health impact of the bike-sharing system in China is needed.

APPENDIX

Table A1 Results of comparison tests of air pollutant exposures between cities

City pair	PM_{10}	$PM_{2.5}$	PM_1	SO_2	NO_2	O_3	CO
Shanghai–Guangzhou	0.025	0.824	0.225	< 0.001	0.174	0.335	< 0.001
Guangzhou–Xi'An	0.760	0.062	0.019	< 0.001	0.239	0.897	0.334
Xi'An–Shanghai	0.027	0.034	0.105	< 0.001	0.755	0.052	0.008

Table A2 Results of comparison tests of air pollutant intakes between cities

City pair	PM_{10}	$PM_{2.5}$	PM_1	SO_2	NO_2	O_3	CO
Shanghai–Guangzhou	0.744	0.148	0.015	< 0.001	0.002	0.116	0.040
Guangzhou–Xi'an	0.104	0.012	0.005	< 0.001	0.037	0.721	0.651
Xi'An–Shanghai	0.036	0.163	0.312	< 0.001	0.540	0.056	0.078

Table A3 Correlations between air pollutant concentrations in the three cities

	PM_{10}	$PM_{2.5}$	PM_1	SO_2	NO_2	O_3	CO
PM_{10}	1.00						
$PM_{2.5}$	0.88	1.00					
PM_1	0.81	0.99	1.00				
SO_2	0.26	0.35	0.38	1.00			
NO_2	0.54	0.55	0.51	0.20	1.00		
O_3	-0.39	-0.35	-0.32	-0.15	-0.54	1.00	
CO	0.78	0.82	0.78	0.21	0.54	-0.44	1.00

Table A4 Results of comparison tests of changes in lung function measures (before and after cycling) between cities

City pair	FVC	FEV_1	$FEV_1\%$	PEF	$FEF_{25–75\%}$
Shanghai–Guangzhou	0.522	0.099	0.005	0.232	0.111
GuangzhouXi'An	0.003	0.006	0.048	0.217	0.926
Xi'An–Shanghai	0.001	0.948	0.001	0.458	0.179

Table A5 Associations between air pollutant exposures and respiratory responses

Lung function	Pollutant	Air pollutant exposures (concentration)			Pollutant intakes		
		Coefficients[1]	95% CI	p[2]	Coefficients	95% CI	p
FVC	PM_{10}	-4.92	(-10.14, 0.31)	**0.065***	-1.65	(-6.08, 2.78)	0.466
	$PM_{2.5}$	-5.57	(-10.35, -0.80)	**0.022****	-3.60	(-8.21, 1.01)	0.125
	PM_1	-5.61	(-10.38, -0.83)	**0.021****	-3.88	(-8.49, 0.73)	**0.099***
	SO_2	-7.58	(-16.32, 1.15)	**0.089***	-2.88	(-9.52, 3.76)	0.395
	NO_2	-5.08	(-10.43, 0.26)	**0.062***	-0.92	(-5.43, 3.59)	0.689
	O_3	2.94	(-2.57, 8.44)	0.296	2.94	(-0.52, 6.40)	**0.096***
	CO	-5.78	(-10.44, -1.11)	**0.015****	-3.05	(-7.12, 1.02)	0.142
FEV$_1$	PM_{10}	-3.61	(-9.59, 2.38)	0.238	-2.32	(-7.23, 2.58)	0.354
	$PM_{2.5}$	-4.75	(-10.28, 0.77)	**0.092***	-3.77	(-8.96, 1.43)	0.155
	PM_1	-4.95	(-10.50, 0.60)	**0.080***	-3.93	(-9.17, 1.31)	0.141
	SO_2	-1.98	(-11.98, 8.03)	0.698	-1.76	(-9.09, 5.56)	0.637
	NO_2	-1.50	(-7.80, 4.80)	0.641	-1.02	(-6.19, 4.14)	0.698
	O_3	0.30	(-5.99, 6.58)	0.927	-0.07	(-3.90, 3.77)	0.972
	CO	-4.62	(-10.00, 0.75)	**0.092***	-3.37	(-7.91, 1.17)	0.146
FEV$_1$%	PM_{10}	0.23	(-4.02, 4.49)	0.915	-0.02	(-3.39, 3.35)	0.992
	$PM_{2.5}$	-0.28	(-4.28, 3.73)	0.891	-0.21	(-3.85, 3.44)	0.912
	PM_1	-0.50	(-4.56, 3.55)	0.807	-0.33	(-4.03, 3.38)	0.863
	SO_2	4.31	(-2.54, 11.15)	0.217	1.75	(-2.96, 6.46)	0.467
	NO_2	2.22	(-2.40, 6.84)	0.346	0.45	(-3.22, 4.11)	0.811
	O_3	-2.02	(-6.45, 2.41)	0.371	-1.48	(-4.13, 1.18)	0.276
	CO	0.29	(-3.54, 4.13)	0.880	0.06	(-3.10, 3.22)	0.970
PEF	PM_{10}	-2.35	(-8.13, 3.44)	0.427	-3.74	(-8.38, 0.89)	0.114
	$PM_{2.5}$	-3.39	(-8.74, 1.97)	0.215	-4.84	(-9.78, 0.10)	**0.055***
	PM_1	-3.81	(-9.19, 1.57)	0.165	-5.20	(-10.19, -0.21)	**0.041****
	SO_2	7.30	(-2.26, 16.86)	0.134	1.90	(-5.18, 8.98)	0.598
	NO_2	3.16	(-2.91, 9.22)	0.308	0.16	(-4.82, 5.14)	0.950
	O_3	-3.70	(-9.72, 2.32)	0.228	-2.77	(-6.39, 0.85)	0.134
	CO	-1.16	(-6.40, 4.07)	0.664	-2.57	(-6.94, 1.81)	0.250
FEF$_{25–75\%}$	PM_{10}	-1.28	(-7.01, 4.45)	0.662	-2.76	(-7.47, 1.94)	0.249
	$PM_{2.5}$	-2.29	(-7.59, 3.00)	0.396	-3.86	(-8.82, 1.10)	0.128
	PM_1	-2.51	(-7.82, 2.80)	0.354	-4.03	(-9.03, 0.96)	0.113
	SO_2	8.29	(-1.13, 17.70)	**0.084***	1.89	(-5.18, 8.95)	0.601
	NO_2	2.23	(-3.72, 8.19)	0.462	-1.20	(-6.11, 3.70)	0.631
	O_3	-1.69	(-7.67, 4.28)	0.579	-1.39	(-5.04, 2.26)	0.456
	CO	-2.61	(-7.76, 2.55)	0.322	-3.44	(-7.80, 0.92)	0.123

1. The unit of coefficients is percentage change (%) per IQR increase in air pollution.
2. p values with * indicate $p < 0.1$, and those with ** indicate $p < 0.05$.

Table A6 Associations between fine-particle exposures and respiratory responses

Lung function	Size (μm)	Coefficients[1]	95% CI	p[2]	Lung function	Size (μm)	Coefficients	95% CI	p
FVC	0.25	-5.19	(-10.88, 0.50)	**0.074***	**PEF**	0.25	2.44	(-3.76, 8.65)	0.441
	0.28	-5.48	(-11.18, 0.23)	**0.060***		0.28	1.05	(-5.17, 7.27)	0.741
	0.30	-5.13	(-10.04, -0.22)	**0.041****		0.30	-1.89	(-7.26, 3.48)	0.491
	0.35	-4.81	(-9.51, -0.11)	**0.045****		0.35	-3.00	(-8.17, 2.17)	0.256
	0.40	-4.59	(-8.86, -0.32)	**0.035****		0.40	-3.08	(-7.75, 1.59)	0.197
	0.45	-3.70	(-7.44, 0.04)	**0.053***		0.45	-2.93	(-7.01, 1.15)	0.159
	0.50	-4.12	(-8.19, -0.06)	**0.047****		0.50	-3.32	(-7.74, 1.09)	0.140
	0.58	-2.55	(-5.23, 0.13)	**0.062***		0.58	-2.1s0	(-4.99, 0.79)	0.154
	0.65	-2.09	(-5.04, 0.85)	0.164		0.65	-2.08	(-5.24, 1.07)	0.196
	0.70	-2.72	(-5.84, 0.41)	**0.088***		0.70	-2.35	(-5.72, 1.01)	0.171
	0.80	-3.69	(-7.68, 0.29)	**0.069***		0.80	-2.69	(-7.00, 1.62)	0.221
	1.00	-2.87	(-7.06, 1.32)	0.179		1.00	-2.35	(-6.88, 2.18)	0.309
FEV_1	0.25	-3.22	(-9.80, 3.36)	0.337	**$FEF_{25–75\%}$**	0.25	2.17	(-4.07, 8.41)	0.495
	0.28	-3.84	(-10.41, 2.72)	0.251		0.28	1.02	(-5.25, 7.28)	0.751
	0.30	-4.35	(-10.00, 1.30)	0.131		0.30	-1.62	(-7.02, 3.79)	0.557
	0.35	-4.34	(-9.80, 1.13)	0.120		0.35	-3.06	(-8.25, 2.13)	0.248
	0.40	-4.18	(-9.11, 0.75)	**0.097***		0.40	-2.63	(-7.33, 2.08)	0.274
	0.45	-3.30	(-7.62, 1.03)	0.135		0.45	-2.46	(-6.57, 1.65)	0.241
	0.50	-3.71	(-8.38, 0.97)	0.120		0.50	-2.57	(-7.03, 1.88)	0.258
	0.58	-2.31	(-5.37, 0.75)	0.139		0.58	-1.40	(-4.33, 1.52)	0.348
	0.65	-1.93	(-5.28, 1.42)	0.258		0.65	-1.23	(-4.42, 1.97)	0.452
	0.70	-2.45	(-6.02, 1.12)	0.179		0.70	-1.51	(-4.92, 1.90)	0.386
	0.80	-3.28	(-7.84, 1.28)	0.159		0.80	-1.87	(-6.22, 2.48)	0.400
	1.00	-3.01	(-7.81, 1.79)	0.219		1.00	-2.40	(-6.95, 2.16)	0.302
$FEV_1\%$	0.25	0.45	(-4.33, 5.23)	0.854	**$FEV_1\%$**	0.50	-0.06	(-3.44, 3.31)	0.970
	0.28	0.04	(-4.67, 4.75)	0.986		0.58	0.12	(-2.06, 2.30)	0.914
	0.30	-0.65	(-4.73, 3.44)	0.755		0.65	0.09	(-2.26, 2.43)	0.943
	0.35	-1.21	(-5.24, 2.83)	0.558		0.70	0.07	(-2.46, 2.61)	0.954
	0.40	-0.50	(-4.09, 3.09)	0.786		0.80	0.04	(-3.23, 3.32)	0.979
	0.45	-0.22	(-3.37, 2.93)	0.892		1.00	-0.47	(-3.94, 3.00)	0.791

1. The unit of coefficients is percentage change (%) per IQR increase in air pollution.
2. p values with * indicate $p < 0.1$, and those with ** indicate $p < 0.05$.

Table A7 Distribution of temperature and relative humidity in the three cities

		N	Min	Median	Mean	Max	IQR	SD
Temperature (℃)	Pooled	140	-4.50	6.00	8.03	22.50	13.13	7.00
	Shanghai	40	2.40	6.15	6.43	10.00	2.33	1.73
	Guangzhou	40	11.00	17.00	16.81	22.50	3.25	2.62
	Xi’An	40	-4.50	1.00	1.45	10.00	3.00	2.63
Relative humidity	Pooled	140	22.00%	63.10%	62.18%	99.00%	26.35%	19.31%
	Shanghai	40	39.50%	69.00%	69.14%	99.00%	22.75%	17.56%
	Guangzhou	40	27.00%	70.00%	64.94%	87.00%	21.25%	14.88%
	Xi’An	40	22.00%	54.00%	54.47%	98.00%	31.20%	21.56%

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