Adverse effect of outdoor air pollution on cardiorespiratory fitness in Chinese children

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Abbreviations

ATS-DLD-78-C: the Children's Questionnaire recommended by the American Thoracic Society

BMI: body mass index

HPD: high-pollution district

LPD: low-pollution district

MFT: multistage fitness test

MPD: moderate-pollution district

NO_2: nitrogen dioxide

O_3: ozone

PM : particulate matter

PM_1: particulate matter less than 1 micrometers in diameter

PM_{10}: particulate matter less than 10 micrometers in diameter

SO_2: sulfur dioxide

VO_{2max}: maximal oxygen uptake

Abstract

Little is known about the health impact of air pollution on children's cardiovascular health. A cross-sectional study was conducted and data was analysed in 2,048 Chinese schoolchildren (aged 8-10 years) in three districts of Hong Kong to examine the association between exposure to outdoor air pollution and cardiorespiratory fitness. Annual means of ambient PM_{10}, SO_2, NO_2 and O_3 from 1996 to 2003 were used to estimate individual exposure of the subjects. Cardiorespiratory fitness was measured for maximal oxygen uptake (VO_{2max}), predicted by the multistage fitness test (MFT). Height and weight were measured and other potential confounders were collected with questionnaires. Analysis of covariance was performed to estimate the impact of air pollution on complete speed in the MFT and predicted VO_{2max}. The results showed that children in high-pollution district had significantly lower complete speed and predicted VO_{2max} compared to those in low- and moderate-pollution districts. Complete speed and predicted VO_{2max} was estimated to reduce 0.327 km/h and 1.53 $ml \cdot kg^{-1} \cdot min^{-1}$ per 10 $\mu g/m^3$ increase in PM_{10} annual mean respectively, with those in girls being greater than in boys. Being physically active could not significantly result in improved cardiorespiratory fitness in polluted districts. The adverse effect seems to be independent of short-term exposure to air pollution. We concluded that long-term exposure to higher outdoor air pollution levels was negatively associated with cardiorespiratory fitness in Chinese schoolchildren, especially for girls. PM_{10} is the most relevant pollutant of the adverse effect. Elevated cardiorespiratory fitness observed in physically activate children could be negated by increased amount of inhaled pollutants during exercise.

Key words: air pollution; long-term effect; cardiorespiratory fitness; maximal oxygen uptake; children

1. Introduction

The adverse effects of exposure to ambient air pollution have been studied with various study design on various outcome indicators, especially respiratory and cardiovascular health (WHO, 2006; Brook, 2007; Ruckerl et al., 2011; Zanobetti et al., 2011). Although both gaseous air pollutants (e.g. O_3, NO_2, SO_2) and particulate matters (PM) can instigate adverse health effects, the most compelling evidence implicates PM is an important risk factor for disease in humans . In addition, the overall evidence currently indicates that the greatest adverse effects of PM occur in the cardiovascular system though exposure to PM was once believed to pose a health risk predominantly to the lungs (Brook, 2007; Pope et al., 2006; Brook et al., 2010).

Maximal oxygen uptake (VO_{2max}) is the highest rate at which oxygen can be taken up and utilized by the body during severe exercise and is usually expressed in milliliters of oxygen per kilogram of body weight per minute ($ml \cdot kg^{-1} \cdot min^{-1}$) (Bassett et al., 2000). VO_{2max} has been considered the single gold standard for measurement of cardiorespiratory fitness, a strong predictor of cardiovascular diseases and mortality (Bassett et al., 2000; Wagner, 1996; Ortega et al., 2008; Kodama et al., 2009). A recent systematic review further indicated strong evidence on a positive association between cardiorespiratory fitness in childhood and adolescence and cardiovascular profile later in life (Ruiz et al., 2009). Cardiorespiratory fitness is mainly dependent on the ability of the cardiovascular system to deliver oxygen to working muscles and the cellular ability to take up and utilize this oxygen in energy production. The chain of physiologic events involved in exercise can be adversely influenced by air pollution which have been linked to reduced lung function, impaired pulmonary gas diffusion, decreased arterial oxygenation, altered autonomic innervations of the heart, cardiac ischemia, impaired vasoregulation of blood vessels, and increased blood viscosity (Brook, 2007; Ruckerl et al., 2011; Zanobetti et al., 2011). However, evidence of the adverse effect of air pollution on cardiorespiratory fitness is scarce.

A Canadian study (n=5,011, aged 6-79 years) with a cross-sectional study design revealed that short-term ambient exposure could decrease cardiorespiratory fitness indicated by aerobic fitness score (Cakmak et al., 2011). To our knowledge, there is only one study examining the chronic effect on cardiorespiratory fitness by our colleagues more than 10 years ago (Yu et al., 2004). Reduced predicted VO_{2max} were observed in primary schoolchildren living in a more polluted district in Hong Kong. As the study was conducted more than 10 years ago, air pollution level and air pollutant components have since changed (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). This study aimed at examining the health effect of ambient air pollution on cardiorespiratory fitness indicated by predicted VO_{2max} by the multistage fitness test (MFT) among schoolchildren who lived in three districts in Hong Kong with different air pollution levels. Beneficial effect of physical activity was also examined among children with different exposure levels.

2. Methods

2.1 Subjects

The cross-sectional study was conducted among Hong Kong primary school students in 2004. Hong Kong has 18 administrative districts, 11 of which have been set up a general air quality monitoring station, including one located in a rural island to measure the background air quality (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). Three districts, labelled as low-pollution district (LPD), moderate-pollution district (MPD) and high-pollution district (HPD), were chosen from the ten districts with urban general air monitoring stations based on their rank of the average annual mean concentrations of PM_{10} during 1996 to 2003, as it is the major ambient air pollutant in Hong Kong and previous studies suggests that particulate matter has the strongest relationship with cardiovascular morbidity and mortality (Brook, 2007; Ruckerl et al., 2011; Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). All of the three districts are urban areas, mainly mixed with residential and commercial buildings. Three to four primary schools in each district, which are located within 1 km from the local air monitoring station and apart within 1 km from each other, were invited to participate into the study (Figure 1). All eligible students in third and fourth grades were investigated and written informed consents were obtained from their parents in advance. Approval was obtained from the Ethics Committees at the Chinese University of Hong Kong. In order to reduce misclassification, only Chinese students aged 8-10 years who had been currently living in their school district for more than 12 consecutive months before the study were recruited. In addition, students who were recommended by doctors not to take PE classes were excluded.

2.2 Data collection

2.2.1 Air pollution data

Four typical ambient air pollutants, including PM_{10}, NO_2, SO_2 and O_3, were studied. Annual means in 1996-2003 and in the year prior to the mid-time point of the study (May 2003 to April 2004) were obtained from the Environmental Protection Department of Hong Kong to estimate the life-time and current exposure levels of the participants respectively (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). Hourly mean averages during 7am to 2pm on the 13 days of test and 24-hour means for PM_{10}, NO_2, SO_2 and 8-hour maximal value for O_3 on one day before each test day were also calculated to reflect the short-term exposure on the spot. Air temperature (°C) and relative humidity (%) on the test days were also obtained as potential confounders.

2.2.2 Questionnaire survey

Two self-administered questionnaires were developed to collect children's personal and household information based on the Children's Questionnaire recommended by the American Thoracic Society (ATS-DLD-78-C) (Ferris, 1978). Parents completed one questionnaire on socioeconomic status, children's respiratory symptoms and diseases in the past 12 months, parental history of asthma, housing indoor environmental factors, as well as children's birth weight, birth place and breastfeeding history. Children reported on their gender, sex, smoking habits, as well as time spent outdoors, amount and type of physical activities, member of sports team and playing with furry toys in the past 12 months.

2.2.3 Anthropometry and multistage fitness test (MFT)

Anthropometry and multistage fitness test (MFT) were performed in the schools in the morning from April to June in 2004. In Hong Kong, the three months are hot and humid with occasional showers and thunderstorms (Leung et al., 2008). It has been reported that monthly mean of daily mean temperature in 1971-2000 was 22.5°C in April, 25.8°C in May and 27.9°C in June and that of daily mean relative humidity was 83%, 84% and 82% respectively (Leung et al., 2008). Height (cm) and weight (kg) were firstly measured by FISCO measuring tape (CMS Weighing Equipment Ltd.) and Tanita electronic digital scale (Model No. HD305) following standard anthropometric methods. Body mass index (BMI, kg/m^2) was then calculated.

The MFT was originally developed by Leger and Lambert in 1982 and has been widely used as a predictive field test for VO_{2max} in sports sciences (Bassett et al., 2000; Wagner, 1996; Leger et al., 1988). Recent systematic reviews concluded that the MFT is a valid and reliable test to estimate cardiorespiratory fitness (Castro-Pinero et al., 2010; Artero et al., 2011; Ruiz et al., 2011). The test consists of 23 stages, each lasting about one minute and comprising a number of 20-meter laps. Each MFT was carried out in a group of 8-12 students and each student was asked to run back and forth on a track of about 1.5 m in width and required to reach the opposite 20-meter lines before or at the same time when an audio sound signal (beep) was emitted from a prerecorded CD. The frequency of the beeps increased in such a way that running speed was increased by 0.5 km/h each minute from a starting speed of 8.5 km/h. The test ended when students missed two consecutive beeps or voluntarily stopped because of fatigue. The total number of completed stages was recorded and used to predict VO_{2max} with Leger's equation derived from healthy children aged 8-17 years (Leger et al., 1988).

2.3 Data analysis

Statistical analyses were performed using the SPSS for windows 16.0 version. Percentages and mean and standard deviation (SD) were calculated to describe the distribution of categorical and continuous variables respectively. Chi-square and one-way ANOVA were applied to compare between-group differences. Hierarchical linear regression was used to select variables as follows: Step 1, background variables, including gender (for all subjects only), age, father's job and birth place were forcedly entered in the model first; Step 2, other independent variables were then selected using $P<0.10$ and $P<0.15$ as entry and removal criteria. Analysis of covariance (ANCOVA) was performed to estimate the difference in complete speed of the MFT and predicted VO_{2max} after adjustment for the background and the selected variables by the corresponding regression model. Least significant difference (LSD) was applied for pair-wise comparisons. Adjusted mean and mean difference and their standard error (SE) were derived.

3. Results

The long-term trends of air pollutants in the three districts were plotted in Figure 2. The concentrations of PM_{10}, SO_2 and NO_2 were low, but that of O_3 was high in LPD. In MPD, the concentration of NO_2 was high, but those of PM_{10}, SO_2 and O_3 were moderate. In HPD, concentrations of PM_{10}, SO_2 and NO_2 were all high but O_3 concentration was low. The mean daily concentrations on and before the test days varied from 20-94 μg/m^3 for PM_{10}, from 25-97 μg/m^3 for NO_2, from 8-82μg/m^3 for SO_2, and from 6-109 μg/m^3 for O_3. The air temperature and relative humidity on the test days ranged from 19.7-35.1℃ and 72-87% respectively.

A total of 3,186 students in 11 primary schools were approached and a participation rate of 82.9%

(n=2,641) was achieved. There were 95.9% (n=2,534) and 94.5% (n=2,497) of the participants completing questionnaires and measured of cardiorespiratory fitness respectively. About 331 participants failed to meet the selection criteria and therefore were excluded from data analysis, leaving 2048 students with data analysed. Table 1 summarises percentages of personal and household characteristics of the students. Differences across the districts reached significance in father's job, birth place, residence relocation, having been breastfed, cough, physical activity, member of sports team, playing with furry toys, more time spent outdoors, mould in the home, incense burning and passive smoking. In terms of the continuous variables, complete speed of the MFT and predicted VO_{2max} in both genders were significantly different across the districts (Table 2). Boys were significantly higher than girls in weight, BMI and predicted VO_{2max}.

Table 3 compares means for complete speed and predicted VO_{2max} among the three districts after adjustment for other confounding factors. Children in HPD had significantly lower complete speed and predicted VO_{2max} than those in LPD and MPD. The differences remained significant after stratification by gender, with the adverse effect being slightly higher in girls. There were no significant differences in the two outcome variables between children in LPD and MPD, except marginally higher values in LPD were found in girls. Complete speed and predicted VO_{2max} were estimated to decrease 0.327 km/h and 1.53 $ml \cdot kg^{-1} \cdot min^{-1}$ per 10 $\mu g/m^3$ increase in PM_{10} annual mean respectively, with those in girls being larger than boys. Covariates adjusted for in the models were listed in Table 3.

Complete speed of the MFT and predicted VO_{2max} values between children who were physically active and those who were not were compared after stratification by district and controlling for other confounders (Table 4). In LPD, physical active children had significantly higher means for both complete speed and predicted VO_{2max} compared to those with physical inactivity before and after stratification by gender. The favourable effects of physical exercise became smaller and insignificant in more polluted districts, suggesting that air pollution may impede children benefiting from physical activity.

4. Discussion

The association between exposure to ambient air pollution and cardiorespiratory fitness indicated by predicted VO_{2max} of the MFT was examined among 2,048 Chinese schoolchildren aged 8-10 years in Hong Kong. After adjustment for potential confounders, predicted VO_{2max} and complete speed in the MFT were negatively associated with air pollution level. Children in HPD had significantly lower values compared to those in LPD and MPD, suggesting an adverse effect of air pollution on children's cardiorespiratory fitness. Predicted VO_{2max} and complete speed were estimated to reduce 1.53 $ml \cdot kg^{-1} \cdot min^{-1}$ and 0.327 km/h per 10 $\mu g/m^3$ increase in PM_{10} annual mean respectively, with those in girls being greater than in boys. Being physically active could not significantly result in improved cardiorespiratory fitness in children who lived in more polluted districts (HPD and MPD). The adverse effect seems to be independent of short-term exposure to air pollution, which was controlled for in data analysis.

The findings on predicted VO_{2max} among children were much higher than that reported by Yu et al. (2004), despite the identical methods used in conducting the MFT (45.0 $ml \cdot kg^{-1} \cdot min^{-1}$ vs. 29.3 $ml \cdot kg^{-1} \cdot min^{-1}$). Several equations have been advocated in the prediction of VO_{2max} among general children and adolescents, which may yield different values in a given complete stage and/or lap (Castro-Pinero et al., 2010). Some studies have cross-validated those equations and found significant relationship across them (Castro-Pinero et al., 2010). The higher estimates in this study could have been due to differences in the equations used to predict VO_{2max} from the MFT results. However, the results are consistent with other studies among healthy general children in the same age range (varied from 45.1-56.0 $ml \cdot kg^{-1} \cdot min^{-1}$) (Leger et al., 1988; Barnett et al., 1993; Matsuzaka et al., 2004). In addition, direct comparisons of complete speed can avoid the discrepancies caused by equations. In this study, the means for complete speed were 9.43 km/h in boys and 9.23 km/h in girls respectively, in line with those reported by Olds et al in an analysis of 109 studies in 37 countries (Olds et al., 2006). Predicted VO_{2max} was also estimated using another two equations derived by Matsuzaka et al. (2004), which are suitable to the subjects in term of the age range. The outcomes revealed that there were slight but significant differences in predicted VO_{2max} values across the three equations. However, those differences did not change the association between air pollution and cardiorespiratory fitness much (data not shown). In addition, consistent association was also observed with complete speed of the MFT, which avoids the discrepancies caused by equations.

Nevertheless, the findings that air pollution is negatively associated with children's predicted VO_{2max} were consistent with Yu's study (2004). Though the differences among districts were much smaller than that observed in Yu's study (e.g. -0.98 $ml \cdot kg^{-1} \cdot min^{-1}$ in the comparison of HPD and LPD vs. -1.9 $ml \cdot kg^{-1} \cdot min^{-1}$ in that study), the predicted VO_{2max} changes per 10 $\mu g/m^3$ change in PM_{10} annual mean were almost the same (1.53 $ml \cdot kg^{-1} \cdot min^{-1}$ vs. 1.57 $ml \cdot kg^{-1} \cdot min^{-1}$, calculated with the identical method). Hence, it is most likely that the larger differences in air pollutant concentrations (especially PM_{10}) contribute the larger predicted VO_{2max} difference between districts in Yu's study (2004). Another possible reason is the components of air pollution may have changed since then and currently it may be less "toxic" than before due to a series of implementations to improve air quality (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). In addition, air pollution data in this study was the annual mean average of an 8-year period (1996-2003), which almost covered the lifetime of the children and therefore represented the exposure level in their whole life. While in that study, only the past year's air pollution data was collected and the exposure level in earlier time was unknown. It is therefore possible that the larger difference in that study may due to a higher air pollution level in early time (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). Giving more than 80% of the children lived in the current district for their whole life and the short-term exposure was adjusted for (Table 3), the relationship observed in our study may better reflect the chronic adverse effect from lifetime exposure. The short-term exposure in this study was indicated by pollutants' concentrations on previous day and the day of the MFT, monitored by the study air monitoring stations. After controlling for other confounding factors, only daily mean for SO_2 on previous day had significant adverse effects on predicted VO_{2max} and complete speed *(B=-0.013, SE=0.019, P=0.005 for predicted* VO_{2max}*, B=-0.003, SE=0.001, P=0.005 for complete speed).* Further gender-specific analysis revealed that the adverse effect was significant for girls *(B=-0.019, SE=0.006, P=0.001 for predicted* VO_{2max}*, B=-0.004, SE=0.001, P=0.001 for complete speed),* but not for boys *(B=-0.009, SE=0.007, P=0.187 for predicted* VO_{2max}*, B=-0.002, SE=0.002, P=0.175 for complete speed).* Other short-term exposure indicators were not significantly associated with predicted VO_{2max} and complete speed in multivariate analysis, though some of them showed significant correlations in univariate analysis (e.g. PM_{10}). Thus, SO_2 on previous day was finally involved in ANCOVA to estimate the health effect of long-term exposure.

It is well-known that predicted VO_{2max} can be improved by regular aerobic exercise (Olds et al., 2006). In this study, physical activity was not associated with a higher predicted VO_{2max} among children in more polluted districts, in contrast to those living in the less polluted district. Individuals who performed physical exercise in a polluted environment may be at an elevated risk because, even at low intensities, a significant rise in pulmonary ventilation and diffusion capacity occurs, meaning that concentration of inhaled pollutants will increase (Sharman et al., 2004). In addition, oral breathing usually occurs during exercise; this can also increase the risk because the fractional penetration of pollutants to the lung is greater when breathing by mouth than by nose (Sharman et al., 2004). A recent study revealed that the total amount of $PM_{0.1}$ deposited in the respiratory tract during moderate exercise was about five times that at rest (Daigle et al., 2003). Another study reported reduced maximal exercise performance among 15 healthy college-aged males after short-term exposure to a high PM_1 (Rundell et al., 2008). A Hong Kong study found that high level of exercise (≥4 times/week) provided less protection against pollution-associated mortality than low or moderate exercise (≥1 time/month and <4 times/week), suggesting that increased amount of inhaled pollutants during intensive exercise tends to negate the apparent benefits of exercise (Wong et al., 2007). Our findings are in line with those studies. It is important to study the relation between level of physical exercise and cardiorespiratory response to determine an appropriate exercise level at different air pollutant concentrations to maximise its health benefits. Guidelines for appropriate exercise time and places should also be established to the public to avoid physical exercise during periods with high air pollutant concentrations (Campbell et al., 2005).

PM is a mixture of solid, liquid or solid and liquid particles suspended in the air and varies in size, composition and origin (WHO, 2006). PM_{10} is particles below 10 μm aerodynamic diameter, which can enter the respiratory tract. As the most commonly used indicator, PM_{10} can be further divided into coarse particles ($PM_{2.5-10}$, particles between 2.5-10 μm in diameter) and fine particles ($PM_{2.5}$, particles less than 2.5 μm) (Brook, 2007). Both $PM_{2.5-10}$ and $PM_{2.5}$ are present, whilst the proportion of two varies substantially between cities around the world, depending on local geography, meteorology and specific PM sources (WHO, 2006). $PM_{2.5}$ has recently received the vast majority of the attention and been regarded to being the primary PM-related mediator of human cardiovascular diseases. Evidence from existing epidemiological studies has shown similar effect estimates of $PM_{2.5}$ for a wide range of cities in both developed and developing countries, suggesting that the health effects of $PM_{2.5}$ may not vary much according its composition and origin (WHO, 2006). Recent studies in which PM_{10} size fractions and/or constituents have been measured suggest that the observed effects of PM_{10} are in fact largely associated with $PM_{2.5}$, not with $PM_{2.5-10}$ (Brook, 2007; Pope et al., 2006). Hong Kong started monitoring $PM_{2.5}$ in 1998 (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). In Hong Kong, measurement of $PM_{2.5}$ started in HPD in 2005 and in other two districts (MPD and LPD) in 2011, making it impossible to calculate the ratio of $PM_{2.5}$ to PM_{10} in each district for the study period (1996-2004) (Environmental Protection Department of Hong Kong, http://www.epd.gov.hk/). Qiu et al analysed data from an urban general monitoring station in 2000-2005 and revealed that the ratio of $PM_{2.5}$ to PM_{10} ranged from 40% to 98% in terms of daily mean concentrations, with an average of 70%. The results are likely to be more representative of Hong Kong's air quality in general (Qiu et al., 2012). With the average ratio, we estimated that a 10 μg/m^3 increase of $PM_{2.5}$ annual mean could result in a 2.19 ml·kg^{-1}·min^{-1} decrease of predicted VO_{2max} and a 0.467 km/h decrease of complete speed respectively.

In this study, MPD had the highest level of NO_2, followed by HPD and then LPD. In order to examine whether NO_2 would affect predicted VO_{2max} or not we combined data of HPD and LPD to compare with MPD. No significant difference was found between the two groups (45.31 ml·kg^{-1}·min^{-1} vs. 45.52 ml·kg^{-1}·min^{-1}, P=0.344), suggesting that NO_2 may not be associated with cardiorespiratory fitness. Although O_3 was highest in LPD and lowest in HPD, it is biologically implausible that exposure to high O_3 can promote cardiorespiratory fitness. Moreover, the overall evidence indicates that it is PM rather than gaseous pollutants (e.g. O_3, NO_2) responsible for cardiovascular morbidity and mortality (Brook, 2007; Ruckerl et al., 2011; Zanobetti et al., 2011). Hence, the decreased cardiorespiratory fitness in this study is likely due to exposure to $PM_{10,}$ whose concentration is negatively correlated with that of O_3.

There are several limitations in this study. This study cannot explain the cause-effect relationship between air pollution and cardiorespiratory fitness due to the cross-sectional study design. The limited number of districts, each with a mixture of several pollutants, constrained our ability to examine their individual effects on health. Furthermore, air pollutants were not consistently high or low across the study districts and over the time and the annual mean differences among the districts were relatively small (e.g. annual mean for PM_{10} in HPD was 8.7 μg/m^3 higher than that in LPD in 1996-2003). Thus, further studies in areas with clear, consistent and well-defined contrasts are needed to confirm the observed association between air pollution and predicted VO_{2max} among children. It is noteworthy that air pollution level in Hong Kong is relatively higher than many countries in Europe. Whether the relationship exists with low exposure or not remains to be clarified. Like most studies, ambient air pollution data in the districts were surrogates for individual exposure. Hence, misclassification in exposure cannot be excluded. In addition, VO_{2max} was not directly measured but predicted by the MFT. Direct measurement of VO_{2max} demands sophisticated instrumentation, laboratory time and trained technicians and cannot deal with a large sample size. Hence it is not suitable for population-based studies. However, the MFT has been widely used because of its reliability and validity (Castro-Pinero et al., 2010; Artero et al., 2011). A satisfactory MFT demands the subjects' motivation and experiences to achieve their VO_{2max}. To minimize these possible influences, the children were briefed in detail and observed a demonstration before the test. The importance of maximal effort was also stressed. During the test, they received standardized verbal encouragements and a pacer ran with them in the first stage to ensure high reliability of the test according to the suggestions by other researchers (Cressler et al., 1988; Pitetti et al., 2001).

5. Conclusions

In conclusion, exposure to ambient air pollution is significantly and negatively related with cardiorespiratory fitness among Chinese schoolchildren. The adverse effects are larger in girls. PM_{10} may be the most relevant pollutant affecting cardiorespiratory fitness. Improved cardiorespiratory fitness by physical activity could be negated by increased amount of inhaled pollutants during exercise. Given the importance of cardiorespiratory fitness to cardiovascular and respiratory health and the feasibility of the MFT in field to measure predicted VO_{2max}, it is necessary to conduct further studies in other groups exposed to different levels of air pollutants. In addition, there is a need for cohort studies to determine the cause-effect relationship.

Contributorship

Dr. Gao designed the study, conducted the survey, did the data analysis and wrote up the MS. Prof. Chan participated in writing up the MS and revised it. Ms. Zhu participated in data analysis and revised the MS. Prof. Wong led and supervised the study and revised the MS.

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Conflict of interest

All of the authors state that there is no conflict of interest for this MS.

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Figure legends:

Figure 1: Location of the study air monitoring stations and primary schools

Figure 2: Annual mean concentrations of air pollutants from 1996-2003

Figure 1
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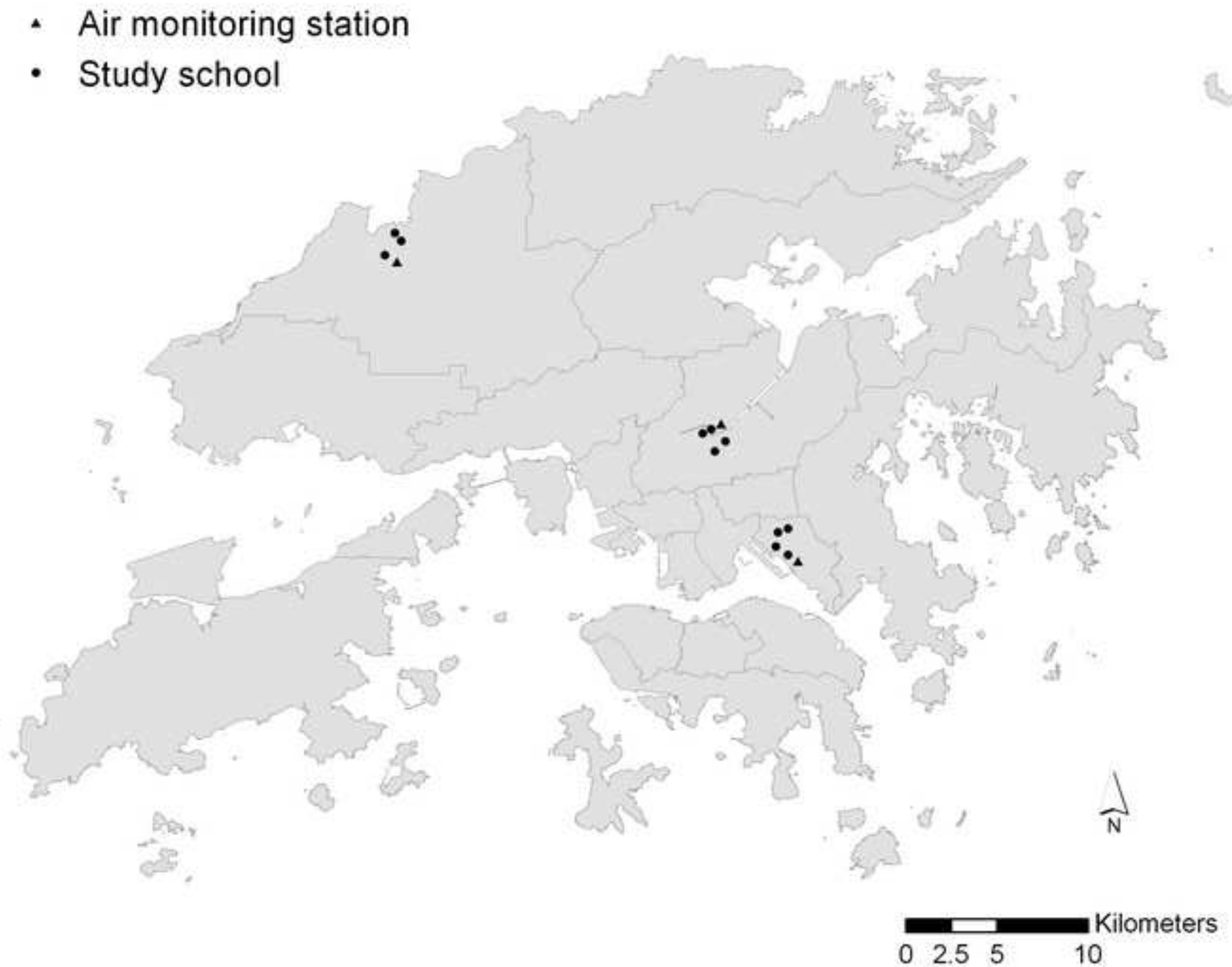
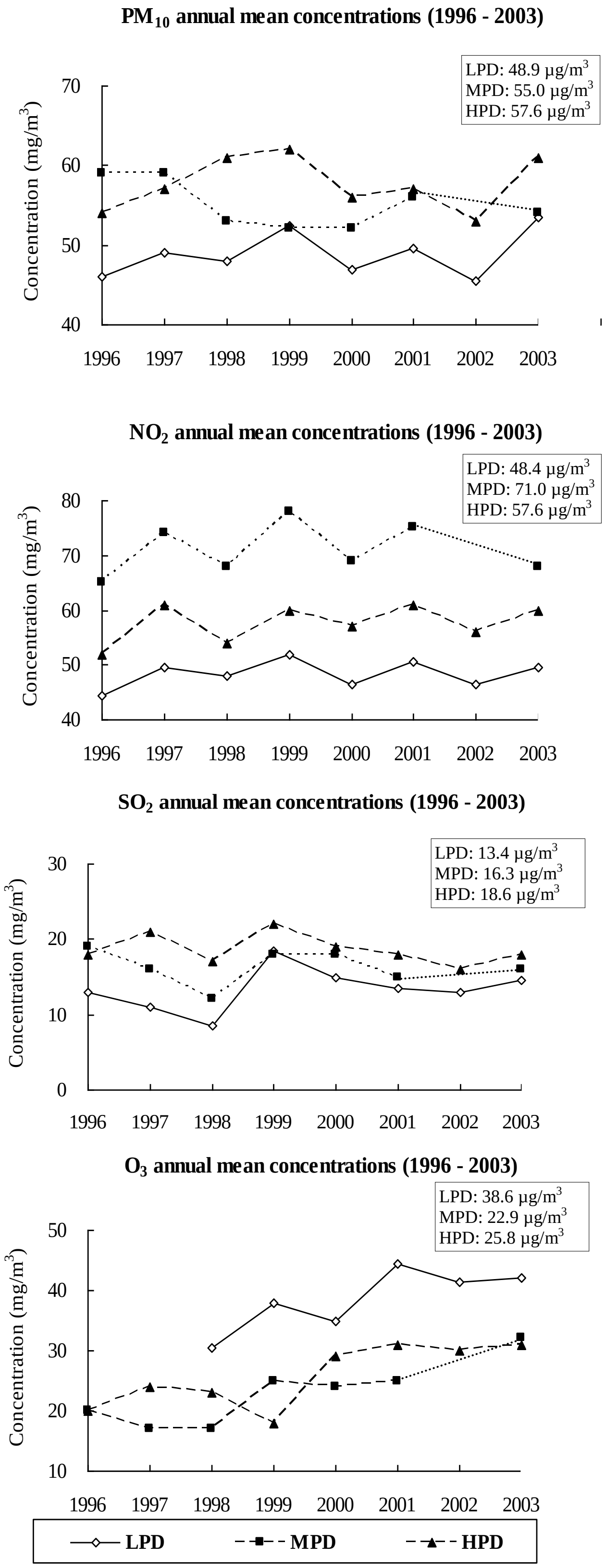


Figure 2



Note:

1. Annual means in 2002 in MPD were not calculated due to insufficient data measured.
2. O_3 measurement in LPD started since 1998.
3. Annual mean average in 1996-2003 were presented in boxes

Figure 2 Annual mean concentrations of air pollutants from 1996-2003

Tables
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Table 1
Characteristics of the subjects

	Boys (n=1056)			Girls (n=992)		
	LPD (n=451)	MPD (n=360)	HPD (n=245)	LPD (n=402)	MPD (n=327)	HPD (n=263)
Personal characteristics						
Blue-collar job of father [a] (%)	63.7***	86.1***	80.5***	54.9***	80.6***	81.3***
Born in Hong Kong (%)	91.8***	76.7***	86.1***	93.7***	75.3***	86.0***
Never relocated [b] (%)	86.0***	75.0***	88.8***	85.0*	77.7*	83.6*
Low birth weight [c] (%)	10.1	8.1	7.6	9.3	13.2	9.4
Having been breastfed (%)	27.8***	47.5***	26.6***	27.8**	36.2**	17.6**
Wheezing (%)	5.0	4.8	5.9	3.6	4.8	6.0
Cough (%)	19.7	24.9	18.9	16.2***	26.3***	27.2***
Phlegm (%)	34.0	31.3	33.8	31.0	32.7	38.0
Asthma (%)	3.1	2.6	4.2	2.1	1.7	2.5
Bronchitis (%)	12.8	9.7	13.0	10.1	10.5	11.5
Active smoking (%)	0.2	1.3	0.8	0.0	0.0	0.0
Physically active [d] (%)	41.9***	29.3***	38.8***	39.3**	29.8**	30.6**
Participated in sports team (%)	26.4***	13.7***	25.1***	23.6*	17.2*	23.0*
Playing with furry toys (%)	18.7*	18.2*	11.4*	47.4	45.9	50.6
More outdoors [e] (%)	50.7	48.1	48.7	49.8	50.3	51.8
Housing environmental characteristics						
Mould in the home (%)	26.3**	21.8**	14.3**	22.9#	22.2#	16.5#
Having new furniture (%)	15.9	18.6	16.3	18.7	21.9	18.3
Incense burning (%)	20.8*	29.0*	24.3*	17.5	20.5	20.9
Passive smoking (%)	16.5***	29.5***	24.0***	17.8***	35.1***	30.9***

LPD: low-pollution district; MPD: moderate-pollution district; HPD: high-pollution district.
#: P<0.10; *: P<0.05; **: P<0.01; ***: P<0.001.
a: Including service workers, shop sales workers, skilled workers, unskilled workers, and other kindred workers.
b: Indicating that children who lived in the current district for their whole life and never removed out to or moved in from other place.
c: Birth weight less than 2500 g.
d: Taking part in sports and/or vigorous free play at least three times a week for at least 30 minutes each time.
e: Indicating that children who spent more hours per week outdoors than the median value for their respective district and gender.

Table 2
Distribution of age, anthropometry, multistage fitness test and predicted VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)[a] by air pollution level and gender

	All	LPD	MPD	HPD
	Mean *(SD)*	Mean *(SD)*	Mean *(SD)*	Mean *(SD)*
Boys				
Age *(year)*	9.00 *(0.70)*	8.98 *(0.71)*	9.05 *(0.71)*	8.96 *(0.66)*
Height *(cm)*	134.6 *(6.8)*	134.3[#] *(6.8)*	135.3[#] *(6.8)*	134.2[#] *(6.5)*
Weight *(kg)*	32.4 *(8.1)*	32.1 *(8.3)*	32.8 *(8.3)*	32.1 *(7.4)*
BMI *(kg/m^2)*	17.7 *(3.2)*	17.6 *(3.2)*	17.7 *(3.3)*	17.7 *(3.1)*
Speed *(km/h)*	9.434 *(0.655)*	9.486[**] *(0.644)*	9.453[**] *(0.672)*	9.312[**] *(0.635)*
VO_{2max} *($ml \cdot kg^{-1} \cdot min^{-1}$)*[a]	45.40 *(3.08)*	45.67[**] *(3.04)*	45.40[**] *(3.07)*	44.90[**] *(3.13)*
Girls				
Age *(year)*	8.95 *(0.71)*	8.96 *(0.72)*	8.96 *(0.71)*	8.94 *(0.69)*
Height *(cm)*	134.4 *(7.4)*	134.1 *(7.2)*	135.1 *(7.3)*	133.9 *(7.8)*
Weight *(kg)*	31.0 *(7.6)*	30.7 *(7.0)*	31.2 *(7.7)*	31.1 *(8.1)*
BMI *(kg/m^2)*	17.0 *(2.9)*	16.9 *(2.8)*	16.9 *(2.9)*	17.2 *(3.1)*
Speed *(km/h)*	9.233 *(0.512)*	9.324[***] *(0.505)*	9.241[***] *(0.553)*	9.084[***] *(0.431)*
VO_{2max} *($ml \cdot kg^{-1} \cdot min^{-1}$)*[a]	44.57 *(2.51)*	44.99[***] *(2.47)*	44.60[***] *(2.61)*	43.88[***] *(2.30)*

LPD: low-pollution district; MPD: moderate-pollution district; HPD: high-pollution district.
SD: Standard deviation.
#: $P<0.10$; *: $P<0.05$; **: $P<0.01$; ***: $P<0.001$.
a: VO_{2max} was predicted with multistage fitness test using Leger's equation.

Table 3

Adjusted means/mean differences (M/MD) of air pollution for complete speed and predicted VO_{2max}[a]

	LPD M *(SE)*	MPD M *(SE)*	HPD M *(SE)*	HPD-LPD MD *(SE)*	MPD-LPD MD *(SE)*	HPD-MPD MD *(SE)*	Average change[b] (per 10 μg/m^3 PM_{10})	Covariates adjusted
All								
Speed *(km/h)*	9.477*** *(0.028)*	9.445*** *(0.029)*	9.266*** *(0.033)*	-0.211*** *(0.033)*	-0.033 *(0.030)*	-0.178*** *(0.034)*	-0.327	girl (-)***, age, blue-collar job of father, born in Hong Kong (-)*, BMI (-)***, cough (-)*, physical activity(+)***, member of sports team (+)***, playing with furry toys (-)***, SO_2 on previous day (-)**
Predicted VO_{2max} *(ml·kg^{-1}·min^{-1})*	45.67*** *(0.13)*	45.52*** *(0.13)*	44.69*** *(0.15)*	-0.98*** *(0.16)*	-0.15 *(0.14)*	-0.84*** *(0.16)*	-1.53	
Boys								
Speed *(km/h)*	9.609** *(0.036)*	9.605** *(0.040)*	9.448** *(0.044)*	-0.161** *(0.046)*	-0.004 *(0.043)*	-0.157** *(0.048)*	-0.265	age, blue-collar job of father, born in Hong Kong (-)*, BMI (-)***, physical activity(+)***, member of sports team (+)***
Predicted VO_{2max} *(ml·kg^{-1}·min^{-1})*	46.22** *(0.17)*	46.21** *(0.19)*	45.46** *(0.21)*	-0.75*** *(0.21)*	-0.01 *(0.20)*	-0.74** *(0.22)*	-1.24	
Girls								
Speed *(km/h)*	9.396*** *(0.035)*	9.322*** *(0.035)*	9.153*** *(0.041)*	-0.243*** *(0.042)*	-0.074# *(0.039)*	-0.169*** *(0.043)*	-0.350	age, blue-collar job of father, born in Hong Kong (-)#, height (+), BMI (-)***, cough (-)*, physical activity(+)**, member of sports team (+)***, playing with furry toys (-)***, SO_2 on previous day (-)**
Predicted VO_{2max} *(ml·kg^{-1}·min^{-1})*	45.35*** *(0.16)*	45.01*** *(0.17)*	44.22*** *(0.19)*	-1.13*** *(0.20)*	-0.34# *(0.18)*	-0.79*** *(0.20)*	-1.63	

LPD: low-pollution district; MPD: moderate-pollution district; HPD: high-pollution district.

SE: standard error.

a: VO_{2max} was predicted with multistage fitness test using Leger's equation.

b: the average of changes in VO_{2max} per 10 μg/m^3 increase in PM_{10} annual mean among the three pairs of comparisons.

Table 4
Adjusted mean and mean differences (M/MD) of physical activity for complete speed and predicted VO_{2max}[a] by air pollution level

	Complete speed *(km/h)*			Predicted VO_{2max} *($ml\cdot kg^{-1}\cdot min^{-1}$)*		
	Physical activity (PA)	Physical inactivity (PIA)	PA - PIA	Physical activity (PA)	Physical inactivity (PIA)	PA - PIA
	M *(SE)*	M *(SE)*	MD *(SE)*	M *(SE)*	M *(SE)*	MD *(SE)*
All						
LPD	9.554*** *(0.045)*	9.360*** *(0.043)*	0.194*** *(0.038)*	46.04*** *(0.21)*	45.14*** *(0.20)*	0.89*** *(0.18)*
MPD	9.451* *(0.0504)*	9.340* *(0.044)*	0.112* *(0.046)*	45.50* *(0.24)*	44.98* *(0.21)*	0.52* *(0.22)*
HPD	9.311 *(0.055)*	9.245 *(0.054)*	0.066 *(0.052)*	44.94 *(0.26)*	44.62 *(0.25)*	0.31 *(0.24)*
Boys						
LPD	9.694*** *(0.056)*	9.468*** *(0.055)*	0.226*** *(0.054)*	46.66*** *(0.26)*	45.62*** *(0.25)*	1.04*** *(0.25)*
MPD	9.549 *(0.074)*	9.437 *(0.064)*	0.112 *(0.069)*	45.84 *(0.35)*	45.33 *(0.30)*	0.51 *(0.32)*
HPD	9.500 *(0.080)*	9.371 *(0.078)*	0.129 *(0.079)*	45.75 *(0.37)*	45.14 *(0.36)*	0.61 *(0.37)*
Girls						
LPD	9.448** *(0.060)*	9.286** *(0.056)*	0.162** *(0.050)*	45.59** *(0.28)*	44.84** *(0.26)*	0.75** *(0.23)*
MPD	9.361 *(0.065)*	9.322 *(0.057)*	0.039 *(0.063)*	45.19 *(0.30)*	45.00 *(0.26)*	0.18 *(0.29)*
HPD	9.174 *(0.060)*	9.134 *(0.059)*	0.040 *(0.060)*	44.32 *(0.28)*	44.13 *(0.27)*	0.19 *(0.28)*

LPD: low-pollution district; MPD: moderate-pollution district; HPD: high-pollution district.
SE: standard error.
#: P<0.10; *: P<0.05; **: P<0.01; ***: P<0.001.
a: VO_{2max} was predicted with multistage fitness test using Leger's equation.