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Chronic exposure to ambient PM$_{2.5}$/NO$_2$ and respiratory health in school children: A prospective cohort study in Hong Kong

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**A R T I C L E  I N F O**

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- Ambient air pollution
- Lung function
- Respiratory health
- Children
- Longitudinal cohort

**A B S T R A C T**

Despite increasing concerns about the detrimental effects of air pollution on respiratory health, limited evidence is available on these effects in the Hong Kong population, especially in children. In this prospective cohort study between 2012 and 2017, we aimed to investigate the associations between exposure to air pollution (concentrations of fine particulate matter [PM$_{2.5}$] and nitrogen dioxide [NO$_2$]) and respiratory health (lung function parameters and respiratory diseases and symptoms) in schoolchildren. We recruited 5612 schoolchildren aged 6–16 years in Hong Kong. We estimated the annual average concentrations of ambient PM$_{2.5}$ and NO$_2$ at each participant’s address using spatiotemporal models. We conducted spirometry tests on all participants to measure their lung function parameters and used a self-administered questionnaire to collect information on their respiratory diseases and symptoms and a wide range of covariates. Linear mixed models were used to investigate the associations between exposure to air pollution and lung function and lung function. Mixed-effects logistic regression models with random effects were used to investigate the associations of exposure to air pollution with respiratory diseases and symptoms. In all of the participants, every 5-μg/m$^3$ increase in the ambient PM$_{2.5}$ concentration was associated with changes of $-13.90$ ml (95% confidence interval [CI]: $-23.65$ ml, $-4.10$ ml), $-4.20$ ml ($-15.60$ ml, 7.15 ml), $27.20$ ml/s ($-3.95$ ml/s, 58.35 ml/s), and $-19.80$ ml/s ($-38.35$ ml/s, $-1.25$ ml/s) in forced expiratory volume in 1 s, forced vital capacity, peak expiratory flow, and maximal mid-expiratory flow, respectively. The corresponding lung function estimates for every 5-μg/m$^3$ increase in the ambient NO$_2$ concentration were $-2.70$ ml ($-6.05$ ml, 0.60 ml), $-1.40$ ml ($-5.40$ ml, 2.60 ml), $-6.60$ ml ($-19.75$ ml, 6.55 ml), and $-3.05$ ml/s ($-11.10$ ml/s, 5.00 ml/s), respectively. We did not observe significant associations between PM$_{2.5}$/NO$_2$ exposure and most respiratory diseases and symptoms. Stratified analyses by sex and age showed that the associations between exposure to air pollution and lung function parameters were stronger in male participants and older participants (11–14 year old group) than in female participants and younger participants (6–10 year old group), respectively. Our results suggest that chronic exposure to air pollution is detrimental to the respiratory health of schoolchildren, especially that of older boys. Our findings reinforce the importance of air pollution mitigation to protect schoolchildren’s respiratory health.

1. Introduction

Increasing evidence shows that short- and long-term exposure to air pollution are associated with lung function impairment and respiratory diseases and symptoms (He et al., 2010; Son et al., 2010; Esposito et al., 2014; Adam et al., 2015; Zeng et al., 2016; Panis et al., 2017; Guo et al.,...
However, information on such associations in children is limited. Children are considered vulnerable to the effects of air pollution as, compared with adults (Bascom et al., 1996; Schwartz, 2004; Chen et al., 2018; Tsui et al., 2018) (i) they are at a developmentally immature stage; (ii) they have higher minute ventilation adjusted for body mass; (iii) they spend more time performing outdoor activities with higher activity levels; (iv) they are more susceptible to early and repeated DNA injury and repair; and (v) they are less likely to adjust their behaviour to reduce their exposure to air pollution (Bennett et al., 2007; Kajekar, 2007). Therefore, it is crucial to investigate the effects of air pollution on children and strategies to mitigate these effects (Lewis et al., 2005; Barraza-Villarreal et al., 2008; Fuertes et al., 2015; Chen et al., 2018; Knibbs et al., 2018).

Moreover, information on the relationships between long-term exposure to air pollution and lung function impairment is inconsistent across published studies. For example, studies from Norway, the Netherlands, and Japan have reported non-significant associations between exposure to air pollution and lung function (Oftedal et al., 2008; Gehring et al., 2013, 2015; Rice et al., 2015; Schultz et al., 2015; Takebayashi et al., 2022), the results of which cannot be generalised to Asian countries, such as Hong Kong, due to the substantial differences in ethnicity, culture, population density, and urbanisation. The lack of sufficient information on associations between exposure to air pollution and lung function parameters or respiratory diseases and symptoms in Hong Kong is especially concerning (Gao et al., 2013), as Hong Kong has many characteristics that predispose it to air pollution, such as a tropical climate, a high population density, tall buildings surrounded by narrow roads with heavy traffic, and many people living in small and cramped residential dwellings. Thus, further studies are warranted to provide more evidence about the health effects of air pollution on the lung function of Asian children, especially those in Hong Kong.

Accordingly, we conducted a cohort study to examine the effects of long-term exposure to ambient air pollution (concentrations of fine particulate matter [PM$_{2.5}$] and nitrogen dioxide [NO$_2$]) on lung function parameters (forced expiratory volume in 1 s [FEV$_1$], forced vital capacity [FVC], peak expiratory flow [PEF], and maximal mid-expiratory flow [MMEF]) and respiratory diseases and symptoms in schoolchildren in Hong Kong. The findings of our study improve our understanding of the respiratory health effects of air pollution on children. Moreover, they may facilitate the enactment of legislation to regulate air pollution and the development of strategies to protect children in Hong Kong and other similar pollution-prone regions in Asia.

2. Material and methods

2.1. Study population and design

This was a longitudinal prospective cohort study of schoolchildren in Hong Kong. Details of this cohort are described elsewhere (Liu et al., 2016, 2017; Zhang et al., 2019). In brief, we recruited and followed up 5612 schoolchildren aged 6–16 years from 31 primary schools across four districts (Hong Kong/outlying islands, Kowloon, New Territories East, and New Territories West) from 2012 to 2017. We excluded 748 participants in this study due to the incomplete information and the procedure of participant selection. Participants were required to undergo a survey (comprising spirometry tests, anthropometric measurements, and a self-administered questionnaire) yearly for 3 consecutive years during the study period. The second and third follow-up surveys were conducted in the same month of the following years to ensure that the same follow-up interval was maintained. As lung function may fluctuate between morning and afternoon, spirometry tests and anthropometric measurements were conducted in the morning. In each survey, parents or guardians were required to complete a self-administered questionnaire that collected extensive information on their schoolchildren’s sociodemographic characteristics, lifestyles, disease history, respiratory health status, and household environment. The participants’ parents/guardians were fully informed of the study’s
purpose and they provided written informed consents prior to each survey. The study protocol was approved by the Joint Chinese University of Hong Kong-New Territories East Cluster Clinical Research Ethics Committee.

2.2. Assessment of air pollution exposure

The ground-level PM$_{2.5}$ concentrations were derived from a satellite-based spatiotemporal model with a resolution of 1 km$^2$ established using aerosol optical depth data from the Moderate Resolution Imaging Spectroradiometer carried on the U.S. National Aeronautics and Space Administration satellite. Details on PM$_{2.5}$ concentration estimation have been documented elsewhere (Lin et al., 2015; Guo et al., 2019; Bo et al., 2021). The estimated concentrations of PM$_{2.5}$ generated by the model were validated against the data obtained from local air pollution monitoring stations, and the corresponding correlation coefficients ranged from 0.72 to 0.86. The NO$_2$ concentrations were estimated using a space-time regression model with the Tropospheric Monitoring Instrument NO$_2$ data and spatiotemporal ancillary data (Huang et al., 2010). The estimated concentrations of NO$_2$ were compared with the data from the National Environmental Monitoring Centre to validate our model. The estimated R$^2$ ranged from 0.86 to 0.92, demonstrating the model’s robust and reliable performance. The participants’ addresses were geo-coded into latitude and longitude data, and address-specific yearly average PM$_{2.5}$ and NO$_2$ concentrations were then calculated. Any changes of address during the study period were also considered in the data analysis.

2.3. Respiratory outcomes

Four lung function parameters, namely FEV$_1$, FVC, PEF, and MMEF, were used as outcomes in our study. FEV$_1$ and FVC are the two main indices of expiratory capacity (Miller et al., 2005) and have been commonly used in previous research (Gauderman et al., 2002; He et al., 2010; Chen et al., 2018; Tsui et al., 2018), while PEF and MMEF are the two standard parameters measured in a spirometry test to assess breathing patterns and identify respiratory conditions (Quanjer et al., 1993).

To measure lung function parameters, spirometry tests and calibration were performed by trained research assistants according to the standards of the American Thoracic Society/European Respiratory Society Task Force (Miller et al., 2005). Each participant was required to blow at least three times that met the standard required to pass the test. Brief rest periods were given between consecutive blows.

Common respiratory diseases and symptoms were also assessed as outcomes in this study. Questions from the European Community Respiratory Health Survey questionnaires (Liu et al., 2016, 2017; Zhang et al., 2019) were used to collect information on doctor-diagnosed respiratory diseases (asthma, allergic rhinitis, sinusitis, bronchitis, bronchiolitis, and pneumonia) and respiratory symptoms (wheezing, dry cough, and phlegm).

2.4. Covariates

During the baseline and each follow-up survey, information on a wide range of covariates, including leisure-time physical activity (at least once a week: yes or no), medical histories of respiratory disease or symptom (yes or no), and a series of household environmental factors including passive smoking (yes or no), keeping a pet (yes or no), keeping a plant (yes or no), recent renovation (yes or no), recent purchased furniture (yes or no), ventilation (frequently opening windows: yes or no), and type of fuels used for cooking (fossil fuels e.g. coal and gas or electricity), was collected from the participants’ parents or guardians using a standard self-administered questionnaire. The detailed descriptions of the covariates gathered via the questionnaire are available elsewhere (Liu et al., 2016, 2017; Zhang et al., 2019). In addition, the height and weight of each participant were measured, with the participants wearing lightweight clothing and no shoes. The body mass index (BMI; kg/m$^2$) was then calculated as body weight (kg)/height square (m$^2$).

2.5. Statistical analysis

In the descriptive analysis, quantitative and qualitative variables are expressed as means ± standard deviations (SDs) and counts (percentages), respectively. For between-group comparisons, Student’s t-test was applied for continuous variables, while the chi-square test was used for categorical variables. The between-school and between-visit differences in the outcomes were detected by variations in the outcome distributions (Figs. 3, 4).

As this was a longitudinal cohort study with repeated measurement data, we applied a linear mixed model with random effects to examine the associations between exposure to air pollution (PM$_{2.5}$ and NO$_2$ concentrations) and lung function parameters (FEV$_1$, FVC, PEF, and MMEF). The linear mixed model incorporates three sources of variation: repeated lung function measurements, participants, and schools. For detailed model specifications, we considered participants and schools as random effects and constructed a three-level mixed model with maximum likelihood estimation. We selected a wide range of covariates based on previous publications (Guo et al., 2019; Zhang et al., 2019) and screened them using the Akaike information criterion (AIC), which reflects the goodness of fit for model selection (Table S1). We finally adjusted the model for age (as continuous), BMI (as continuous), paternal educational level (primary school or lower, secondary school, or tertiary school or higher), follow-up visits (baseline, the first time, the second time), history of passive smoking (yes or no), history of wheezing (yes or no), and history of asthma (yes or no) as time-dependent covariates, which allowed us to take into account the change in these covariates over the study period. The results are reported as the changes ($Δ = β$) in lung function associated with every 5-unit increase in the concentrations of air pollutants (PM$_{2.5}$ and NO$_2$), with 95% confidence intervals (CIs) based on $β ± 1.96 × SE$, where $β$ and SE are the regression coefficient estimate and its standard error, respectively. We also use two pollutants models for comparison and testing the robustness of the association despite the concern about the correlation between PM$_{2.5}$ and NO$_2$.

For the respiratory diseases and symptoms included as binary outcomes, we adopted mixed-effects logistic regression models with school and participants as random effects to examine the impact of long-term exposure to air pollution (Austin, 2017). Odds ratios (ORs) with 95% CIs for the respiratory diseases and symptoms were calculated for every 1-unit change in the concentrations of air pollutants (PM$_{2.5}$ and NO$_2$). We then selected a wide range of covariates (including age, BMI, and history of passive smoking etc.) based on previous publication (Zhang et al., 2019) and screened them using the AIC. Two-pollutant models were also applied for comparisons.

We additionally conducted subgroup analyses stratified by sex (boys and girls) and age group (6–10 and 11–14 year old groups). The cross-product terms (i.e. sex × pollutant and age group × pollutant) were added to the models to test the significance of effect modifications. The following sensitivity analyses were also performed to assess the robustness of the results. (1) For the results of lung function parameters, we repeated analyses (a) by including only the participants with at least two spirometry tests, to observe potential differences in the results between participants with single measurements and those with repeated measurements; and (b) by excluding observations with an FEV$_1$/FVC ratio ≥ 95%, to avoid bias due to potential technical error. (2) For the results of respiratory diseases or symptoms, we excluded the participants with only one survey.

All statistical analyses were conducted in the R language environment (R Core Team, 2021) and statistical models were established using the packages “nlme” (Pinheiro et al., 2021) and “lme4” (Bates et al., 2021).
Results

Repeated follow-ups of the 4864 participants, who were aged 6–16 years, generated 7985 observational records. Overall, 3184 (65.5 %) participants completed two surveys and 429 (8.82 %) completed three surveys (the mean number of visits was 2.07 [range: 1–3]).

Table 1 shows the general characteristics of the participants at baseline. Approximately half were boys, and 74.06 % performed at least one session of physical exercise per week. The mean age was 9.24 years (SD = 1.07 years), and the mean (SD) BMI was 17.49 (3.26) kg/m². The mean concentrations (SD) of PM$_{2.5}$ and NO$_2$ across the participants’ addresses were 29.07 (5.00) μg/m$^3$ and 46.38 (19.23) μg/m$^3$, respectively. The mean (SD) FEV$_1$, FVC, PEF, and MMEF were 1665.47 (383.6) ml, 1918.58 (388.05) ml, 3767.49 (815.70) ml/s, and 1902.57 (535.80) ml/s, respectively. Most fathers of children received the education level of secondary school (66.92 %). Most of the participants were exposed to household environments in which plants were kept (51.09 %), that were frequently ventilated (97.13 %), and in which cooking was done with gaseous fossil fuels (85.90 %). The three most predominant respiratory diseases or symptoms were allergic rhinitis (40.90 %), dry cough (28.12 %), and phlegm (12.87 %). Age, BMI, FEV$_1$, FVC, PEF, physical activity, the proportion of cooking with gaseous fossil fuels, and the proportions of most respiratory diseases or symptoms (except for pneumonia and phlegm) were significantly different between boys and girls.

PM$_{2.5}$ concentrations peaked in 2013 and then gradually decreased in subsequent years. In contrast, there were slight variations in the annual concentrations of NO$_2$ (Fig. 2). The measurements of lung function parameters (FEV$_1$, FVC, PEF, and MMEF) differed across schools and follow-up surveys (Figs. 3 and 4).

Regarding the associations between exposure to air pollution and lung function parameters (Table 2), PM$_{2.5}$ was significantly associated with a decrease in FEV$_1$ and MMEF. In one-pollutant models and in all participants, every 5-μg/m$^3$ increase in the ambient PM$_{2.5}$ concentration was associated with a change of –13.90 ml (95 % CI: –23.65 ml, –4.10 ml), –4.20 ml (–15.60 ml, 7.15 ml), 0.27 ml/s (–3.95 ml/s, 5.85 ml/s), and –19.80 ml/s (–38.35 ml/s, –1.25 ml/s) in FEV$_1$, PEF, FVC, and MMEF, respectively. For every 5-μg/m$^3$ increase in the ambient NO$_2$ concentration, the changes in FEV$_1$, FVC, PEF, and MMEF were –2.70 ml (–6.05 ml, 0.60 ml), –1.40 ml (–5.40 ml, 2.60 ml), –6.60 ml/s (–19.75 ml/s, 6.55 ml/s), and –3.05 ml/s (–11.10 ml/s, 5.00 ml/s), respectively. Subgroup analyses by sex and age yielded similar results but with these associations being stronger in male participants and older participants (11–14 year-old group) than in female participants and younger participants (6–10 year-old group), respectively (Tables 2 and S2).

Tables 3 and S3 show the associations between exposure to air pollution and respiratory diseases and symptoms. Two-pollutant models did not demonstrate marked changes in the risk estimates compared with the one-pollutant models. The effect estimates of every 5-unit increase in PM$_{2.5}$ and NO$_2$ concentrations for most diseases or symptoms, except sinusitis and allergic rhinitis, were not statistically significant. Specifically, every 5-μg/m$^3$ increase in the ambient PM$_{2.5}$ concentration was significantly associated with an increased risk of sinusitis (OR: 1.161; 95 % CI: 1.020, 1.320). Sex and age group had no modifying effects on these associations (Tables 3 and S3). Sensitivity analyses generally yielded similar results (Tables S4–S5).

Discussion

Overall, this study of the latest Hong Kong schoolchildren cohort showed weak evidence of positive associations between primary air pollutants and respiratory health including lung function and respiratory diseases or symptoms. The results showed that long-term exposure to ambient PM$_{2.5}$ was significantly associated with a reduction in FEV$_1$ and MMEF and an increased risk of sinusitis. Although the associations between exposure to these two pollutants and other lung function parameters did not reach statistically significance, most coefficients were negative, showing the potential harmful effects of exposure to air pollution. In addition, we observed stronger associations between exposure to air pollution and lung function in male participants and older participants (11–14 year old group) than in female participants and younger participants (6–10 year old group).

Ambient PM$_{2.5}$ concentration was significantly negatively associated with FEV$_1$ and MMEF in the participants, which is consistent with the findings of most previous studies (Lewis et al., 2005; Rojas-Martinez et al., 2007; Barranza-Villarreal et al., 2008; Gao et al., 2013, 2020) that have reported adverse health effects of exposure to air pollution on lung function. However, most of the previous studies examining the effects of...
long-term exposure to PM\textsubscript{2.5} in schoolchildren, including the European Study of Cohorts for Air Pollution Effects project (Geirng et al., 2013), the U.S. birth cohort study (Rice et al., 2015), the Prevention and Incidence of Asthma and Mite Allergy birth cohort study (Milanzi et al., 2018), the Oslo Birth Cohort Study (Oftedal et al., 2008), and the Swedish birth cohort BAMSE study (Schultz et al., 2015), have been conducted in high-income Western countries. The present study answers the call for studies in Asian populations and provides new evidence for associations between exposure to air pollution and lung function in Hong Kong schoolchildren. In addition, some previous studies have reported conflicting results regarding the associations between long-term exposure to PM\textsubscript{2.5} and NO\textsubscript{2} and lung function. For example, some studies have shown that a per-unit (1 µg/m\textsuperscript{3}) increase in PM\textsubscript{2.5} concentration was associated with a 0.2–12 % decrease in lung function (Oftedal et al., 2008; Geirng et al., 2013, 2015), consistent with our study. Furthermore, in contrast to two studies that have found significant associations between NO\textsubscript{2} exposure and lung function (James Gauderman et al., 2000; Barone-Adesi et al., 2015), we observed non-significant associations between NO\textsubscript{2} exposure and lung function in the participants. Other previous studies have also reported such non-significant associations between NO\textsubscript{2} exposure and lung function (Barraga-Villarreal et al., 2008; Gao et al., 2013; Fuertes et al., 2015; Chen et al., 2018; Li et al., 2020; Takebayashi et al., 2022). These inconsistencies may be attributable to heterogeneity in study populations, such as different age ranges of the children studied, as the vulnerability to air pollution differs with age (Barone-Adesi et al., 2015; Takebayashi et al., 2022), and taking only outdoor air pollution estimates, as children may be more exposed to indoor air pollution than adults (Gillespie-Bennett et al., 2011). We also found a weak correlation between PM\textsubscript{2.5} and NO\textsubscript{2} concentrations (the correlation coefficient based on the individual data was 0.010) in our study. The results from the two-pollutant models were similar to the results from the one-pollutant models, which are consistent with previous studies (Rojas-Martinez et al., 2007; Chen et al., 2018).

Although the exact biological mechanisms by which air pollution causes reduced lung function remain uncertain, several potential mechanisms or factors that mediate the negative associations between air pollution and lung function have been proposed (Rojas-Martinez et al., 2007; Guo et al., 2019). There is evidence that inhaled pollutant particles can interact with pneumocytes after entering the lungs and may cause a chain of local and systemic inflammatory responses (Ghio et al., 2000; Pradhan et al., 2005). In addition, some studies have reported that elevated oxidative stress is involved in the adverse health effects of air pollution on the lungs (Kelly, 2003; Hatzis et al., 2006). Evidence from animal studies suggests that PM can consume and reduce antioxidants and related enzymes, produce free radicals, and then trigger oxidative stress, inflammation, and respiratory impairment (Hatzis et al., 2006).

We found that increased concentrations of PM\textsubscript{2.5} were associated with increased risks of sinusitis, which is consistent with the deleterious effects of long-term exposure to air pollution on lung function that have been reported (Goldberg, 2008; Mann Jennifer et al., 2010; Esposito et al., 2014; Luong et al., 2019). Furthermore, the associations detected by our two-pollutant models were not markedly different from those estimated by our one-pollutant models. This is somewhat consistent with the mechanisms proposed for how air pollution affects lung function, i.e., the mechanisms by which air pollutants mediate harmful effects on respiratory health involve biological changes in the respiratory system and organs (Lee et al., 2021). Air pollutants may directly interact with airway neuroreceptors and epithelium, thereby triggering inflammation (Guarnieri and Balmes, 2014), and interfere with defence and immune functions in the lungs (Olivieri and Scoditti, 2005). Moreover, when pulmonary cells are exposed to air pollutants, the resulting generation of reactive oxygen species, oxidative stress, and harmful innate and adaptive immune reactions can lead to oxidant-mediated damage (Nel et al., 2006). Certain pollutants, such as NO\textsubscript{2}, can also make the airway hyper-responsive to triggers of inflammation (Guarnieri and Balmes, 2014).

In investigations of air pollution–lung function associations, our stratified analyses revealed the modifying effects of sex and age group. Specifically, we observed stronger air pollution–lung function associations in male participants and older participants than in female participants and younger participants, in line with the findings of some previous studies (He et al., 2010; Schultz et al., 2012; Gao et al., 2013). However, other studies have reported stronger associations in girls than in boys (Rojas-Martinez et al., 2007; Liu and Zhang, 2009; Chen et al., 2018). Furthermore, in contrast to previous studies (Rumchev et al., 2007; Dong et al., 2011; Demoulin-Alexikova et al., 2016), we found that sex had no significant modifying effect on the associations of exposure to air pollution with respiratory diseases and symptoms. It is well recognised that biological sex differences are associated with biological, hormonal, behavioural, and social differences, which may contribute to the sex-associated differences in adverse effects of exposure to air pollution (Dong et al., 2011). We also observed larger reductions in lung function in older participants (11–14 year old group) than in younger participants. This could be explained by the fact that compared with younger participants, older participants would have had a longer cumulative exposure to air pollution and thus suffered greater cumulative damage to lung function (Gauderman et al., 2007;
Rosenlund et al., 2009). However, despite these plausible mechanisms for how sex and age modify the effects of exposure to air pollution, the exact reasons and mechanisms remain unclear.

Our study has some important strengths. First, the longitudinal prospective cohort design enabled us to establish the temporal relationships between exposure to air pollution and lung function and respiratory disease and symptoms and also enabled us to account for the effects of changes in air pollution exposure and a wide range of covariates. Second, the relatively large sample size enabled us to obtain relatively stable results and precise estimates. Third, we controlled for a wide range of potential confounders, which enabled us to accurately characterise the associations between exposure to air pollution and the
participants’ respiratory health. Finally, our models were based on high-resolution satellite-derived data, which enabled us to estimate pollution exposure at the address of each of the participants. These models helped us to overcome the spatial coverage limitation that is typically present when using data obtained only from monitoring stations. The exposure data at the individual participant (address) level also enabled us to avoid ecological fallacies.

This study also has some limitations. First, we estimated ambient air pollutant (PM$_{2.5}$ and NO$_2$) concentrations at participants’ home addresses but did not take into account participants’ activity patterns and the exposure in school. In addition, data on indoor air pollution were not included, due to unavailability. Compared with adults, schoolchildren are more likely to spend time indoors rather than outdoors (Saksena et al., 2007; Nandasena et al., 2013). Although previous studies have shown strong correlations between indoor and outdoor air pollution (Kuo and Shen, 2010; Meadow et al., 2014), we could not exclude the possible influence of factors that may affect indoor concentrations of PM$_{2.5}$ and NO$_2$, such as the type of cooking fuel used and the characteristics of home ventilation. However, we considered smoking and incense burning, which are the primary sources of indoor air pollution in developed countries in Asia. Future studies with a more comprehensive exposure assessment, including of both indoor and outdoor air pollution, are warranted. Second, information on respiratory disease and symptoms and most covariates was collected using a self-administered questionnaire answered by parents or guardians; thus, the potential influence of recall bias cannot be excluded. Third, although the coefficients were generally negative, showing potentially harmful effects of NO$_2$ on lung function, the associations of NO$_2$ with lung function parameters did not reach statistical significance (Table 2). This phenomenon was possibly because we only conducted two follow-up surveys for the participants (i.e., the maximum period was two years). The relatively short follow-up duration might limit us to have sufficient statistical power to detect the differences. Finally, only two pollutants were considered; therefore, the effects of other pollutants, such as ozone and sulphur dioxide, need to be assessed in future studies.

5. Conclusions

Given its ubiquity, the WHO has stated that air pollution is the largest single environmental risk in the world. Children are most vulnerable.
Table 3
Associations (odds ratios with 95% confidence intervals) between air pollutants and respiratory diseases/symptoms in the participants in Hong Kong from 2012 to 2017.

<table>
<thead>
<tr>
<th>Respiratory symptoms</th>
<th>PM$_{2.5}$</th>
<th>Air pollution exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Boys</td>
</tr>
<tr>
<td>Asthma</td>
<td>1.064 (0.932, 1.214)</td>
<td>1.164 (0.937, 1.445)</td>
</tr>
<tr>
<td>Allergic rhinitis</td>
<td>0.969 (0.901, 1.041)</td>
<td>0.990 (0.897, 1.048)</td>
</tr>
<tr>
<td>Sinusitis</td>
<td>1.140 (1.003, 1.296)</td>
<td>1.187 (1.013, 1.390)</td>
</tr>
<tr>
<td>Bronchitis</td>
<td>0.986 (0.894, 1.080)</td>
<td>0.995 (0.889, 1.114)</td>
</tr>
<tr>
<td>Bronchiolitis</td>
<td>1.096 (0.941, 1.275)</td>
<td>1.056 (0.876, 1.273)</td>
</tr>
<tr>
<td>Pneumonia</td>
<td>1.076 (1.086, 1.168)</td>
<td>0.923 (0.697, 1.239)</td>
</tr>
<tr>
<td>Wheezing</td>
<td>1.043 (0.932, 1.168)</td>
<td>1.135 (1.003, 1.285)</td>
</tr>
<tr>
<td>Dry cough</td>
<td>0.988 (0.937, 1.043)</td>
<td>0.990 (0.915, 1.072)</td>
</tr>
<tr>
<td>Phlegm</td>
<td>0.956 (0.880, 1.040)</td>
<td>1.032 (0.918, 1.159)</td>
</tr>
</tbody>
</table>

Effects are expressed as odds ratios for respiratory diseases or symptoms for every 5-unit increase in air pollutant concentrations.

This longitudinal study showed that long-term exposure to ambient PM$_{2.5}$ pollution was associated with decreased FEV$_1$ and MMEF and an increased risk of sinusitis. Our findings reinforce the importance of air pollution mitigation to protect children’s pulmonary health.

CRediT authorship contribution statement

**Chen Jinjian**: Conceptualization, Methodology, Software, Investigation, Writing – original draft.

**Zeng Yiqian**: Data curation, Writing – review & editing.

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Data availability

The data that has been used is confidential.

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This longitudinal study showed that long-term exposure to ambient PM$_{2.5}$ pollution was associated with decreased FEV$_1$ and MMEF and an increased risk of sinusitis. Our findings reinforce the importance of air pollution mitigation to protect children’s pulmonary health.

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J. Chen et al.