Major air pollutants and risk of COPD exacerbations: a systematic review and meta-analysis

Jinhui Li1,2, Shengzhi Sun1,2, Robert Tang1,2, Hong Qiu2, Qingyuan Huang3, Tonya G Mason3, Linwei Tian1,2

1Shenzhen Institute of Research and Innovation, Nanshan, The University of Hong Kong, Shenzhen, People’s Republic of China; 2School of Public Health, The University of Hong Kong, Pok Fu Lam, Hong Kong Special Administrative Region; 3Department of Thoracic Surgery, Shanghai Chest Hospital, Shanghai Jiao Tong University, Minhang, Shanghai, People’s Republic of China

Background: Short-term exposure to major air pollutants (O3, CO, NO2, SO2, PM10, and PM2.5) has been associated with respiratory risk. However, evidence on the risk of chronic obstructive pulmonary disease (COPD) exacerbations is still limited. The present study aimed at evaluating the associations between short-term exposure to major air pollutants and the risk of COPD exacerbations.

Methods: After a systematic search up until March 30, 2016, in both English and Chinese electronic databases such as PubMed, EMBASE, and CNKI, the pooled relative risks and 95% confidence intervals were estimated by using the random-effects model. In addition, the population-attributable fractions (PAFs) were also calculated, and a subgroup analysis was conducted. Heterogeneity was assessed by I2.

Results: In total, 59 studies were included. In the single-pollutant model, the risks of COPD were calculated by each 10 μg/m3 increase in pollutant concentrations, with the exception of CO (100 μg/m3). There was a significant association between short-term exposure and COPD exacerbation risk for all the gaseous and particulate pollutants. The associations were strongest at lag0 and lag3 for gaseous and particulate air pollutants, respectively. The subgroup analysis not only further confirmed the overall adverse effects but also reduced the heterogeneities obviously. When 100% exposure was assumed, PAFs ranged from 0.60% to 4.31%, depending on the pollutants. The adverse health effects of SO2 and NO2 exposure were more significant in low-/middle-income countries than in high-income countries: SO2, relative risk: 1.012 (95% confidence interval: 1.001, 1.023); and NO2, relative risk: 1.019 (95% confidence interval: 1.014, 1.024).

Conclusion: Short-term exposure to air pollutants increases the burden of risk of COPD acute exacerbations significantly. Controlling ambient air pollution would provide benefits to COPD patients.

Keywords: COPD exacerbations, air pollution, meta-analysis, acute exposure

Introduction

Air pollution has been a serious environmental problem and a major concern for public health worldwide. It continues to be a major environmental health risk, particularly in developing countries where the motor vehicle traffic and industrialization increase quickly.1 The respiratory system (tract and lung) is vulnerable to air pollutants, including ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and particulate matters (PM10, PM2.5). In the course of pulmonary ventilation and gas exchange, these pollutants could induce oxidative stress and inflammation, resulting in airway injury and dysfunction.2
Chronic obstructive pulmonary disease (COPD) is the third leading cause of mortality worldwide. It is estimated that the number of COPD patients has reached a record of 7.3 billion in 2015. Factors that cause exacerbation of COPD include clinical and medical care status, natural and social environmental changes, and lifestyles. The exacerbation symptoms mainly include the increase in dyspnea, sputum production, or purulence and then the emergency hospitalization or even mortality. In some parts of the world, acute exacerbation of COPD accounts for 1 of 10 leading causes of hospital admission, which bring formidable challenges to the world health and socioeconomic systems.

The acute effects of air pollution exposure on COPD exacerbations have been investigated by several studies, but the results still remain inconsistent. Some reported that air pollutants significantly increased the risk of exacerbation or mortality, whereas others found no associations or relationships only for selected pollutants. Moreover, several recent investigations were conducted in certain regions and were just focused on particulate air pollutants.

To the authors’ knowledge no comprehensive and systematic meta-analysis has yet been published to investigate the association of acute COPD exacerbations with short-term air pollutants exposure. Therefore, the aim of the present study was to systematically review the evidence evaluating the acute risk for COPD patients when exposed to short-term air pollution.

**Methods**

**Search strategy**

Systematic searches were performed to identify the studies on the associations between major air pollutants and COPD exacerbation. The comprehensive online electronic databases included both English and Chinese databases through March 30, 2016: Web of Science (1956–2016), Ovid MEDLINE and Ovid MEDLINE in the process (1946–2016), EMBASE (1974–2005), Environmental Sciences and Pollution Management Index, CINAHL, Google Scholar and Cochrane database (2005–2016), and CNKI. Moreover, references were checked for additional publication details. Supplementary material S1 contains the search strategy. Duration of up to 7 days (lag6) was selected. If the included papers had insufficient data, the corresponding authors were contacted by email, and the papers were excluded only if there was no response from the corresponding authors.

**Selection of studies**

The inclusion criteria (Supplementary material S2) were as follows: 1) a case-crossover or time-series study; and 2) evaluation of the short-term effects of air pollutants on the acute risk of COPD with recorded end points. Figure 1 summarizes the selection procedures in a flow chart.

One reviewer (JH Li) performed all the initial evaluations of titles and abstracts. The other investigator (QY Huang) randomly assessed 500 samples, and no controversy was found. Full text of these potential studies was then screened to determine the eligibility by these two authors independently. During full-text selection, conflicts were settled by consensus or adjusted by a third reviewer (SZ Sun).

**Quality score assessment**

This meta-analysis was conducted according to the items of PRISMA and MOOSE. Although Mustafic et al suggested to evaluate the quality of time-series or case-crossover studies, there were still no validated scales recommended. Therefore, a 4-component scoring system (0–1 point for each item) was designed as follows: 1) the quality of air pollution assessment (<25% of the values for one specific day were missing); 2) the validation of COPD exacerbation (the disease was coded according to the International Classification of Diseases, Revision 10, American Thoracic Society or other laboratory/clinical prognosis golden criteria, such as FEV1/FVC <0.7 for lung function); 3) the adjustment for confounders (temperature, seasonality, long-term trend, etc were adjusted); and 4) the generalizability of the outcomes (providing clear defined hospitals or health maintenance organizations).

**Data extraction and statistical synthesis**

The two investigators (JH Li and QY Huang) conducted the data extraction independently, and discordance was resolved by discussing with another researcher (LW Tian). By assuming a linear relationship between air pollution and COPD, the relative risks (RRs) with 95% confidence interval (CI) for a standardized increment of pollutants’ concentrations were pooled as follows: 10 μg/m³ for PM2.5, PM10, NO2, SO2, and O3, and 100 μg/m³ for CO. These values were frequently used in the previous air-pollution-related studies. If percentage change with 95% CI were reported, then it could be transformed to RR with 95% CI. Besides, if odds ratios were found, they could be considered equivalent to RRs in time-series or case-crossover studies. Then, the standardized risk was unified according to the method by Yang et al.

The present study was designed to have short-term exposure because the risk factors varied constantly in this period and could not be promptly confounded by fluctuating and meteorological parameters. There had been no standard criteria for reporting lag patterns so far, and most studies...
Short-term air pollution exposure to COPD patients

employed single-day lag; therefore, lag selection procedure was based on “priori lag” theory of Atkinson et al. Briefly, when only one lag estimate was presented, it would be adopted first; if numerous lags were reported, our selection was based on the following algorithms: 1) the most frequently used lag in all the selected studies was under consideration; and 2) compared to the cumulative/distributed lags, single lags were chosen as priorities.

The heterogeneity was assessed by $I^2$. When heterogeneity was significant ($I^2 > 25\%$), the random-effects model was applied; otherwise, the fixed-effects model was used. In order to explore the sources of heterogeneity, subgroup and meta-regression analyses were performed based on study design, population location, age, and outcome category. In order to determine whether the findings could be affected by removing one or two studies, sensitivity analysis was conducted to explore robustness. If the omission of any study would not affect the overall results, then the outcome of the review can be regarded with a higher degree of certainty.

The population-attributable fractions (PAFs) are reduced proportions of disease hospitalization or mortality in the population when the exposure risk factor was reduced to an expected scenario. First, they were assumed to be 100% in some industrialized areas according to the recognized method by Dr Mustafic. Besides, in some light-polluted regions, the prevalence percentages were suggested to be assumed lower, in which case the estimated prevalence values were 80% and 20% in the present study. The equation is as follows: $\{PAF = k\times(RR-1)/[k\times(RR-1)+1]\}$ (where $k$ indicates the air pollution exposure percentages).

---

**Figure 1** PRISMA flow chart of identified, included, and excluded studies.

**Abbreviation:** COPD, chronic obstructive pulmonary disease.
Publication bias was evaluated by using Begg’s funnel plot method and confirmed by Egger’s method. Asymmetry was then corrected through trim and fill method, and an adjusted summary was achieved by using all the original studies together with “filled” data. Moreover, the pooled effect estimates based on income status of country defined by the gross national income per capita of World Bank were also explored.

The statistical analyses were conducted by using STATA Version 12.1 (STATA/SE, College Station, TX, USA) and R Software (Version 3.1.2). Significance for pooled estimates was defined as two-sided P<0.05.

<table>
<thead>
<tr>
<th>Study (year)</th>
<th>Location</th>
<th>Design</th>
<th>Period</th>
<th>Outcome</th>
<th>Population</th>
<th>Events</th>
<th>Age</th>
<th>Confounders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kloog et al (2014)</td>
<td>USA</td>
<td>CC</td>
<td>2000–2006</td>
<td>HA</td>
<td>58.0 million</td>
<td>0.42 million</td>
<td>≥65 yrs</td>
<td>A</td>
</tr>
<tr>
<td>Meng et al (2013)</td>
<td>China</td>
<td>TS</td>
<td>1996–2008</td>
<td>Mortality</td>
<td>34.0 million</td>
<td>32.2/day</td>
<td>All</td>
<td>A.B</td>
</tr>
<tr>
<td>Wordley et al (1997)</td>
<td>UK</td>
<td>TS</td>
<td>1992–1994</td>
<td>Both</td>
<td>1 million</td>
<td>HA 3.2/day, M 2/day</td>
<td>All</td>
<td>A.B</td>
</tr>
<tr>
<td>Schikowski et al (2014)</td>
<td>Taiwan</td>
<td>CC</td>
<td>2006–2010</td>
<td>HA</td>
<td>1.5 million</td>
<td>7.7/day</td>
<td>All</td>
<td>A.B.C.E.I</td>
</tr>
<tr>
<td>Peel et al (2005)</td>
<td>USA</td>
<td>TS</td>
<td>1993–2000</td>
<td>HA</td>
<td>0.8 million</td>
<td>7.4/day</td>
<td>All</td>
<td>A.B.C.G.F.D.N</td>
</tr>
<tr>
<td>Schouten et al (1996)</td>
<td>the Netherlands</td>
<td>TS</td>
<td>1977–1989</td>
<td>HA</td>
<td>0.76 million</td>
<td>1.7/day</td>
<td>All</td>
<td>A.B.C.D.F</td>
</tr>
<tr>
<td>Kan et al (2003)</td>
<td>China</td>
<td>TS</td>
<td>2000–2001</td>
<td>HA</td>
<td>0.8 million</td>
<td>11.0/day</td>
<td>All</td>
<td>A.B.</td>
</tr>
<tr>
<td>Schwartz et al (1992)</td>
<td>USA</td>
<td>TS</td>
<td>1973–1980</td>
<td>HA</td>
<td>1.7 million</td>
<td>0.9/day</td>
<td>All</td>
<td>A.B.C.E.O</td>
</tr>
<tr>
<td>Wong et al (2009)</td>
<td>Hong Kong</td>
<td>TS</td>
<td>1996–2000</td>
<td>Both</td>
<td>8.0 million</td>
<td>HA M 5.9/day</td>
<td>All</td>
<td>B.H</td>
</tr>
</tbody>
</table>

(Continued)
North America (the USA and Canada), South America (Mexico and Brazil), Australia, and Europe; 12 citations focused on the association between short-term air pollution exposure and COPD mortality, whereas 41 focused on the COPD emergency hospitalization. The final 6 citations paid attention to both. The most frequently reported age-group was all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.

Overall analysis
There was a significant association between short-term exposure and the risk of COPD exacerbations for all the gaseous and particulate pollutants (Figure 2; Table 2). Figure S1 shows the details explicitly. Table 2 presents PAFs with all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.

Overall analysis
There was a significant association between short-term exposure and the risk of COPD exacerbations for all the gaseous and particulate pollutants (Figure 2; Table 2). Figure S1 shows the details explicitly. Table 2 presents PAFs with all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.

Overall analysis
There was a significant association between short-term exposure and the risk of COPD exacerbations for all the gaseous and particulate pollutants (Figure 2; Table 2). Figure S1 shows the details explicitly. Table 2 presents PAFs with all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.

Overall analysis
There was a significant association between short-term exposure and the risk of COPD exacerbations for all the gaseous and particulate pollutants (Figure 2; Table 2). Figure S1 shows the details explicitly. Table 2 presents PAFs with all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.

Overall analysis
There was a significant association between short-term exposure and the risk of COPD exacerbations for all the gaseous and particulate pollutants (Figure 2; Table 2). Figure S1 shows the details explicitly. Table 2 presents PAFs with all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.

Overall analysis
There was a significant association between short-term exposure and the risk of COPD exacerbations for all the gaseous and particulate pollutants (Figure 2; Table 2). Figure S1 shows the details explicitly. Table 2 presents PAFs with all age-group, followed by the group >65 years old. Table 1 shows the potentially adjusted confounders. Furthermore, Table S1 lists the components of air pollution and average concentrations. Most publications provided multiple estimates for single lags (eg, lag0, lag1, and lag2), whereas some provided cumulative or distributed lags that were adopted only in the overall analysis. The 4-score system showed that the majority was judged to be of good or intermediate quality.
| CO (13 studies; 1.006 [1.002, 1.011]; *P* = 0.163), PM$_{2.5}$ (15 studies; 1.001 [1.000, 1.001]; *P* = 0.187), and PM$_{10}$ (34 studies; 1.001 [1.000, 1.001]; *P* = 0.187) were proved to be unfavorable associations.

### Property classification

As shown in Figure 3, this analysis was conducted based on COPD exacerbation outcomes (hospitalization or mortality), geographical location (Asia or non-Asia), population...
Table 2 Subgroup analysis by gaseous and particulate pollutants

<table>
<thead>
<tr>
<th>Gaseous pollutants</th>
<th>Carbon monoxide</th>
<th>Nitrogen dioxide</th>
<th>Sulfur dioxide</th>
<th>Ozone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increment</td>
<td>100 μg/m³</td>
<td>10 μg/m³</td>
<td>10 μg/m³</td>
<td>10 μg/m³</td>
</tr>
<tr>
<td>Mean pollutant</td>
<td>1.18</td>
<td>64.56</td>
<td>26.47</td>
<td>54.90</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.38</td>
<td>20.32</td>
<td>10.75</td>
<td>22.87</td>
</tr>
<tr>
<td>Number of studies</td>
<td>15</td>
<td>29</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Number of estimates</td>
<td>17</td>
<td>32</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>RR (95% CI)</td>
<td>1.008</td>
<td>1.045</td>
<td>1.006</td>
<td>1.028</td>
</tr>
<tr>
<td>(1.004, 1.013)</td>
<td>(1.028, 1.062)</td>
<td>(1.001, 1.012)</td>
<td>(1.011, 1.044)</td>
<td></td>
</tr>
<tr>
<td>Heterogeneity, F</td>
<td>97.0</td>
<td>98.0</td>
<td>80.8</td>
<td>98.8</td>
</tr>
<tr>
<td>P-value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Publication bias</td>
<td>Egger regression test, P-value</td>
<td>0.160</td>
<td>0.147</td>
<td>0.007</td>
</tr>
<tr>
<td>Adjusted estimates (95% CI)</td>
<td>1.002</td>
<td>1.021</td>
<td>1.004</td>
<td>0.976</td>
</tr>
<tr>
<td>(1.001, 1.003)</td>
<td>(1.004, 1.018)</td>
<td>(0.998, 1.011)</td>
<td>(0.962, 0.991)</td>
<td></td>
</tr>
<tr>
<td>(1.004, 1.011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particulate pollutants</td>
<td>PM₁₀&lt;sub&gt;₃&lt;/sub&gt;</td>
<td>PM₁₀&lt;sub&gt;₃&lt;/sub&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increment</td>
<td>14.84</td>
<td>46.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean pollutant</td>
<td>2.70</td>
<td>5.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.79</td>
<td>1.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range (minimum–maximum)</td>
<td>5.20–94.59</td>
<td>11.98–135.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of studies</td>
<td>14</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of estimates</td>
<td>15</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR (95% CI)</td>
<td>1.024</td>
<td>1.017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1.005, 1.043)</td>
<td>(1.012, 1.022)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heterogeneity, F</td>
<td>97.1</td>
<td>86.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: CI, confidence interval; NA, not available; RR, relative risk; PAF, population attributable fraction.

age (all age or age >65 years), and study design (time-series or case-crossover). When classified by geographical locations, the positive relationships were more significant in Asian countries than in the non-Asian countries for air pollutants. Similar associations were also observed in age subgroups: there was a tendency toward stronger relationships between these air pollutants and COPD. The property subgroups of case-crossover study and COPD deaths had borderline significance.

Furthermore, it was also identified that subgroup of age >65 years for SO₂ and O₃, COPD mortality subgroup for NOₓ, CO, and PM₁₀, and subgroup of non-Asian population for PM₁₀ reduced the heterogeneities of their pooled effects compared to overall analyzes. Table S4 shows further details.

Stratification by national income

Among all the included studies, 20% of the publications were from low-/middle-income countries in which ~60% of the population originated from the People’s Republic of China. SO₂, NOₓ, and PM₁₀ were commonly measured in low-/middle-income countries, such as Mexico and Brazil. Compared with the developed countries, the SO₂ and NOₓ short-time exposure showed more pronounced associations with COPD acute risk in the developing countries. For them, the RRs (95% CI) in low-/middle-income and high-income countries were as follows: SO₂, 1.012 (1.001, 1.023) and 1.005 (0.996, 1.014); and NOₓ, 1.019 (1.014, 1.024) and 1.017 (1.015, 1.019) (Figure 4). The mean concentrations of SO₂ and NOₓ in low-/middle-income countries were relatively higher than those of high-income countries, which was particularly concerning for the reason that these countries have disproportionate burdens of global acute exacerbation of COPD.

Heterogeneity by meta-regression

Considering the substantial heterogeneity exhibited in the overall analysis, meta-regression analysis identified that study design of NOₓ (coefficient = −0.166; P = 0.014) and O₃ (coefficient = −0.072; P = 0.017) contributed to heterogeneities significantly (Table S4). However, heterogeneity exploration similar to subgroups of location, age, and COPD subtype showed no significant contributors.

Discussion

Principal findings

To the authors’ concurrent knowledge, this was the first study to report the comprehensive association between main gaseous and particulate pollutants’ short-term exposure and COPD acute risk, indicating that improving air quality could reduce the risk of sudden onset of COPD and the burden of COPD worldwide. The present study found a significant association between short-term exposure to major air pollutants and COPD emergency risk, especially for O₃ and NOₓ. Subgroup analysis showed lower heterogeneities and yielded similar associations in the overall analysis. The pooled estimates stratified by financial levels demonstrated stronger
### Sulfur Dioxide

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>RR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall  (n=31)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td></td>
</tr>
<tr>
<td>Mortality (n=6)</td>
<td>1.00 (1.00, 1.00)</td>
</tr>
<tr>
<td>Hospitalization (n=25)</td>
<td>1.00 (1.00, 1.01)</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
</tr>
<tr>
<td>Asian (n=14)</td>
<td>1.00 (1.00, 1.00)</td>
</tr>
<tr>
<td>Non-Asian (n=17)</td>
<td>1.00 (1.00, 1.01)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>All (n=8)</td>
<td>1.00 (1.00, 1.00)</td>
</tr>
<tr>
<td>Age ≥65 (n=25)</td>
<td>1.00 (1.00, 1.01)</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td></td>
</tr>
<tr>
<td>Time-series (n=24)</td>
<td>1.00 (1.00, 1.00)</td>
</tr>
<tr>
<td>Case-crossover (n=7)</td>
<td>1.02 (1.01, 1.02)</td>
</tr>
</tbody>
</table>

### Ozone

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>RR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall  (n=34)</td>
<td>1.03 (1.01, 1.04)</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td></td>
</tr>
<tr>
<td>Hospitalization (n=29)</td>
<td></td>
</tr>
<tr>
<td>Mortality (n=5)</td>
<td></td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
</tr>
<tr>
<td>Non-Asian (n=10)</td>
<td>0.96 (0.96, 0.96)</td>
</tr>
<tr>
<td>Asian (n=5)</td>
<td>1.02 (1.01, 1.02)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>All (n=11)</td>
<td>0.96 (0.95, 0.96)</td>
</tr>
<tr>
<td>Age ≥65 (n=23)</td>
<td>1.01 (1.01, 1.01)</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td></td>
</tr>
<tr>
<td>Time-series (n=24)</td>
<td>0.96 (0.96, 0.96)</td>
</tr>
<tr>
<td>Case-crossover (n=10)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
</tbody>
</table>

### Nitrogen Dioxide

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>RR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall  (n=34)</td>
<td>1.04 (1.03, 1.06)</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td></td>
</tr>
<tr>
<td>Hospitalization (n=27)</td>
<td>1.02 (1.01, 1.02)</td>
</tr>
<tr>
<td>Mortality (n=7)</td>
<td>1.02 (1.01, 1.02)</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
</tr>
<tr>
<td>Asian (n=16)</td>
<td>1.01 (1.01, 1.01)</td>
</tr>
<tr>
<td>Non-Asian (n=17)</td>
<td>1.02 (1.02, 1.03)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>Age ≥65 (n=25)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td>All (n=8)</td>
<td>1.02 (1.02, 1.02)</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td></td>
</tr>
<tr>
<td>Time-series (n=24)</td>
<td>1.01 (1.01, 1.02)</td>
</tr>
<tr>
<td>Case-crossover (n=9)</td>
<td>1.03 (1.02, 1.03)</td>
</tr>
</tbody>
</table>

### Carbon Monoxide

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>RR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall  (n=15)</td>
<td>1.02 (1.01, 1.03)</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
</tr>
<tr>
<td>Non-Asian (n=10)</td>
<td>1.01 (1.00, 1.02)</td>
</tr>
<tr>
<td>Asian (n=5)</td>
<td>1.00 (0.99, 1.00)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>Age ≥65 (n=12)</td>
<td>0.98 (0.96, 1.00)</td>
</tr>
<tr>
<td>All (n=3)</td>
<td>1.00 (1.00, 1.00)</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td></td>
</tr>
<tr>
<td>Time-series (n=8)</td>
<td>1.00 (0.99, 1.00)</td>
</tr>
<tr>
<td>Case-crossover (n=7)</td>
<td>1.02 (1.02, 1.03)</td>
</tr>
</tbody>
</table>

### PM$_{2.5}$

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>RR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall  (n=15)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td></td>
</tr>
<tr>
<td>Hospitalization (n=13)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td>Mortality (n=2)</td>
<td>1.02 (1.01, 1.04)</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
</tr>
<tr>
<td>Non-Asian (n=10)</td>
<td>0.99 (0.99, 0.99)</td>
</tr>
<tr>
<td>Asian (n=5)</td>
<td>1.01 (1.01, 1.02)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>All (n=3)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td>Age ≥65 (n=12)</td>
<td>1.02 (1.01, 1.02)</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td></td>
</tr>
<tr>
<td>Time-series (n=8)</td>
<td>1.00 (1.00, 1.01)</td>
</tr>
<tr>
<td>Case-crossover (n=7)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
</tbody>
</table>

### PM$_{10}$

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>RR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall  (n=36)</td>
<td>1.02 (1.01, 1.02)</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td></td>
</tr>
<tr>
<td>Hospitalization (n=14)</td>
<td>1.00 (1.00, 1.01)</td>
</tr>
<tr>
<td>Mortality (n=124)</td>
<td></td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
</tr>
<tr>
<td>Non-Asian (n=13)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td>Asian (n=25)</td>
<td>1.01 (1.01, 1.01)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>Age ≥65 (n=15)</td>
<td>1.00 (1.00, 1.01)</td>
</tr>
<tr>
<td>All (n=26)</td>
<td>1.01 (1.01, 1.01)</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td></td>
</tr>
<tr>
<td>Time-series (n=11)</td>
<td>1.01 (1.00, 1.01)</td>
</tr>
<tr>
<td>Case-crossover (n=27)</td>
<td>1.01 (1.01, 1.01)</td>
</tr>
</tbody>
</table>

**Figure 3** Subgroup analysis for all gaseous and particulate air pollutants stratified by outcome, location, age, and study design. **Abbreviations:** CI, confidence interval; COPD, chronic obstructive pulmonary disease; RR, relative risk.
Short-term air pollution exposure to COPD patients

There were plenty of in vivo and in vitro studies to explain the plausible biomedical mechanisms for the relationship between short-term air pollution exposure and adverse outcome of COPD. One of the main mechanisms was oxidative-mediated. Air pollution could absorb chemical substances from the environment, which participated in the production process of reactive oxygen species. Oxidative stress could cause an injury in the epithelium of the airway, making the airways of COPD patients more sensitive to further damage, and impair the resistance ability of the immune system. Another pathogenesis mechanism is that air pollutants can cause inflammation in the lungs and can further impair the reduced pulmonary function in COPD patients. However, the COPD exacerbation-relevant determinants are still largely unknown. As most research studies have focused on smoking and pneumonia risk for COPD exacerbation,
further studies considering the significant roles of environmental pollution are required.

Interpretation
In the present analysis, all the air pollutants showed acute disadvantageous effects on COPD patients, especially NO\textsubscript{2} and O\textsubscript{3}. Both of these two gaseous pollutants caused an increased risk of COPD significantly (RR, 95% CI): 1.04, (1.03, 1.06); and 1.03, (1.01, 1.04). One study reported that every 10 μg/m\textsuperscript{3} increase of O\textsubscript{3} and NO\textsubscript{2} would result in 0.58% and 0.38% increment in the COPD risk, respectively.\textsuperscript{31} In addition, exposure to SO\textsubscript{2} and CO showed weaker associations with COPD in the present study, which was consistent with a previous study. Fusco et al found that no effects were identified for SO\textsubscript{2}, and only weak associations was found for CO (2.8% increase per interquartile range (IQR), 1.5 mg/m\textsuperscript{3}).\textsuperscript{34} NO\textsubscript{2} and O\textsubscript{3} played important roles in acute respiratory attack, whereas CO seemed to be strongly associated with seasonality, especially in warmer seasons. In combination studies, it was difficult to separate all the estimates of CO by the adjustment of seasonality.\textsuperscript{24,35} For the different effects of O\textsubscript{3} compared to other pollutants, the most important factor is the properties of O\textsubscript{3}. It is the component of photochemical reaction and shows obvious seasonality fluctuation that could affect the exacerbation rate of COPD patients.\textsuperscript{15} Moreover, it is relatively more complex to form O\textsubscript{3} in the ambient air, depending closely on solar radiation and brightness.\textsuperscript{36} As for the adjustment of temperature, different methods adopted cause RR estimates to vary, and in the pooled analysis, it is hard to just limit the pollutants to a certain period.\textsuperscript{37}

Particulate pollutants have always been considered to be responsible for the most adverse cardiovascular and respiratory diseases, and some adverse impacts induced by PM\textsubscript{2.5} might be aggravated by PM\textsubscript{10}.\textsuperscript{19} In the present study, particulate pollutants showed significant adverse impact on COPD patients, which further confirmed that elevated levels of particulate matters in polluted environments could promote the exacerbation of COPD. A study in New Zealand reported an 3.37% increase for each 14.8 mcg/m\textsuperscript{3} increase in PM\textsubscript{10}, and an Australian study also showed a 4% increase in admissions for every 10 μg/m\textsuperscript{3} increase of PM\textsubscript{10}.\textsuperscript{38} However, there were still limited studies about PM\textsubscript{10} in developing countries. In an Asian time-series study, per 10 μg/m\textsuperscript{3} increase in PM\textsubscript{10} indicated an 0.36% increase in respiratory mortality.\textsuperscript{39} Because of a disproportional burden of COPD exacerbation in these middle-/lower-income counties, more studies on PM\textsubscript{10} are required to explore the combined effects of particulate pollutants.

The heterogeneities of the air pollutants CO, NO\textsubscript{2}, and O\textsubscript{3} were more significant than that of SO\textsubscript{2}. For particulate pollutants, the heterogeneity of PM\textsubscript{2.5} was greater than that of PM\textsubscript{10}. Subgroup analysis indicated that lag exposure and age >65 years contributed heterogeneities more significantly. In individual studies, they measured daily variations of each pollutant in limited areas for the time period from 0 to 7 days and adjusted different kinds of confounders.\textsuperscript{37} Therefore, lag exposure for them would be a source of heterogeneity. Subgroup of mortality and age >65 years were also the origins for heterogeneity because COPD showed signs between the ages of 35 and 40 years primarily and it then developed very fast after 65 years. Once exposed to risk factors, COPD patients would exacerbate quickly, and mortality rate increased.\textsuperscript{40} A high quality study with higher score tends to have the higher methodological quality.\textsuperscript{41}

The current analysis also indicated that the association between SO\textsubscript{2} and NO\textsubscript{2} short-term exposure and COPD acute risk seemed to be more pronounced in low-/middle-income countries than in high-income countries, and only 20% of the included studies were from low-/middle-income countries, and more than half of them originated from the People’s Republic of China (Figure 4). This finding was of great importance because urban cities in some developing countries were in a rapid industrialization process and under the threat of severe environmental problems.\textsuperscript{42} Moreover, data from these countries were scarce, resulting from a lack of cohesive air quality policies, inadequate environmental monitoring, and a paucity of disease surveillance data.\textsuperscript{19} More monitoring information is in great demand for developing countries in order to investigate the health impacts of air pollutants. Considering the severe air pollution and disproportionately burden of COPD acute risk in the developing countries, this highlighted issue needs more attention.

Practical implications
The findings of the present study have provided evidence for the association between short-term air pollution exposure and the risk of COPD exacerbations. This called for improvement and implementation of regulations on the air quality that will provide measurable benefits to public health. More policies should be implemented to reduce major air pollutants, such as adoption the absorbers of noxious gases before release, utilization of environmentally-friendly fuels, and adoption of advanced technologies.\textsuperscript{43} Our results urge future research studies on the relationship between concentration of air pollutants and the risk estimation and also for more cooperative actions to issue alerts to high-risk populations in order to facilitate substantial public health benefits.
Limitations

It was acknowledged that several limitations should be considered. First, the lag selection in methodologies was controversial. Exclusion of any lag from lag0 to lag7 might miss considerable information for pooled analysis. In this analysis, all the methodologies used had been reviewed. Therefore, the “priori lag” method was chosen based on the most commonly used approach. Besides, there were still potential sources of bias in the present study: the estimates included were from each publication, and whether multiple hospitalizations might occur for the same patients was not identified. Moreover, the concentration–response relationships are really fundamental references in air quality standards, but lack of details to construct the dose–response functions may limit the ability for setting criteria. Finally, for the air pollutants under the single-pollutant model, underlying interactive effects might exist. There was no clearly stated selection of models in combined analysis, and most of the parameters preferred the idea that multiple models for air pollutants in meta-analysis were still imperfect; therefore, the single-air pollutant model was used in the present study for estimations.

Conclusion

This systematic review and meta-analysis confirmed that short-term exposure to major air pollutants could significantly increase the risk for COPD exacerbations. Environmental and public health policies that can decrease the concentrations of air pollution might reduce the exacerbation burden of COPD.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (41272180).

Disclosure

The authors report no conflicts of interest in this work.

References


