Pricing air pollution: evidence from short-term exposure to air pollution on hospitalization of acute bronchitis and chronic obstructive pulmonary disease in southwestern China

Pei Zhang and Xiaoyuan Zhou*

West China School of Public Health and West China Fourth Hospital, Sichuan University, Chengdu, 610041, China

*Corresponding author: Tel: +86-28-85503396; E-mail: zhouxyuan@scu.edu.cn

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Existing evidence suggests that ambient air pollution has serious adverse effects on respiratory diseases, yet there is little direct evidence from China regarding corresponding economic losses. Here we quantified air pollution–related acute health effects and related economic losses of the most common two respiratory diseases in southwestern China, acute bronchitis and chronic obstructive pulmonary disease (COPD). We applied a distributed lag non-linear model to analyse the relationship between ambient air pollutants and hospital admissions of acute bronchitis and COPD, then applied the cost of illness method to explore the attributing economic burden. During the study period, 528,334 and 99,419 hospital admissions of acute bronchitis and COPD, respectively, were recorded. As a result, during the study period the total hospitalization economic losses attributable to air pollution were 486.40 and 254.74 million yuan for acute bronchitis and COPD, respectively, accounting for 0.015% of local gross domestic product. Our research provides intuitive evidence on the health and economic impacts of short-term exposure to air pollution, which is a key basis for the formulation of environmental policies.

Keywords: ambient air pollution, cost of illness method (COI), DLNM, economic loses, hospital admissions.

Introduction

Ambient air pollution has become one of the most concerning issues around the world. More than 91% of the population worldwide are living in places where air quality exceeds World Health Organization (WHO) guidelines, resulting in 4.2 million premature deaths each year.1,2 In the past few decades, adverse effects of ambient air pollutants on respiratory diseases have been drawing universal attention. Previous studies provided consistent evidence that exposure to air pollutants could augment the burden of respiratory diseases from hospital outpatient visits,3 emergency department visits,4,5 hospital admissions6,7 and mortality.8,9 These studies primarily estimated disease burden through disability-adjusted life years (DALYs)10 and years of life lost (YLL).11

Recently, research in this field has been promoted through the introduction of economic evaluation methods. The most commonly used methods include the value of statistical life (VSL),12,13 the human capital approach (HCA)14,15 and the cost of illness method (COI).16 Among these methods, the VSL and HCA are mainly used to assess the economic burden of mortality, while the COI is often used to evaluate the economic burden of morbidity. Because of these methods, health effects of air pollutants can now be measured not only by the risk of disease, but also by economic burden. For instance, a study in Los Angeles suggested that near-roadway nitrogen dioxide (NO2) exposure would lead to an external economic loss to society of $104 million in 2007.12 Another study in Beijing found that the external costs of 2.5 μm particulate matter (PM2.5) equalled around 0.3% of regional gross domestic product (GDP) in 2012.14

Despite the application of the aforementioned new methods, however, the economic impact of air pollutants on respiratory diseases still has not been fully explored. Existing studies around the world largely focus on long-term exposure when assessing the economic burden associated with air pollution, without adequate consideration for short-term exposure.17 In addition, as non-fatal diseases, although respiratory diseases may cause patients more morbidity than mortality, most scientific evidence from existing research refers to the economic burden of mortality rather than morbidity.17-19 Furthermore, only a limited number of studies have focused on measurement of the economic burden of respiratory diseases in underdeveloped areas, although people in these areas are more seriously harmed by air pollutants than their counterparts in developed areas.1,20
This study aimed to quantify the association between short-term exposure to air pollutants (NO₂, ozone [O₃], PM₁₀, PM₂.₅ and sulphur dioxide [SO₂]) and hospital admissions of acute bronchitis and chronic obstructive pulmonary disease (COPD) and the corresponding hospitalization economic burden of these two diseases caused by air pollutants in southwestern China. To our knowledge, this is the first attempt to evaluate the hospitalization economic burden attributable to short-term exposure to air pollution in China. The results of this study may provide a scientific basis for policymakers to formulate and optimize environmental policies.

**Methods**

**Study area and population**

Chengdu, located in southwestern China (latitude 30°05′–31°26′ N and longitude 102°54′–104°53′ E), is the capital city of Sichuan Province and the largest city in southwestern China. With the rapid development of industrialization and urbanization, the local air pollution problem is becoming increasingly severe. The large population, unfavourable atmospheric diffusion conditions and relatively high humidity have turned it into one of the most polluted cities in the country. Our study involved almost all acute bronchitis and COPD hospital admissions cases in Chengdu, guaranteeing enough statistical power to reveal the association between air pollution and hospitalization for these two diseases.

**Data collection**

**Hospitalization data**

Official records of hospital admissions for acute bronchitis (International Classification of Diseases, Tenth Revision [ICD–10] code: J20.904) and COPD (ICD–10 code: J44.901) between 1 January 2013 and 15 October 2017 (1749 days in total) were obtained from the local Compulsory Medical Insurance Database. These hospital admissions data came from 1161 hospitals where the ICD–10 was used to classify diagnoses. During the study period, 528334 hospital admissions for acute bronchitis and 99419 for COPD were recorded. In order to keep the patients information safe, the identification numbers and names of the patients were separated from the admissions and claims data, which were only manipulated for modelling.

**Pollution data**

Daily average concentrations of NO₂, PM₁₀, PM₂.₅ and SO₂ and the daily maximum 8-h average concentration of O₃ were collected from the Sichuan Environmental Monitoring Center. Since our study included almost all acute bronchitis and COPD hospital admissions cases in Chengdu, we obtained the ambient concentration data by averaging the daily mean values of the 12 environmental monitoring stations in the study area.

**Meteorological data**

To control the confounding factors, we also collected the meteorological data. Data on daily average temperature (in °C) and relative humidity (in %) during the study period were obtained from the China Meteorological Data Sharing Service System.

**Modelling**

To estimate the health and economic impact of hospitalization attributed to ambient air pollution, we conducted our statistical analysis in three steps: estimating the exposure–response function, calculating the total number of air pollution–related hospital admissions and evaluating the corresponding hospitalization economic burden.

**Estimating the exposure–response function**

In our model, quasi-Poisson regression was used as the linked function because daily hospital admissions typically followed an overdispersed Poisson distribution. Natural spline functions were used to control for the influence of temperature, relative humidity and long-term trends. The model formula is as follows:

\[
Y \sim \text{quasiPoisson}(\mu)
\]

\[
\mu = \alpha + w_{x_{1},t} + \text{NS}(\text{Temp}, df_1) + \text{NS}(\text{RH}, df_2) + \text{NS}(\text{Time}, df_3) + \text{Dow}.
\]

where \(Y\) is daily hospital admissions, \(\mu\) is the estimate of \(Y\), \(\alpha\) is the intercept and \(w_{x_{1},t}\) is the cross-basis of an exposure–lag response bidimensional function. We used a natural cubic spline function to estimate the lag effects and a linear function to mimic the exposure–response patterns of air pollutants and hospital admissions. NS refers to the natural spline function; \(df\) is the degrees of freedom; Temp and RH are daily mean temperature and relative humidity, respectively; Time is included to control long-term temporal trends and Dow is the day of the week, which can be set as a dummy variable to control the systematic variation within a week. According to previous studies, we chose 7 as the maximum lag for air pollutants, used 3 as the degrees of freedom of temperature and relative humidity and set the degrees of freedom of the date variable to 7 per year.

After analysing the overall effects, we explored whether the effects of air pollutants on hospital admissions were modified by gender, age and season. The results were illustrated as percentage changes of hospital admissions for a 10 μg/m³ increase in air pollutant concentrations.

To test the robustness of our model, we examined the potential influence of \(df\) by changing the \(df\) value for the date variable from 6 to 8 and changing the \(df\) value for temperature from 2 to 4 (the results of the sensitivity analysis are provided in the Supplementary Materials, Table S1). All analyses were completed in R version 3.5.3 (R Foundation for Statistical Computing, Vienna, Austria), using the DLNM package. Statistical tests were two-tailed and a p-value <0.05 was considered statistically significant.

**Calculating the total number of air pollution–related hospital admissions**

Based on the exposure–response coefficients obtained by DLNM, we further calculated the number of air pollution–related...
hospital admissions of acute bronchitis and COPD. Given the fact that existing research has not yet established a threshold that would not have a detrimental effect on health,\textsuperscript{22,29,30} we set the reference concentration of all air pollutants to 0 $\mu$g/m$^3$ in this part of the analysis. The formula is as follows:

$$RR_{ij} = e^{\beta_1(x_{ij}-x_0)}$$

Percentage change$_{ij}$ = $RR_{ij} - 1$

$$AR_{ij} = \left( \frac{RR_{ij} - 1}{RR_{ij}} \right) = e^{\beta_1(x_{ij}-x_0)} - 1,$$  

$$\Delta n = \sum_{j=1}^{1749} \sum_{i=1}^{n} (AR_{ij} \times n_i)$$

where $i$ represents the day number of the study period (from 1 to 1749); $j$ represents air pollutants NO$_2$, PM$_{10}$, PM$_{2.5}$ and SO$_2$, which have been shown to be harmful to the respiratory system in the first analysis stage; $AR_{ij}$ is attributable risk; $\beta_1$ is the exposure–response coefficient obtained from the first stage, which means the change in hospital admissions caused by a unit change of air pollutants concentration, keeping all the other explanatory variables constant; $x_{ij}$ is the daily concentration of air pollutants; $x_0$ is the reference concentration; $n$ is the number of daily hospital admissions and $\Delta n$ is the total number of hospital admissions attributable to these four air pollutants during the study period.

**Evaluating the corresponding hospitalization economic loss**

We adopted the COI method\textsuperscript{31} when evaluating the air pollution–related hospitalization economic loss. The COI method took into account both the costs of hospitalization and the costs due to absence of work. Because we could not obtain the income information of each hospital admission, we used the regional daily GDP per capita to calculate the economic costs resulting from absence of work. The economic burden was obtained according to the following calculations:

$$meanC = C_n + GDP_p \times meanT_n$$

$$\Delta C = \Delta n \times meanC,$$

where $meanC$ is the average economic costs per hospital admission, which includes costs due to hospitalization and those attributable to absence of work; $C_n$ is the mean cost per hospital admission; $GDP_p$ is the daily GDP per capita; $meanT_n$ is the mean hospitalization days per hospital admission and $\Delta C$ is the total economic costs due to ambient air pollutants during the 1749 study days.

In China, hospitals are categorized into three levels according to Chinese Hospital Classification Management Standard: primary, secondary and tertiary. Generally, tertiary hospitals are top-quality service. Hospitalization costs differ a lot in different hospital levels. Therefore subgroup analysis of gender, age and hospital level was also conducted.

**Results**

Descriptive results of daily air pollutant concentrations, meteorological factors and hospital admissions of acute bronchitis and COPD during the study period are summarized in Table 1. Compared with the WHO air quality guidelines of 25 $\mu$g/m$^3$ and 50 $\mu$g/m$^3$ for PM$_{2.5}$ and PM$_{10}$, the corresponding average concentration in Chengdu were 1.8 and 1.3 times higher during the study period. The mean relative humidity was 80.51%, with a standard deviation of 8.57%. The mean temperature was 16.91°C, ranging from −1.9°C to 29.8°C. On each day, the mean number of hospital admissions was 302 and 57 for acute bronchitis and COPD, respectively. Stark differences were observed in age distributions of acute bronchitis and COPD hospitalizations, as shown in Figure 1. Acute bronchitis covered a wider age range and included three peak age groups, while COPD predominantly occurred in the elderly. This finding provided us with clues for a more practical subgroup analysis of age. During the entire study period we defined unequal subgroups of age for these two diseases (age $\leq$20, 20–55 and $\geq$55 y for acute bronchitis; age $\leq$65, 65–80 and $\geq$80 y for COPD).

Figure 2 illustrates the lag-specific relationship of air pollutants and hospital admissions of acute bronchitis and COPD with a 10 $\mu$g/m$^3$ increase in pollutant concentrations. All pollutants except O$_3$ had substantially negative impacts on both acute bronchitis and COPD ($p<0.05$). They shared a similar lag pattern, with effects most pronounced on lag 0 d and least for 2–3 d. Also, we found the so-called harvest phenomenon easily when analysing the effects of PM$_{2.5}$ on acute bronchitis. Overall cumulative exposure–response associations and three-dimensional graphs of bidimensional exposure–lag response are provided in the Supplementary Materials, Figures S1 and S2, respectively.

Table 2 shows the percentage changes in hospital admissions for different subgroups with a 10 $\mu$g/m$^3$ increase in pollutant concentrations at lag 0 d. In the subgroup analysis of gender, it was obvious that air pollutants were more harmful to women. In the subgroup analysis of age, the results of these two diseases were quite different. For acute bronchitis, NO$_2$ seriously harmed the elderly, while PM$_{10}$, PM$_{2.5}$ and SO$_2$ had the greatest influence on people $\leq$20 y of age. For COPD, all kinds of air pollutants harmed people ages 65–80 y the most, except SO$_2$, where the adverse effect peaked among people $\geq$80 y of age. O$_3$ had no significant influence on hospital admissions for any of the subgroups. The results of subgroup analysis for seasons are also summarized in the Supplementary Materials, Figure S3.

Table 3 indicates the economic burden caused by NO$_2$, PM$_{2.5}$, PM$_{10}$, PM$_{2.5}$ and SO$_2$ from 2013 to 2017. The total economic costs due to air pollutants were approximately 486.40 and 254.74 million yuan for acute bronchitis and COPD, respectively, accounting for 0.015% of local GDP. Most of the air pollutant–related economic burden was attributed to NO$_2$ and SO$_2$. For acute bronchitis, the pollution-related economic burden of hospitalization mostly comes from people $\leq$55 y of age, while for COPD it was people 65–80 y of age.

**Discussion**

In this study we found that short-term exposure to ambient air pollutants may increase hospital admissions of acute bronchitis and COPD after adjusting for temperature and relative humidity. It was also shown that air pollutants caused a heavy economic burden for hospitalization to the society. The results provide
Table 1. Daily data on air pollutant concentrations, meteorological factors and hospital admissions in Chengdu (2013–2017)

| Variables                | Mean±SD | Minimum | P25 | Median | P75 | Maximum |
|--------------------------|---------|---------|-----|--------|-----|---------|
| NO₂ (μg/m³)              | 55.93±18.32 | 15.0 | 43.0 | 53.0   | 66.0 | 144.0   |
| O₃ (μg/m³)               | 90.25±53.12  | 4.0  | 49.0 | 80.0   | 129.0 | 301.0   |
| PM₁₀ (μg/m³)             | 114.74±77.96 | 16.0 | 61.0 | 93.0   | 146.3 | 862.0   |
| PM₂.₅ (μg/m³)            | 70.88±51.03  | 6.0  | 36.0 | 55.0   | 90.0  | 427.0   |
| SO₂ (μg/m³)              | 18.16±12.3   | 4.0  | 11.0 | 14.0   | 21.0  | 96.0    |
| Relative humidity (%)    | 80.51±8.57   | 42.0 | 76.0 | 81.0   | 87.0  | 98.0    |
| Mean temperature (°C)    | 16.91±7.25   | −1.9 | 10.3 | 18.0   | 23.1  | 29.8    |
| HAs of acute bronchitis  | 302.08±105.49 | 49.0 | 234.0 | 295.0 | 360.0 | 1312.0  |
| Man                      | 127.25±43.17 | 20.0 | 101.0 | 124.0 | 150.0 | 541.0   |
| Woman                    | 174.82±64.04 | 26.0 | 132.0 | 169.0 | 210.0 | 771.0   |
| Age ≤20 y                | 77.54±33.82  | 1.0  | 56.0 | 75.0   | 93.0  | 508.0   |
| Age >20–<55 y            | 117.20±41.21 | 17.0 | 89.0 | 113.0  | 142.0 | 384.0   |
| Age ≥55 y                | 107.40±42.59 | 13.0 | 78.0 | 102.0  | 132.0 | 420.0   |
| HAs of COPD              | 56.84±24.92  | 2.0  | 42.0 | 54.0   | 68.0  | 385.0   |
| Man                      | 32.45±13.74  | 1.0  | 24.0 | 31.0   | 39.0  | 210.0   |
| Woman                    | 24.40±12.29  | 1.0  | 17.0 | 23.0   | 30.0  | 175.0   |
| Age ≤65 y                | 13.10±7.00   | 1.0  | 9.0  | 12.0   | 16.0  | 80.0    |
| Age >65–<80 y            | 29.18±13.47  | 1.0  | 21.0 | 28.0   | 36.0  | 209.0   |
| Age ≥80 y                | 14.65±6.61   | 1.0  | 10.0 | 14.0   | 18.0  | 96.0    |

P25: 25th percentile; P75: 75th percentile; HAs: hospital admissions.

Figure 1. Age distributions of acute bronchitis and COPD hospitalizations. The y-axis represents the daily number of hospital admissions. The x-axis represents different ages.

Updated evidence for policymakers to formulate more effective environmental protection policies.

In the overall analysis, we found positive associations between NO₂, PM₁₀, PM₂.₅ and SO₂, and hospital admissions of acute bronchitis and COPD. Consistent with existing research in China, the greatest adverse effects of NO₂, PM₁₀, PM₂.₅ and SO₂ occurred at lag 0 d, followed by a sharp decrease afterwards.³,²⁴,²⁹ These effects lasted 2–3 d. The results indicate that people were more susceptible to exposures of these pollutants during very short periods between exposure and hospital admission. These adverse effects were explained in previous studies⁷,³² as a result of airway inflammation caused by pollution-induced oxidative stress. Nonetheless, for O₃, we did not observe any significant adverse effect in the analysis. Although studies in Guangzhou⁴ and Beijing³³ had results similar to ours, abundant published literature in other countries states that O₃ is harmful to the respiratory system.⁹,³⁴,³⁵ For example, a study in Greece found that an increase of 10 μg/m³ in weekly O₃ concentration was associated with a...
Figure 2. The lag-specific effects of ambient air pollutants on acute bronchitis (AB) and COPD. The y-axis represents daily hospital admissions. The x-axis represents different lag days. The vertical lines represent 95% confidence intervals. The points represent the percent change in hospital admissions.

Table 2. Percentage changes in hospital admissions for different subgroups with a 10 μg/m³ increase in pollutant concentrations

| Disease       | Group        | NO₂   | O₃    | PM₁₀  | PM₂.₅ | SO₂   |
|---------------|--------------|-------|-------|-------|-------|-------|
|               |              | (95% CI) | (95% CI) | (95% CI) | (95% CI) | (95% CI) |
| Acute bronchitis | Overall      | 1.95 (1.39 to 2.51) | −0.25 (−0.58 to 0.08) | 0.24 (0.09 to 0.39) | 0.28 (0.03 to 0.53) | 3.28 (2.17, 4.41) |
|               | Male         | 1.69 (1.09 to 2.28) | −0.28 (−0.63 to 0.06) | 0.24 (0.07 to 0.40) | 0.27 (0.00 to 0.54) | 3.08 (1.89 to 4.29) |
|               | Female       | 2.14 (1.56 to 2.72) | −0.22 (−0.56 to 0.12) | 0.24 (0.09 to 0.40) | 0.28 (0.02 to 0.54) | 3.43 (2.27 to 4.59) |
|               | Age ≤20 y    | 1.86 (1.07 to 2.65) | −0.24 (−0.70 to 0.22) | 0.39 (0.18 to 0.61) | 0.69 (0.13 to 0.85) | 3.74 (2.12 to 5.38) |
|               | Age ≥20–≤55 y| 1.92 (1.34 to 2.49) | −0.21 (−0.54 to 0.13) | 0.21 (0.06 to 0.37) | 0.26 (0.00 to 0.51) | 3.14 (2.00 to 4.29) |
|               | Age ≥55      | 2.20 (1.57 to 2.84) | −0.37 (−0.74 to 0.00) | 0.18 (0.01 to 0.36) | 0.17 (−0.11 to 0.45) | 3.43 (2.17 to 4.70) |
| COPD          | Overall      | 2.24 (1.46 to 3.02) | 0.30 (−0.16 to 0.76) | 0.35 (0.15 to 0.55) | 0.47 (0.14 to 0.81) | 3.51 (2.01 to 5.03) |
|               | Male         | 1.96 (1.14 to 2.80) | 0.27 (−0.21 to 0.76) | 0.32 (0.10 to 0.54) | 0.44 (0.09 to 0.80) | 2.91 (1.30 to 4.54) |
|               | Female       | 2.61 (1.69 to 3.54) | 0.34 (−0.21 to 0.89) | 0.39 (0.15 to 0.63) | 0.51 (0.12 to 0.90) | 4.27 (2.52 to 6.05) |
|               | Age ≤65 y    | 2.16 (1.08 to 3.26) | 0.28 (−0.36 to 0.93) | 0.22 (0.07 to 0.51) | 0.29 (−0.18 to 0.75) | 2.54 (0.50 to 4.61) |
|               | Age ≥65–≤80 y| 2.47 (1.60 to 3.35) | 0.50 (−0.01 to 1.02) | 0.45 (0.22 to 0.68) | 0.62 (0.25 to 1.00) | 3.76 (2.07 to 5.47) |
|               | Age ≥80 y    | 1.88 (0.90 to 2.86) | −0.14 (−0.70 to 0.43) | 0.26 (0.00 to 0.52) | 0.34 (−0.08 to 0.76) | 4.03 (2.13 to 5.96) |

decrease in forced vital capacity and forced expiratory volume in 1 s. Another study in the USA suggested that ozone was associated with pediatric respiratory morbidity in multiple US cities, and the strongest overall association was in Atlanta (odds ratio 1.08 [95% confidence interval (CI) 1.06 to 1.11]). This discrepancy may result from demographic specificity, which means the susceptibility to air pollutants varies by ethnicity. More relevant epidemiological studies are needed to verify this statement. Also, we found the so-called harvest phenomenon at lag 4–6 d when exploring the effects of PM₂.₅ on acute bronchitis. This may be because acute bronchitis can occur in fragile people immediately after exposure to PM₂.₅, leaving limited numbers of subjects at risk, and the overall long-term hazard was reduced. The results of subgroup analysis were different. In the subgroup analysis of gender, we found that women suffered more from air pollutants than men for both acute bronchitis and COPD.
SO₂ significantly affected people with diseases and pollutants. For acute bronchitis, PM₁₀, PM₂.₅ and SO₂ pollution strategies. In the subgroup analysis of age, effects varied attributed to differences in study design, sample size and mod-

gender differences were inconsistent with our findings, possibly research that persons worst impact on people 65–80 y of age, which refined previous group in future studies. For COPD, ambient air pollution had the talizations, indicating more attention should be paid to this age account for more than two-thirds of all acute bronchitis hospi-

For example, an increase of 10 μg/m³ in NO₂ resulted in a 2.61% (95% CI 1.69 to 3.54) increase in female COPD hospitalizations compared with 1.96% (95% CI 1.14 to 2.80) in males. This result was in line with previous research. However, a recent study in Chengdu showed that air pollution was more harmful to males, according to hospital admissions data from 2015 to 2016. Such gender differences were inconsistent with our findings, possibly attributed to differences in study design, sample size and mod-

The economic burden analysis revealed that the total economic burden due to air pollution was 486.40 and 254.74 million yuan for acute bronchitis and COPD hospitalizations, respectively, accounting for 0.015% of the regional GDP. Although the cost of an acute bronchitis hospitalization was only one-third that of a COPD hospitalization, the total economic burden of acute bronchitis hospitalization was much higher because of the large number of hospital admissions. Therefore, although existing studies around the world largely focus on COPD, asthma and pneumonia, more attention should be paid to acute bronchitis in future research. In terms of different pollutants, the greatest economic burden came from NO₂, which reached 239.19 and 113.48 million yuan for acute bronchitis and COPD, respectively, followed by SO₂, PM₁₀, and PM₂.₅. This order of harmfulness was also found in previous studies in China. The results warned us that more attention should be given to NO₂ and SO₂. Although PM₁₀ and PM₂.₅ were the leading pollutants in Chengdu, the role of NO₂ and SO₂ cannot be ignored when it comes to the hospitalization economic burden due to air pollution.

In subgroup analysis of gender, the results of acute bronchitis and COPD varied. The external economic burden of acute bronchi-
tis was mostly caused by female hospital admissions, in contrast to COPD, which came mainly from males. This difference may re-

Our study has some limitations. First, we did not consider the spatial heterogeneity of air pollutants, because specific informa-

| Disease     | Subgroup          | Total number of HAs | Hospitalization cost per capita (yuan)³ | Economic cost due to pollutants (million yuan) | NO₂ | PM₁₀–₁₀ | PM₂.₅ | SO₂ | Total |
|-------------|-------------------|---------------------|-----------------------------------------|-----------------------------------------------|-----|---------|-------|-----|-------|
| Acute bronchitis | Tertiary hospitals | 61 017              | 3593.51                                  | 29.02                                         | 6.83 | 14.91   | 14.97 | 65.73 |
|              | Secondary hospitals| 121 288             | 2738.72                                  | 63.06                                         | 11.78 | 26.77   | 30.5  | 132.11 |
|              | Primary hospitals  | 346 029             | 1758.35                                  | 136.79                                        | 20.64 | 36.05   | 82.68 | 276.16 |
| Age ≤20 y    | 135 392            | 1756.97             | 46.91                                    | 14.19                                         | 27.24 | 31.16   | 119.50|
| Age ≥20–≤55 y| 205 026            | 2131.39             | 86.34                                    | 14.72                                         | 26.09 | 48.64   | 175.79|
| Age ≥55 y    | 187 916            | 2580.99             | 105.94                                   | 19.55                                         | 18.85 | 55.98   | 200.32|
| Total        | 528 334            | 2196.48             | 239.19                                   | 48.46                                         | 72.18 | 135.78  | 486.40|
| COPD         | Tertiary hospitals | 16 419              | 14 806.52                                | 15.75                                         | 2.14  | 2.08    | 30.99 |
|              | Secondary hospitals| 27 318              | 7474.46                                  | 39.54                                         | 13.99 | 26.34   | 16.92 | 96.79 |
|              | Primary hospitals  | 55 682              | 2902.02                                  | 41.63                                         | 6.77  | 16.29   | 23.63 | 88.32 |
| Age ≤65 y    | 22 826             | 5422.85             | 22.92                                    | 2.77                                          | 6.71  | 9.36    | 41.76 |
| Age ≥65–≤80 y| 51 001             | 5977.16             | 62.66                                    | 19.55                                         | 34.33 | 32.17   | 148.71|
| Age ≥80 y    | 25 592             | 7043.70             | 27.9                                     | 5.54                                          | 11.03 | 19.8    | 64.27 |
| Total        | 99 419             | 6125.31             | 113.48                                   | 27.86                                         | 52.07 | 61.33   | 254.74|

³US$1 is approximately equal to 6.82 yuan.

HAs: hospital admissions.
Therefore further studies that also consider the spatial variability of air pollution and more sources of economic burden are needed. Findings in this study will not only focus attention on environmental protection, but also provide evidence for decision makers to develop more targeted policies. Also, in the analysis of economic burden we optimized the time scale to days and considered variations in costs at different hospital levels. The results offer a more precise evaluation of the economic burden of hospitalization.

Conclusions
Short-term exposure to NO₂, PM₁₀, PM₂.₅ and SO₂ may contribute to increased hospital admissions of acute bronchitis and COPD, while O₃ shows no adverse effects on these two diseases. This study indicates that these pollutants have caused a heavy economic burden of hospitalization to society. Evaluating the economic burden caused by ambient air pollutants provides a complementary approach to clarify the ill effects of air pollution. It is highly recommended that policymakers consider research conclusions when allocating health resources and formulating environmental protection policies.

Supplementary data
Supplementary data are available at International Health online (http://inthealth.oxfordjournals.org).

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Data availability: All data and material will be available from the corresponding author, Xiaoyuan Zhou upon reasonable request.

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