Effects of air pollutants on pneumonia hospital admissions in Lanzhou: Evidence of ecological time-series study using distributed lag non-linear model

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Research Article

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Abstract

Introduction:

A study on effects of air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, $O_3$8h, and CO) on pneumonia hospital admissions was performed in Lanzhou (an ex-heavily polluted city in Northwestern China).

Methods

A time-series design with distributed lag non-linear model (DLNM) was used for statistical analysis. Daily pneumonia hospital admissions data in Lanzhou from January 1, 2014, to December 31, 2019, were collected, as well as air pollutant data and meteorological data. We used DLNM to estimate relative risk (RR) and 95% confidence interval (CI) of pneumonia hospital admissions associated with per 10μg/m^3 rise in exposure to air pollutants (per 1 mg/m^3 rise in CO). stratification analysis was performed by gender (male and female), age (0–14 years, 15–64 years and ≥ 65 years old), and season (warm season and cold season).

Results

A total of 20,071 pneumonia hospital admissions were enrolled for analysis. Pneumonia hospital admissions risk were 1.044(1.029,1.060), 1.009(1.005,1.013), 1.086(1.053,1.121), 1.073(1.052,1.093), and 1.157(1.094, 1.223), respectively, corresponding to per 10μg/m^3 rise in exposure to $PM_{2.5}$, PM_{10}, SO_2, NO_2, and 1 mg/m^3 rise in exposure to CO. Every 10μg/m^3 increase in $O_3$8h was associated with decreased of pneumonia hospital admissions, the RR(95%CI) was 0.949(0.935, 0.962). The adverse effects for gaseous pollutants (except $O_3$8h) on pneumonia hospital admissions were stronger than particulate matter. Six exposure-response curves between air pollutants and pneumonia hospital admissions were approximate linear with no thresholds. Female and children (0–14 years age group) were more sensitive to the effects of air pollutants, particularly in cold season.

Conclusion

Exposure to air pollutants(except $O_3$8h) might be associated with increased risk of pneumonia hospital admissions. The association remained signifcant after adjustment for other environmental factors.

Introduction

The Global Burden of Disease(GBD) study 2019 has shown that air pollution is the leading Level 2 risk factor for GBD among all environmental and occupational risks and the fourth leading cause of global attributable death for humans [1]. Air pollution pose great threat to respiratory health by directly promoting or aggravating respiratory diseases or through the increasing exposure to risk factors for respiratory diseases. For example, atmospheric particulates ($PM_{2.5}$, PM_{10}) may absorbs a large number of pathogenic microorganisms or a variety of harmful substances and elevate airway reactivity through promoting oxidative stress and causing inflammation, which thereby reduce host immune defense mechanisms and exacerbate pre-existing or ongoing respiratory diseases [2–4]; gaseous pollutant (SO_2□NO_2□CO□O_3) can lead inflammation and oxidative damage by stimulating the respiratory tract, impairment of lung function and respiratory diseases [5–8].

Pneumonia refers to inflammation of the terminal airways, pulmonary alveoli, and pulmonary interstitial, which is a common respiratory disease, meanwhile, pneumonia is a huge burden on the healthcare system, and it is the world's leading cause of death among children under 5 years of age [9]. It is estimated that there were about 2.5 million cases of pneumonia occur annually in China, and 5% of them die from pneumonia-related diseases [10]. The reasons of pneumonia include: infection of pathogenic microorganisms, physical and chemical factors, immune-related pneumonia, drug-associated pneumonia, and so on. In recent years, epidemiological studies have found a positive relation between air pollutants and pneumonia. Such as, a case–crossover study in New York State, America indicated that interquartile range increases in $PM_{2.5}$ over the previous 7 days were associated with increased excess rates of pneumonia hospitalizations (2.5%; 95% CI, 1.7–3.2%) [11]. A population-based case-control study of old people aged 65 years or more in Hamilton, Canada showed that a 5th-95th percentile range increase in NO_2 and $PM_{2.5}$ corresponded to effect estimates (odds ratio, OR) = 2.30 (95%CI: 1.25, 4.21) and OR = 2.26 (95%CI: 1.20, 4.24) increase of pneumonia hospitalization, but SO_2 did not appear to have any association [12]. A study in São Paulo, Brazil [13] reported that the more PM_{10} and SO_2 were present in the atmosphere, the more hospitalizations of patients with pneumonia will occur. A study in Nis, Serbia [14] found that a 10 μg/m^3 increase in daily concentrations of $PM_{2.5}$ and PM_{10}, the risk of hospital admissions for pneumonia increased by 0.6% and 0.4%. Priyankara et al.[15] used the generalized additive model to estimate the short-term effect of ambient PM on pneumonia hospitalization in Kandy, Sri Lanka, and found that compared to the low air pollution reference period, statistically and significantly increased hospital admissions were observed for pneumonia diseases during the high air pollution period. Qiu et al.[5] applied an ecological time-series study to examine the city-specific association between O_3 and pneumonia hospitalizations in Hong Kong and Taipei, China, the result showed that an interquartile range (IQR) increment of O_3 in Hong Kong and Taipei was associated with a 7.04% (95%CI: 5.35–8.76%) and 3.41% (95% CI: 1.63–5.22%) increase in hospital admissions for pneumonia, respectively. And a national time-series study in 184 major Chinese cities also observed increased pneumonia hospital admissions associated with O_3 exposure, each 10μg/m^3 increment of ozone was associated with a 0.14% (95% CI: 0.03–0.25%) increase in pneumonia admissions [7]. Studies in other cities in China, such as Shenzhen [3], Qingdao [6], Jinan [16], also showed that PM or SO_2 or other gaseous pollutant had significant adverse effects on adult or children pneumonia hospitalizations.

However, the majority of these studies were conducted in some cities in South America or North America [11–14] and also in some cities in China, including Hong Kong and Taipei [5], Shenzhen [3], as well as Qingdao [6], but less so in an arid inland city of northwest China, where constituents of ambient air pollution, meteorological conditions, and demographic characteristics may vary according to geographical region. Thus, research on the association between air pollutants and pneumonia hospital admissions is necessary to understand the effects of local air pollution. Meanwhile, studies mentioned above mainly discussed only one or a few of the air pollutants, so it's not comprehensive enough. In addition, most studies only analyzed the health effects of air pollution among children or old residents. There are few in-depth subgroup analysis on whether there are differences in the health effects of factors such as gender, age and season on air pollution.

Lanzhou, which is located in the inland northwest China, so the unique basin topography and special meteorological conditions make air pollutants difficult to diffuse. Therefore, in this study, we explored the exposure-lag-response relationship between air pollution and pneumonia disease among different subpopulation in Lanzhou by conducting a distributed lag nonlinear model (DLNM).

Materials And Methods

Study area

Lanzhou, the capital city of Gansu Province, is situated in the interior of northwest China (35.57° ~ 37.12°N, 102.59 ~104.57°E). The city has a valley terrain, which is located at a narrow, long, NW-SE oriented valley basin, and the distance from east to west, and from north to south of Lanzhou are about 40 km and 3-8 km, respectively [4]. It is dominated with petrochemical, metallurgy and machinery industries.

Data sources

Data on daily pneumonia hospital admissions from January 1, 2014, to December 31, 2019, were collected from three large general hospitals, including gender, age, residential address, date of hospital admission, principal diagnosis, and their corresponding codes of International Classification of Diseases, 10th Revision (ICD-10). The locations of these three hospitals are densely populated areas with convenient transportation (the locations are shown in Fig. 1). And More than 80% of local residents choose to seek treatment in these hospitals [4, 17]. Inclusion criteria: ICD-10 codes J12-J18 and patients with residential address inside of the urban districts in Lanzhou. Exclusion criteria: records with incomplete information.

Data on hourly air pollution from January 1, 2014, to December 31, 2019, were collected from three national environmental monitoring stations in the city of Lanzhou, including particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3). Fig. 1 shows the locations of the three monitoring stations for air pollutants. First, we calculated the daily 24h mean concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and the maximum daily 8h moving average of O_3 (from 10:00 to 18:00, $O_3$8h) per monitoring station, then the average concentrations of six air pollutants were calculated among all three monitoring stations. Meteorological data near the ground of Lanzhou on daily average temperature (°C) and daily average relative humidity (%) were collected from China Meteorological Data Service Center (National Meteorological Information Center) (http://data.cma.cn/).

Statistical analysis

The basic statistical descriptive analysis of mean, standard deviation (SD), minimum (Min), percentile 25 (P_{25}), median (P_{50}), percentile 25 (P_{75}), maximum (Max) were used for environmental and health data. The data of daily pneumonia hospital admissions, daily concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and $O_3$8h and daily meteorological data were disobey normal distribution, so spearman correlation analysis was used to explore the relationship between them. And differences between two groups were compared with the Two-Sample Kolmogorov-Smirnov Test (Nonparametric test). For those statistical analysis were done using SPSS software, version 22.

The daily pneumonia hospitalizations are generally regarded as rare events, which roughly follow a quasi-Poisson distribution, and most previous studies have suggested that there is a potentially nonlinear and lagged association between air pollution and pneumonia outcomes [6, 10]. Therefore, a quasi-Poisson generalized additive model combined with the distributed lag nonlinear model (DLNM) was used to investigate the effect of six air pollutants on pneumonia admissions, which can describe simultaneously complex non-linear exposure-response relationships and lag effects [18]. Meanwhile, we used the function of natural cubic spline (*ns*) to control for nonlinear confounders such as long-term and seasonal trends of the daily pneumonia hospital admissions (*Time*), daily mean temperature (*Tem*) and relative humidity (*RH*). The public holiday effects (*Hol*) and day of the week (*Dow*) were also adjusted. The constructed model is shown below:

$$\mathrm{Log}[E(Y_t)] = a + b\, X_{t,l} + ns(Time, df{=}7/\mathrm{year}) + ns(Tem_t, df{=}3) + ns(RH_t, df{=}3) + Dow + Hol$$

Where t is the time observed (days); $E(Y_t)$ is the expected mean of number of pneumonia hospital admissions at t day; a is the constant of regression model; $X_{t,l}$ represents cross basis matrix obtained by series of transformations for daily mean concentration of a certain air pollutant, l is the maximum lag days; β is the coefficient of the matrix; *ns* is the function of natural cubic spline, *Time* is the time variable, *df* is the degree of freedom; Tem_t and RH_t represent the average temperature and average relative humidity on day *t; Dow* and *Hol* represent the day of the week effect and holiday effect. All degrees of freedom in the model were selected by minimum quasi-Poisson Akaike Information Criterion (QAIC). For air pollutant, we adopted an *ns* function to estimate the lag space with 3 internal knots placed at equally-spaced values on the log scale and polynomial transformations with 3 *df*.

We conducted the analysis by DLNM based on the total population and stratification analysis was performed by the gender (male and female), age (0-14 years, 15-64 years and ³ 65 years old), and season (warm season and cold season). The warm season is from May to October, and the cold season is from November to the next April. Furthermore, sensitivity analyses were performed to check the robustness of the results, we chose the lag day with the largest estimated effect in the single-pollutant model to perform the sensitivity analysis. (1) The two-pollutant models were used to investigate the confounding effects among air pollutants; as the strong correlation between $PM_{2.5}$ and PM_{10} (r = 0.857, Table2), they were not tested for mutual effects. (2) To evaluate whether more flexible splines will have a substantial impact on the results, we changed the *df* of the *ns* function of *Time* from 6 to 10.

We reported our risk estimates as the relative risk (RR) and its corresponding 95% confidence interval (CI) associated with each 10 μg/m^3 increase for each of air pollutants, except for CO (per 1mg/m^3). The regression analysis of DLNM were done by using R software version 3.6.3, with its "dlnm" package.

Results

Statistical description

Table 1 shows the results of the descriptive statistics on pneumonia hospital admissions in Lanzhou City during 2014-2019. There were a total of 20,071 pneumonia hospital admissions during 2014 - 2019, including 11,539 cases of males, 8,532 cases of females, 12,713 cases in age group 0-14 years, 2,957 cases in age group 14-64 years, 4,401 cases in age group ³ 65 years. Moreover, there were 12,306 cases in the cold season, and 7,765 cases in the warm season. The daily pneumonia hospital admissions per day for all, male, female, age 0-14 years, age 15-64 years and age ≥ 65 years were 9, 5, 4, 6, 1 and 2, respectively. Moreover, pneumonia hospital admissions in cold season (11 cases/day) was much higher than in warm season (7 cases/day) (Kolmogorov-Smirnov Z=5.698, P<0.0001).

Fig.2 and TableS1 summarizes the results of the statistical description and the distributing characteristic of the air pollutants and meteorological factors by season. The concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO had similar seasonal characteristic with the number pneumonia hospital admissions, which were higher in cold season than in warm season (All P values<0.0001). However, the concentrations of $O_3$8h showed an inverse seasonal characteristic, which was lower in cold season than in warm season (P<0.0001). The mean temperatures in cold and warm season were 3.14 °C and 19.50 °C, respectively. There was no significant difference in relative humidity in cold season and warm season (P=0.317), and the daily average relative humidity were 51.03% (full year) (Table S1).

Table 2 shows the spearman rank correlation between daily pneumonia hospital admissions, air pollutants and meteorological factors. In general, daily pneumonia hospital admissions, air pollutants and weather conditions were correlated. Daily pneumonia hospital admissions was significantly positively correlated with daily $PM_{2.5}$, PM_{10}, SO_2, and NO_2 concentrations, but, significantly negatively correlated with daily $O_3$8h, and temperature. There were significant correlations among daily air pollutants concentrations, especially between $PM_{2.5}$ and PM_{10} (r=0.857, P<0.0001), SO_2 and CO (r=0.799, P<0.0001), $PM_{2.5}$ and CO (r=0.715, P<0.0001), $PM_{2.5}$ and SO_2 (r=0.659, P<0.0001). All air pollutants were negatively and significantly correlated with temperature (except for $O_3$8h, r=0.643, P<0.0001) and relative humidity (except for CO, P>0.05).

Association of air pollutants with pneumonia hospital admissions analyzed by DLNM

Fig. 3 shows the contour plots of relative risks (RRs) of pneumonia hospital admissions along single-pollutant models at lag 0~lag 7 days (exposure–lag–response). The contour plots showed that there were positive correlations between pneumonia hospital admissions and $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO, but negative correlated with $O_3$8h. The plots also indicated that there were lag effects on the impact of all six air pollutants on pneumonia hospital admissions, and the lag-response curves were nonlinear. For $PM_{2.5}$, at a concentration of 278μg/m^3, the effect on pneumonia hospital admissions reached a maximum at lag7 day, with RR95%CI of 1.446 (1.194, 1.750); for PM_{10}, at a concentration of 1485μg/m^3, the harmful effect at lag7 day was biggest, with RR95%CI of 1.477 (1.134, 1.925); for SO_2 (at a concentration of 82μg/m^3, lag7 day), the highest effect value was 1.291 (1.126, 1.482); for NO_2 (147μg/m^3, lag2 day), the highest effect value was 1.319 (1.142, 1.523); for $O_3$8h, at a concentration of 222μg/m^3, the protect effect at lag1 day was strongest, with RR95%CI of 0.795 (0.653, 0.968); for CO (4.65mg/m^3, lag7 day), the highest adverse effect value was 1.296 (1.126, 1.491).

Association of air pollutants with pneumonia hospital admissions in single-pollutant models were showed in Table 3. All six air pollutants were statistically significant associated with pneumonia hospital admissions. 10μg/m^3 increase in $PM_{2.5}$ at lag0, lag6, lag7, and all cumulative lags, PM_{10} at lag 6, lag7, lag04 to lag07, SO_2 at lag6, lag7, and all cumulative lags, NO_2 at lag0, lag2, lag3, lag6, lag7, and all cumulative lags, and 1mg/m^3 increase in CO at lag2, lag6, lag7, and all cumulative lags were associated with increased of pneumonia hospital admissions. On the contrary, 10μg/m^3 increase in $O_3$8h at all lag days except lag2 and lag 3 day were associated with decreased of pneumonia hospital admissions. And the strongest association were all observed at lag 07, the RR95%CI for $PM_{2.5}$ was 1.044(1.029,1.060), for PM_{10} was 1.009(1.005,1.013), for SO_2 was 1.086(1.053,1.121), for NO_2 was 1.073(1.052,1.093), for $O_3$8h was 0.949(0.935, 0.962), and for CO was 1.157(1.094, 1.223). This was obvious that $O_3$8h was negatively and significantly correlated with pneumonia hospital admissions, and CO had the strongest adverse effect on pneumonia hospital admissions. We can also find out that the adverse effect of $PM_{2.5}$ were higher than PM_{10}, and the adverse effects for all gaseous pollutants except $O_3$8h were stronger than particulate matter.

The exposure-response curves of air pillutants with pneumonia hospital admissions were showed in Fig.4. The effects of air pollutants at lag07 day on pneumonia hospital admissions were highest at all lag days (Table 3), thus, we focused on pneumonia hospital admissions related to air pollutants at lag07 day (Fig. 4). In brief, all six exposure-response curves were approximate linear with no thresholds. The exposure-response curves for pneumonia hospital admissions and $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO showed positive relationship, with increasing concentration, the RR increased, but for $O_3$8h, a negative relationship was observed.

Stratified analyses by gender, age and season were investigated to identify the effect modifiers of the association between air pollutants and pneumonia hospital admissions. Frist, stratified analyses by gender(Fig.5) showed that $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO were statistically and positively significant associated with pneumonia hospital admissions in both male and female, however, $O_3$8h was statistically associated with decreased of pneumonia hospital admissions in both gender. The highest RR estimate were all observed at lag 07 for all six air pollutants in male and female, and we also observed that the RR estimate of air pollutants on pneumonia hospital admissions in female was higher than male(Fig.5). Second, regarding age, in aged 0-14 years group, $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO were significantly and positively associated with pneumonia hospital admissions, and the most obvious effects were all observed on lag07. In aged 15-64 years, only NO_2 at lag 03, lag 04 were associated with increased of pneumonia hospital admissions. In aged ³ 65years, the positive association was just found between $PM_{2.5}$ (lag 07) and pneumonia hospital admissions. Nevertheless, $O_3$8h showed negative associations in children (aged 0-14 years) and the elderly (aged ³ 65years) pneumonia hospital admissions. Simultaneously, the strongest associations were all observed in children for six air pollutants. Thirdly, with respect to season, $PM_{2.5}$, PM_{10}, SO_2, and CO had statistical adverse effects on pneumonia hospital admissions during the cold season, while no statistical effects were observed in the warm season; NO_2 had statistical adverse effects on pneumonia hospital admissions in both cold and warm season (lag3), and the adverse effects in warm season was weaker than in cold season; whereas, $O_3$8h had protective effects on pneumonia hospital admissions during the cold season, no statistical effects were observed in the warm season. To sum up, female, children were more vulnerable to air pollutants exposure, and the effect of air pollutants were greater in the cold season.

Two-pollutant models (Fig.8 and Table S3) and changing the *df* for calendar time (6-10 *df* per year) (Table 4) were conducted to examine the sensitivity of findings between pneumonia hospital admissions and air pollutants. We analyzed the two-pollutant models for all pollutant pairs except $PM_{2.5}$ and PM_{10}, because the correlations between $PM_{2.5}$ and PM_{10} (r=0.857) was the highest. To sum up, the significant results of air pollutants still maintained significance in two-pollutant models, although some effect estimates shifted. When changing the *df* for calendar time, the significant results of air pollutants still maintained significance too. The above results all indicated that the DLNM fitted well and findings between pneumonia hospital admissions and air pollutants were robust.

Discussion

In general, there are few systematic studies on the relationship between air pollutants and pneumonia hospital admissions, this time-series study provides more systematic insight into the association between air pollutants and pneumonia morbidity by using DLNM model in Lanzhou from 2014 to 2019. The findings showed statistically significant associations between short-term exposure to all six air pollutants and pneumonia hospital admissions and the associations had apparent lag effects: $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO had adverse effects on pneumonia, but $O_3$8h had a negitive association. And the exposure-response curves for six pollutants were linear and without obvious thresholds. The effects of the six pollutants all reached the maximum value on the lag07 day. In the subgroup analysis, the association between six air pollutants and pneumonia were stronger in females, individuals aged 0–14 years and in cold season. Our results provides systematic evidence to build the relationships between air pollution and pneumonia and offers basal data for the prevention of pneumonia and the control of air pollution in Lanzhou.

Our findings showed that, particulate matter (PM) were responsible for increasing pneumonia hospital admissions: the largest effect estimates (relative risks, RRs) of pneumonia hospital admissions with a 10μg/m^3 increment of $PM_{2.5}$ and PM_{10} were found at lag07 day with 1.044(1.029,1.060) and 1.009(1.005,1.013), respectively, the effects in single-day lags were lower than in multi-day lags, which were consistent with most previous studies. A case–crossover in New York State, America [11] indicated that increase rete of pneumonia was associated with increased $PM_{2.5}$ concentration during the previous week, an interquartile range increase in $PM_{2.5}$ was associated with pneumonia admissions, with RR of 1.025(95% CI: 1.017, 1.032). Luo et al [19] applied ecological time-series study using generalized additive model to explored the effect of air pollutants on pneumonia hospital admissions in Taiyuan, China, and they found that a 10μg/m^3 increase in $PM_{2.5}$ and PM_{10} was associated with pneumonia admissions, with RR of 1.010(95% CI: 1.004, 1.016) and 1.008(95% CI: 1.005, 1.012), respectively. Another nationwide time series study in 184 Chinese cities [10] showed short-term elevations in $PM_{2.5}$ and PM_{10} concentrations were associated with increased pneumonia admissions, with RR of 1.003(95% CI: 1.002, 1.005) and 1.002(95% CI: 1.001, 1.003). And study in Kandy, Sri Lanka [15] and Qingdao, China [6] also found similar results: PM had adverse effects on pneumonia, moreover the harmful effect of $PM_{2.5}$ on pneumonia is slightly greater than that of PM_{10}. We also found differences in effect estimates (RR) for different cities. PM can absorbs various harmful substances such as heavy metals and pathogenic bacteria and sneak into the lower respiratory tract and even the lungs, thus damaging human respiratory. Meanwhile, compared to PM_{10}, $PM_{2.5}$ has a smaller particle size and longer residence time in the air, therefore, it is more likely to causes harm to the human respiratory system than PM_{10} [15, 20, 21]. Estimates of the impact of PM on pneumonia vary across cities, which may be related to diversity of climatic and topographic conditions, as well as differences in research methods, study population, PM concentration, etc. [22].

In this study, pneumonia hospital admissions risk was 1.086(1.053,1.121), corresponding to per 10μg/m^3 rise in exposure to SO_2 at lag07 days. This was consistent with most previous studies [6, 19, 23]. A study in Taiyuan [19] concluded that after controlling the effects of meteorological and other factors, the estimated effect of SO_2 on pneumonia hospital admissions was statistically significant, the RR95%CI = 1.083(1.045,1.122). Another study conducted by Tao et al. in Lanzhou city (2001–2005) [23] indicated that SO_2 was significantly associated with male pneumonia hospital admissions, the RR95%CI = 1.096(1.004, 1.196). However, other study conducted in Nis, Serbia [14] showed that there was no significant association between SO_2 concentration and pneumonia hospital admissions. It may be related to different concentration of SO_2 in different cities. the mean concentration of SO_2 in Nis, Serbia [14] was 8.38 μg/m^3, which was lower than that in Taiyuan (69.34 μg/m^3) [19], and Lanzhou (2001–2005, 79.09μg/m^3) [23], the mean concentration of SO_2 in this study (Lanzhou, 2014–2019) was 21.13 μg/m^3. SO_2 mainly comes from the combustion of coal and other fossil fuels. In recent year, the concentration of SO_2 showed a downward trend in Lanzhou by deploying flue gas desulfurization at power plants, controlling SO_2 industrial emissions and using clean energy in Lanzhou [24], and the average concentration of SO_2 meets the requirements of the secondary standard (60 μg/m^3) in Chinese Ambient Air Quality Standard.

But SO_2 still increased the risk of pneumonia hospital admissions in this study. This practically meant that the lower concentration of SO_2 is also significant. Therefore, stricter and more effective measures must be taken to control the pollution of SO_2 and prevent its adverse effects in Lanzhou city.

In line with previous studies, we found that short-term exposure to NO_2 (the mean concentration: 47.36μg/m^3) is positively associated with the daily rates of pneumonia hospital admissions. Furthermore, the adverse effect of NO_2 on pneumonia hospital admissions was greater than PM, every 10 μg/m^3 increase in NO_2 corresponded to a RR (95%CI) = 1.073(1.052,1.093) increase in pneumonia hospital admissions. An ecological time series analysis in São Paulo [25] using generalized additive model (GAM) to estimate the association between air pollutants and hospital admissions for pneumonia in children, and found that NO_2 (the mean concentration: 56.5μg/m^3) represented a risk factor for lag 1and lag5, and 10 μg/m^3 increments of this pollutant lead to increase of 7% in relative risk. Another time-series study using GAM in Taiyuan [19] to evaluate the association between NO_2 (the mean concentration: 43.41μg/m^3) and respiratory disease hospitalization, found that the highest pneumonia hospital admissions risk was 1.027(1.010,1.044), corresponding to per 10μg/m^3 rise in exposure to NO_2. Yang et al. [6] used DLNM to estimate the effect of NO_2 (the mean concentration: 34.6μg/m^3) on adult pneumonia hospitalization in the coastal city of Qingdao, found that every 10 μg/m^3 increase in NO_2 corresponded to a RR (95%CI) = 1.05(1.01, 1.10) increase in adult pneumonia hospital admissions. Another case-crossover study in Qingdao [26] also found the pneumonia admissions risk was 1.067(1.010, 1.127), corresponding to per 10μg/m^3 rise in NO_2 (the mean concentration: 35.7μg/m^3). The results of above studies are all similar to the present study, that is, NO_2 is a risk factor for pneumonia, but the estimated effects (RR) of the different studies are different. The differences may be due to different study designs, different study areas, various climate, study periods, target population, NO_2 concentration, etc., and it may also be related to different NO_2 emission sources in different regions [22]. However a study conducted in Nis, Serbia [14] showed that NO_2 had no significant effect on pneumonia hospital admissions, the average concentration of NO_2 in Nis, Serbia was 29.24μg/m^3, which is lower than all syudies mentioned above and this study.

At present, studies findings for the effects of O_3 on pneumonia are inconsistent. This study found that 10μg/m^3 increase in $O_3$8h was associated with decreased of pneumonia hospital admissions, the RR95%CI = 0.949(0.935, 0.962), and the association was statistically significant in the cold season, but not in the warm season. this is consistent with studies São Paulo, Brazil [25] and Shenyang [27], Qingdao [6], China. However, an ecological study on the city-specific association between short-term O_3 exposure and hospital admissions for pneumonia in Hong Kong and Taipei [5], a nationwide time-series study on the impact of O_3 on pneumonia hospitalizations in China [7] and a meta-analysis study on short-term association between air pollution and pneumonia hospitalization in children [28] all showed positive association between O_3 and pneumonia hospital admissions, meanwhile, the nationwide study in China [7] found the association of O_3 with pneumonia hospital admissions during warm season were stronger than in cold season. And there are also some studies [6, 19, 21, 29] showing no association between O_3 and pneumonia hospitalizations. In light of the conflicting findings, more work are needed to ascertain the relationship between O_3 and pneumonia hospitalizations.

The toxicity of CO deriving from its stronger ability to bind emoglobin than oxygen, and CO can cause damage to health at high-exposure levels or lower-exposure concentrations [8]. This time series study also found strongest effects of CO on pneumonia hospital admissions in six air pollutants, every 1 mg/m^3 increase in CO corresponded to a RR (95%CI) = 1.157(1.094, 1.223) increase in pneumonia hospital admissions. The findings are similar to previous studies in North Carolina, United States [30], Bangkok, Thailand [31], Ankara, Turkey [32], and other Chinese cities. For instance, a study in Qingdao [6] suggested a statistically significant positive association between CO and pneumonia hospital admissions, and RR(95% CI) of pneumonia hospitalizations for CO at the 95th percentile compared to the 25th percentile was 1.08(1.03,1.14). In Shenyang study conducted by Chang et al. [27], CO showed significant positive association with pneumonia hospital admissions (RR = 1.025%, 95% CI: 1.020, 1.029). A case-crossover study in Shijiazhuang [33] showed significant effects of increased CO on hospitalization for pneumonia, and pneumonia hospital admissions risk was 1.087 (95%CI:1.030–1.148), corresponding to per 1mg/m^3 rise in exposure to CO at lag3 days. The mean concentration of CO was 1.24 mg/m^3 in this study, 0.8 mg/m^3 in Qingdao [6], 1.02 mg/m^3 in Shenyang [27], and 2.04 mg/m^3 in Shijiazhuang [33], the CO concentrations in these cities are all meet the requirements of the primary standard (4 mg/m^3) in Chinese Ambient Air Quality Standard. Like SO_2, CO also had adverse effects on pneumonia at low concentrations.

Rarely studies from China have explored the exposure-response curves between air pollutants and pneumonia hospital admissions. In this time series study, the exposure-response curves showed pneumonia hospital admissions were positively correlated with $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, but negatively correlated with $O_3$8h. All six exposure-response curves were approximate linear with no thresholds. A study in Dongguan [8] examined the association between ambient CO and hospital outpatient visits for pneumonia dieases, and suggested that a general linear relationship between CO concentration and outpatient visits risk for pneumonia. A national time series analysis in 184 cities in China [10] found a slightly nonlinear exposure-response curves between PM and adult pneumonia admissions (aged ≥ 18 years), the curve of the association between $PM_{2.5}$ and adult pneumonia admissions appeared to be a plateau at higher concentrations, and the curve of PM_{10} increased sharply at concentrations below 100 μg/m^3 and then climbed relatively moderately as concentration increased. Another study in Qingdao [6] showed exposure-response curves of six air pollutant and adult pneumonia hospital visits (aged ≥ 14 years) exhibit nonlinear characteristics, and the slopes are steep at low concentrations and level off at high concentrations. The differences in the exposure-response curves are likely associated with different population (inclusion-exclusion criteria), air pollutant characteristics, socioeconomic factors in different regions and periods [6], which worth further study in future.

Existent results on gender difference in air pollution epidemolgy were not uniform, the subgroup analysis in this study suggested that female pneumonia patients were more sensitive to the effects of air pollutants. Some previoue epidemological studies also supported this result [21, 23, 27, 29] which could be related to genetic and biological differences, females have smaller respiratory tract diameters and female may have weaker lung immunity and be more vulnerable to air pollution. However, some inconsistent results have been reported, some studies confirmed that male for pneumonia were more vulnerable to air pollution than female [14, 15, 33], which could be related to male's occupation such as industry or taxi driving or more outdoor activities, poorer awareness of occupational protection, and smoking, drinking, and other unhealthy habits, therefore there is higher susceptibility to pneumonia after exposure to air pollution. Even some other studies showed that air pollution effects on pneumonia hospital admissions were similar for males and females [3, 7, 10]. Gender differences in associations of air pollutants with pneumonia hospitalization remains to be further explored.

Age-stratified analyses in this study suggested that 0–14 years age group (children) was more sensitive to all six air pollutants than other two age groups, which is consitent with other similar studyies conducted in China [3, 26, 34], as well as in Euroupean country [14]. This result maybe related to children spending more time at outdoor activities which make them exposed to more atmospheric pollution, and their high breathing rate, narrow airways, and developing lungs and immune systems [34], which finally leads to their high sensitivity to the air pollutants. However, there are also different findings showing that the elderly (≥ 65 years old) are more sensitive to air pollutants due to poor immune function and comorbidity [5, 27, 33]. Most studies had inconsistent results in terms of age-stratified analyses, the possible reason for this might be due to the different demographics in different regions, the inclusion-exclusion criteria, the different composition of air pollutants, diversity of climatic and topographic conditions, and the number of cases in various studies. And age differences in associations of air pollutants with pneumonia hospitalization remains to be further explored too.

The season-specific analysis in this study indicated that the relationship between pneumonia hospital admissions and $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO were statistically significant in the cold season, but not in the warm season, that is to say, the associations of air pollutants with pneumonia hospital admissions during the cold season were stronger than in the warm season. The findings are consitent with most studies on the relationship between air pollutants and pneumonia hospitalization, such as studies in Shenzhen ($PM_{2.5}$) [3], Qingdao (five pollutants except O_3) [6, 26], Shijiazhuang ($PM_{2.5}$ and PM_{10}) [33], Taiwan ($PM_{2.5}$ and NO_2) [21], China, and in Turkey [32]. However a study in Jinan [34] showed that children was at statistically significant risk of hospital admission for pneumonia due to PM, particularly on warm days. Lanzhou is located in northwest China with stable stratification especially inversion and coal using (from November to March of the following year) in cold season, which blocks the air streams and makes the pollutants difficult to disperse [17], those increase the level of air pollution in cold season. And this may explain why we found the greater harmful effects of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO on pneumonia hospital admissions in cold season.

The present study has a few advantages compared with previous studies. For example, this study systematically analyzed whether the relationship between all six air pollutants and pneumonia hospital admissions were affected by gender, age or season, and the exposure-response curves of air pollutants with pneumonia hospital admissions were also analyzed in this study. Those may provide more convincing evidence in the association between air pollutants and pneumonia. In addition, compared with the traditional model, we used DLNM to explore the relationships among exposure, lag effect, and pneumonia hospital admissions comprehensively, and this was the first study to analyze the relationship between air pollutants and pneumonia hospital admissions in Lanzhou, China.

Some limitations should nevertheless be recognized. Firstly, this time-series study is an ecological study, so there may be ecological fallacy for the following reasons: the exposure levels to air pollutants were only averaged levels and not the true exposure levels of individual; the individual-level confounders such as smoking, drinking, occupational history, indoor stay time, and daily ventilation time, etc. cannot be controlled. So this study is helping us to generate the etiological hypothesis, but caution should be used in causal inference. Secondly, these data only come from Lanzhou city, and the potential spatial heterogeneity of the health effects of air pollutants in multiple cities is worthy for further study.

Conclusions

In summary, this study found that daily pneumonia hospital admissions were positively associated with $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, but negitive associated with $O_3$8h. The adverse effects for all gaseous pollutants except $O_3$8h on pneumonia hospital admissions were stronger than particulate matter. All six exposure-response curves were approximate linear with no thresholds. Female and children (0–14 years age group) were more sensitive to the effects of air pollutants, particularly in cold season.

Declarations

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Authors' contributions

Limei Jin: Conceptualization; Data collection, data compilation, data analysis; Methodology; Writing original draft; Graphics. Shuya Fang and Xiaowen Zhou: Data collection, data analysis; Collating and checking data; Graphics. Bisen Han: Data collection; Checking data. Tian Zhou: Conceptualization; Data collection; the manuscript revises. Yana Bai: Conceptualization; Data collection. All gave final approval and agree to be accountable for all aspects of work ensuring integrity and accuracy.

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Availability of data and materials

Data will be available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

Not applicable.

Compliance with ethical standards

Competing interests

The authors declare that they have no competing interests.

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References

1. Collaborators GRF. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet. 2020; 396(10258):1223–49. https://doi.org/10.1016/s0140-6736(20)30752-2.
2. Jia H, Liu Y, Guo D, He W, Zhao L, Xia S. $PM_{2.5}$-induced pulmonary inflammation via activating of the NLRP3/caspase-1 signaling pathway. Environ Toxicol. 2021; 36(3):298–307. https://doi.org/10.1002/tox.23035.
3. Zhang Y, Ding Z, Xiang Q, Wang W, Huang L, Mao F. Short-term effects of ambient PM_1 and $PM_{2.5}$ air pollution on hospital admission for respiratory diseases: Case-crossover evidence from Shenzhen, China. Int J Hyg Environ Health. 2020; 224:113418. https://doi.org/10.1016/j. ijheh.2019.11.001.
4. Dong J, Wang Y, Wang J, Bao H. Association between atmospheric $PM_{2.5}$ and daily outpatient visits for children's respiratory diseases in Lanzhou. Int J Biometeorol. 2021; 65(7):989–99. https://doi.org/10.1007/s00484-021-02080-6.
5. Qiu H, Chuang KJ, Bai CH, Fan YC, Chang TP, Yim SH, et al. Association of ambient ozone with pneumonia hospital admissions in Hong Kong and Taipei: a tale of two Southeast Asian cities. Environ Int. 2021; 156:106634. https://doi.org/10.1016/j.envint.2021.106634.
6. Yang L, Yang J, Liu M, Sun X, Li T, Guo Y, et al. Nonlinear effect of air pollution on adult pneumonia hospital visits in the coastal city of Qingdao, China: a time-series analysis. Environ Res. 2022; 209:112754. https://doi.org/10.1016/j.envres.2022.112754.
7. Tian Y, Wu Y, Liu H, Si Y, Wu Y, Wang X, et al. The impact of ambient ozone pollution on pneumonia: a nationwide time-series analysis. Environ Int. 2020; 136:105498. https://doi.org/ 10.1016/j.envint.2020.105498.
8. Zhao Y, Hu J, Tan Z, Liu T, Zeng W, Li X, et al. Ambient carbon monoxide and increased risk of daily hospital outpatient visits for respiratory diseases in Dongguan, China. Sci Total Environ. 2019; 668:254–60. https://doi.org/10.1016/j.scitotenv.2019.02.333
9. Top 20 Pneumonia Facts—2019. American Thoracic Society. Available from: https://www.thoracic.org/patients/patient-resources/resources/top-pneumonia-facts.pdf.
10. Tian Y, Liu H, Wu Y, Si Y, Li M, Wu Y, et al. Ambient particulate matter pollution and adult hospital admissions for pneumonia in urban China: a national time series analysis for 2014 through 2017. PLoS Med. 2019; 16(12):e1003010. https://doi.org/10.1371/journal. pmed.1003010/.
11. Croft DP, Zhang W, Lin S, Thurston SW, Hopke PK, Masiol M, et al. The association between respiratory infection and air pollution in the setting of air quality policy and economic change. Ann Am Thorac Soc. 2019; 16(3):321–30. https://doi.org/10.1513/AnnalsATS.201810-691OC.
12. Neupane B, Jerrett M, Burnett RT, Marrie T, Arain A, Loeb M. Long-term exposure to ambient air pollution and risk of hospitalization with community-acquired pneumonia in older adults. Am J Respir Crit Care Med. 2010; 181(1):47–53. https://doi.org/ 10.1164/rccm.200901-0160OC. Epub 2009 Oct 1. https://doi.org/10.1164/rccm.200901-0160OC.
13. Chaves LE, Nascimento LFC, Rizol P. Fuzzy model to estimate the number of hospitalizations for asthma and pneumonia under the effects of air pollution. BMC public health 2017, 51:55. https://doi.org/10.1590/S1518-8787.2017051006501.
14. Stosic L, Dragic N, Stojanovic D, Lazarevic K, Bijelovic S, Apostolovic M. Air pollution and hospital admissions for respiratory diseases in Nis, Serbia. Pol J Environ Stud. 2021; 30(5):4677–86. https://doi.org/10.15244/pjoes/132796.
15. Priyankara S, Senarathna M, Jayaratne R, Morawska L, Abeysundara S, Weerasooriya R, et al. Ambient $PM_{2.5}$ and PM_{10} exposure and respiratory disease hospitalization in Kandy, Sri Lanka. Int J Environ Res Public Health. 2021; 18(18):9617. https://doi.org/10.3390/ijerph18189617
16. Liu J, Li Y, Li J, Liu Y, Tao N, Song W, et al. Association between ambient PM2.5 and children's hospital admissions for respiratory diseases in Jinan, China. Environ Sci and Pollut Research International. 2019; 26(23):24112–20. https://doi.org/10.1007/s11356-019-05644-7.
17. Dong J, Liu Y, Bao H. Revalue associations of short-term exposure to air pollution with respiratory hospital admissions in Lanzhou, China after the control and treatment of current pollution. Int J Hyg Environ Health. 2021; 231:113658. https://doi.org/ 10.1016/j.ijheh.2020.113658.

18. Sofwan NM, Mahiyuddin WRW, Latif MT, Ayub NA, Yatim ANM, Mohtar AAA, et al. Risks of exposure to ambient air pollutants on the admission of respiratory and cardiovascular diseases in Kuala Lumpur. Sustainable Cities and Society. 2021; 75:103390. https://doi.org/10.1016/j.scs.2021.103390.
19. Luo L, Zhang Y, Jiang J, Luan H, Yu C, Nan P, et al. Short-term effects of ambient air pollution on hospitalization for respiratory disease in Taiyuan, China: A time-series analysis. Int J Environ Res Public Health. 2018; 15(10):2160. https://doi.org/10.3390/ijerph15102160.
20. Bao H, Dong J, Liu X, Tan E, Shu J, Li S. Association between ambient particulate matter and hospital outpatient visits for chronic obstructive pulmonary disease in Lanzhou, China. Environ Sci Pollut Res Int. 2020; 27(18):22843–54. https://doi.org/10.1007/s11356-020-08797-y.
21. Cheng CY, Cheng SY, Chen CC, Pan HY, Wu KH, Cheng FJ. Ambient air pollution is associated with pediatric pneumonia: a time-stratified case-crossover study in an urban area. Environ Health. 2019; 18(1):77. https://doi.org/10.1186/s12940-019-0520-4.
22. Jin LM, Zhou T, Fang SY, Zhou XW, Bai YN. Association of air pollutants and hospital admissions for respiratory diseases in Lanzhou, China, 2014–2019. Environ Geochem Health. 2022; Online ahead of print:1–19. https://doi.org/10.1007/s10653-022-01256-2.
23. Tao Y, Mi S, Zhou S, Wang S, Xie X. Air pollution and hospital admissions for respiratory diseases in Lanzhou, China. Environ Pollut. 2014; 185:196–201. https://doi.org/ 10.1016/j.envpol.2013.10.035.
24. Wang Z, Shi X, Pan C, Wang S. Spatial and temporal characteristics of environmental air quality and its relationship with seasonal climatic conditions in Eastern China during 2015–2018. Int J Environ Res Public Health. 2021; 18(9):4524. https://doi.org/ 10.3390/ijerph18094524
25. Souza LS, Nascimento LF. Air pollutants and hospital admission due to pneumonia in children: a time series analysis. Rev Assoc Med Bras. 2016; 62(2):151–6. https://doi.org/10.1590/1806-9282.62.02.151.
26. Zhang J, Ren D, Cao X, Wang T, Geng X, Li X, et al. Ambient air pollutants and hospital visits for pneumonia: a case-crossover study in Qingdao, China. BMC Public Health. 2021; 21(1):66. https://doi.org/ 10.1186/s12889-020-10065-0.
27. Chang Q, Zhang H, Zhao Y. Ambient air pollution and daily hospital admissions for respiratory system-related diseases in a heavy polluted city in Northeast China. Environ Sci Pollut Res Int. 2020; 27(9):10055–64. https://doi.org/10.1007/s11356-020-07678-8.
28. Nhung NTT, Amini H, Schindler C, Kutlar Joss M, Dien TM, Probst-Hensch N, et al. Short-term association between ambient air pollution and pneumonia in children: A systematic review and meta-analysis of time-series and case-crossover studies. Environ Pollut. 2017; 230:1000–8. https://doi.org/10.1016/j.envpol.2017.07.063.
29. Wang HT, Zhang H, Xue FZ, Zhao L, Cao WC. Associations of air pollutants with pneumonia hospital admissions in Qingdao, China: a prospective cohort study. Environ Sci Pollut Res Int. 2022; 29(19):27779–87. https://doi.org/ 10.1007/s11356-021-17892-7.
30. Kravchenko J, Akushevich I, Abernethy AP, Holman S, Ross WG, Lyerly HK. Long-term dynamics of death rates of emphysema, asthma, and pneumonia and improving air quality. Int J Chron Obstruct Pulmon Dis. 2014; 9:613–27. https://doi.org/10.2147/copd.s59995.
31. Phosri A, Ueda K, Phung VLH, Tawatsupa B, Honda A, Takano H. Effects of ambient air pollution on daily hospital admissions for respiratory and cardiovascular diseases in Bangkok, Thailand. Sci Total Environ. 2019; 651(Pt 1):1144–53. https://doi.org/ 10.1016/j.scitotenv.2018.09.183.
32. Tasci SS, Kavalci C. Relationship of meteorological and air pollution parameters with pneumonia in elderly patients. Emerg Med Int. 2018; 2018:4183203. https://doi.org/ 10.1155/2018/4183203.
33. Duan Z, Han X, Bai Z, Yuan Y. Fine particulate air pollution and hospitalization for pneumonia: a case-crossover study in Shijiazhuang, China. Air Qual Atmos Health. 2016; 9(7):723–33. https://doi.org/10.1007/s11869-015-0383-y.
34. Lv C, Wang X, Pang N, Wang L, Wang Y, Xu T, et al. The impact of airborne particulate matter on pediatric hospital admissions for pneumonia among children in Jinan, China: A case-crossover study. J Air Waste Manag Assoc. 2017; 67(6):669–76. https://doi.org/10.1080/10962247.2016.1265026.

Tables

Table 1. Descriptive statistics of hospital admissions for pneumonia in Lanzhou City, 2014–2019

	Daily hospital admissions						Total of hospital admissions
	Mean±SD	*Min*	P_{25}	P_{50}	P_{75}	*Max*	
All	9±6	0	4	8	13	37	20071
Gender							
Male	5±4	0	2	4	7	24	11539
Female	4±3	0	2	3	6	20	8532
Age							
0-14 years	6±5	0	2	5	8	29	12713
15-64 years	1±1	0	0	1	2	9	2957
≥65 years	2±2	0	1	2	3	11	4401
Season							
Cold	11±7	0	6	10	16	37	12306
Warm	7±5	0	4	6	10	27	7765

Table 2. The coefficient of spearman rank correlation (*r*) between daily pneumonia hospital admissions, air pollutants and meteorological data in Lanzhou, 2014-2019

	pneumonia	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_38h	CO	Temperature	Relative humidity (RH)
pneumonia	1.000	0.081*	0.073*	0.132*	0.310*	-0.081*	0.040	-0.335*	-0.015
$PM_{2.5}$		1.000	0.857*	0.659*	0.454*	-0.414*	0.715*	-0.511*	-0.135*
PM_{10}			1.000	0.580*	0.435*	-0.220*	0.552*	-0.373*	-0.381*
SO_2				1.000	0.494*	-0.483*	0.799*	-0.639*	-0.250*
NO_2					1.000	-0.044^{D}	0.567*	-0.281*	-0.167*
O_38h						1.000	-0.478*	0.643*	-0.303*
CO							1.000	-0.540*	-0.038
Temperature								1.000	-0.012
RH									1.000

Note. $^{*}P<0.0001$, ^{D} $P=0.041<0.05$

Table 3. RR (95% CIs) of pneumonia hospital admissions with an increase of 10μg/m^3 in air pollutants (and 1 mg/m^3 in CO) in Lanzhou, China, 2014-2019: single-pollutant models

Lag days	$PM_{2.5}$			PM_{10}			SO_2			NO_2			O_38h			C
	RR	95% CI		RR	95% CI		RR	95% CI		RR	95% CI		RR	95% CI		R
lag0	1.012	(1.002,	1.022)	1.002	(1.000,	1.005)	1.023	(0.998,	1.048)	1.017	(1.003,	1.031)	0.991	(0.982,	0.999)	1
lag1	1.000	(0.990,	1.010)	0.999	(0.996,	1.002)	1.006	(0.980,	1.033)	0.999	(0.985,	1.014)	0.990	(0.981,	0.999)	1
lag2	1.006	(0.999,	1.013)	1.001	(0.999,	1.003)	1.018	(1.000,	1.036)	1.019	(1.009,	1.029)	0.997	(0.990,	1.004)	1
lag3	1.003	(0.998,	1.008)	1.001	(1.000,	1.002)	1.004	(0.992,	1.015)	1.011	(1.004,	1.017)	0.996	(0.992,	1.001)	1
lag4	1.001	(0.996,	1.005)	1.001	(0.999,	1.002)	0.993	(0.981,	1.005)	1.000	(0.994,	1.007)	0.994	(0.989,	0.998)	0
lag5	1.002	(0.998,	1.007)	1.001	(1.000,	1.002)	0.997	(0.986,	1.008)	1.000	(0.994,	1.006)	0.993	(0.988,	0.997)	0
lag6	1.007	(1.004,	1.010)	1.002	(1.001,	1.003)	1.012	(1.004,	1.020)	1.007	(1.003,	1.011)	0.993	(0.990,	0.997)	1
lag7	1.013	(1.006,	1.020)	1.003	(1.001,	1.004)	1.032	(1.015,	1.049)	1.017	(1.008,	1.027)	0.994	(0.987,	1.001)	1
lag01	1.012	(1.001,	1.022)	1.001	(0.999,	1.004)	1.029	(1.003,	1.056)	1.016	(1.002,	1.030)	0.980	(0.971,	0.990)	1
lag02	1.017	(1.007,	1.028)	1.002	(1.000,	1.005)	1.047	(1.021,	1.074)	1.036	(1.022,	1.050)	0.978	(0.967,	0.988)	1
lag03	1.021	(1.009,	1.032)	1.003	(1.000,	1.006)	1.051	(1.022,	1.081)	1.047	(1.031,	1.063)	0.974	(0.963,	0.985)	1
lag04	1.021	(1.009,	1.033)	1.004	(1.001,	1.007)	1.044	(1.015,	1.073)	1.047	(1.031,	1.064)	0.968	(0.956,	0.979)	1
lag05	1.023	(1.010,	1.037)	1.005	(1.002,	1.008)	1.041	(1.010,	1.073)	1.047	(1.029,	1.066)	0.961	(0.949,	0.973)	1
lag06	1.031	(1.017,	1.045)	1.007	(1.003,	1.010)	1.053	(1.021,	1.086)	1.054	(1.036,	1.074)	0.954	(0.942,	0.967)	1
lag07	1.044	(1.029,	1.060)	1.009	(1.005,	1.013)	1.086	(1.053,	1.121)	1.073	(1.052,	1.093)	0.949	(0.935,	0.962)	1

Table 4 Sensitivity analysis of association between pneumonia hospital admissions and air pollutants (per 10 μg/m^3 increase and 1 mg/m^3 increase in CO): controlling for different degrees of freedom (*df*) for time [a]

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_38h	CO
df=6	1.050(1.034,1.065)	1.011(1.007,1.015)	1.100(1.067,1.135)	1.081(1.061,1.102)	0.942(0.929,0.955)	1.189(1.126,1.256)
df=7	1.044(1.029,1.060)	1.009(1.005,1.013)	1.086(1.053,1.121)	1.073(1.052,1.093)	0.949(0.935,0.962)	1.157(1.094,1.223)
df=8	1.051(1.035,1.067)	1.010(1.006,1.014)	1.087(1.054,1.121)	1.071(1.051,1.092)	0.949(0.936,0.962)	1.162(1.099,1.228)
df=9	1.046(1.031,1.062)	1.010(1.006,1.014)	1.055(1.022,1.090)	1.060(1.039,1.081)	0.955(0.942,0.969)	1.112(1.050,1.177)
df=10	1.051(1.035,1.067)	1.010(1.006,1.014)	1.087(1.054,1.122)	1.071(1.050,1.091)	0.949(0.936,0.963)	1.164(1.100,1.232)

Note. [a] Results obtained from single-pollutant models for lag07 day

Figures

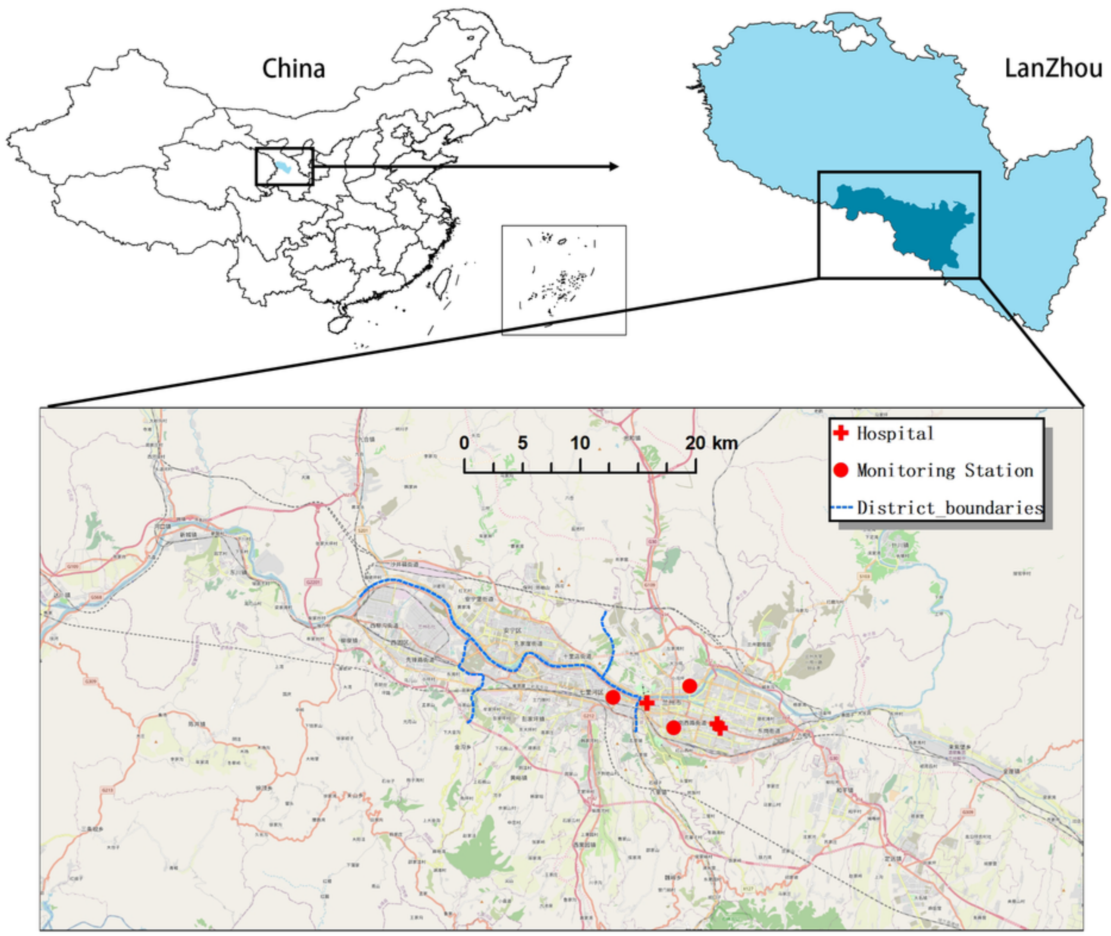

Figure 1

The locations of Lanzhou in China, hospitals, and air pollutants monitoring stations.

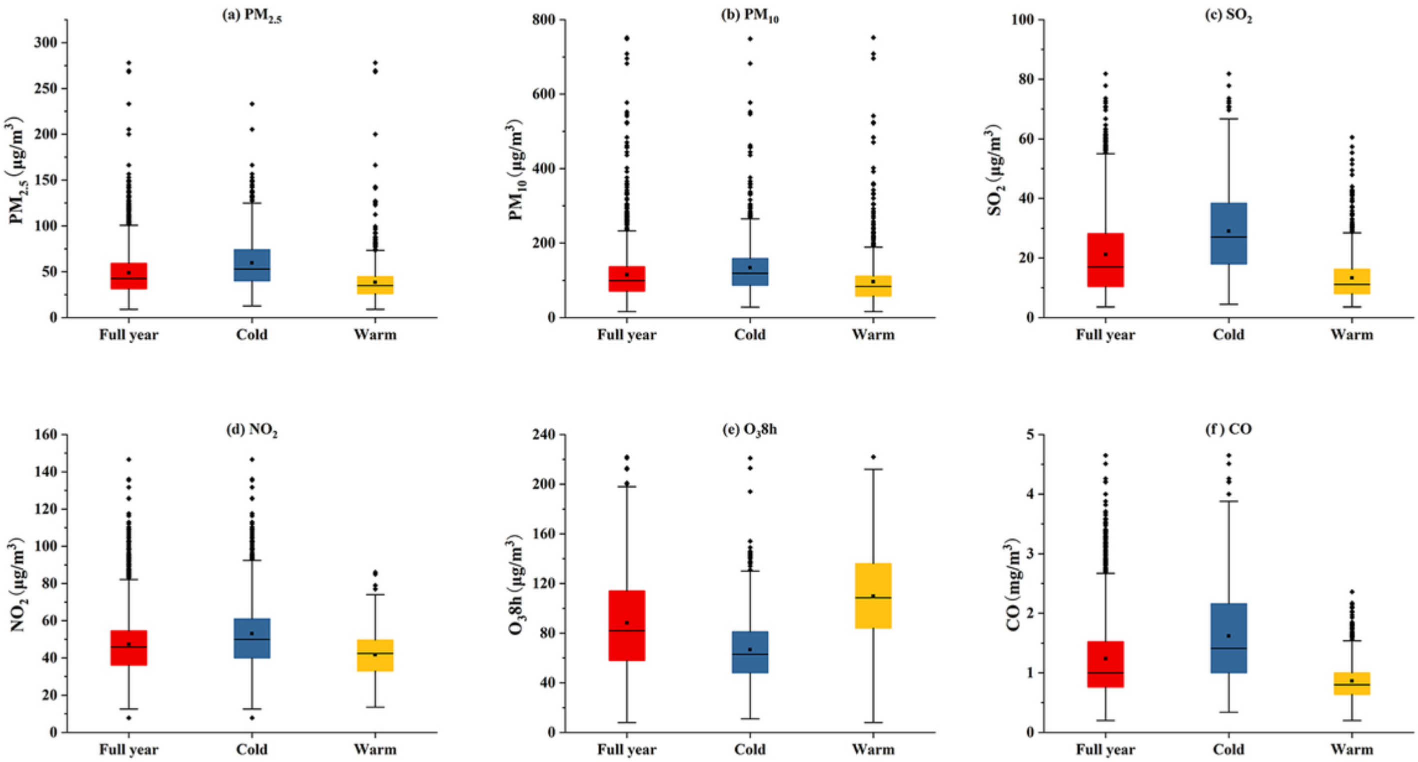

Figure 2

Box plots of the concentrations of air pollutants by season in Lanzhou, China, 2014–2019. The black squares represent the average concentrations, the middle line of the color boxes represent the median values, the top and bottom lines of the color boxes represent P_{25} and P_{75}, respectively, with the color boxes representing the interquartile range (IQR=P_{75}-P_{25}). The black lines above and below the color boxes indicate the upper (P_{75}+1.5IQR) and lower (P_{25}-1.5IQR) range, and with outliers marked by black diamonds.

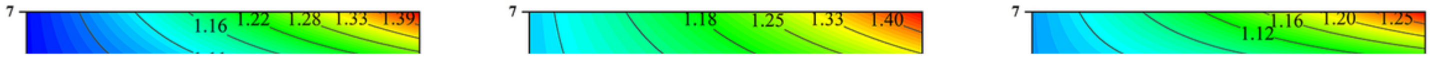

Figure 3

Contour plots of relative risks (RRs) in pneumonia hospital admissions associated with air pollutants concentrations along single-pollutant models at single lag days

Figure 4

Exposure-response curves between air pollutants and pneumonia hospital admissions at lag07

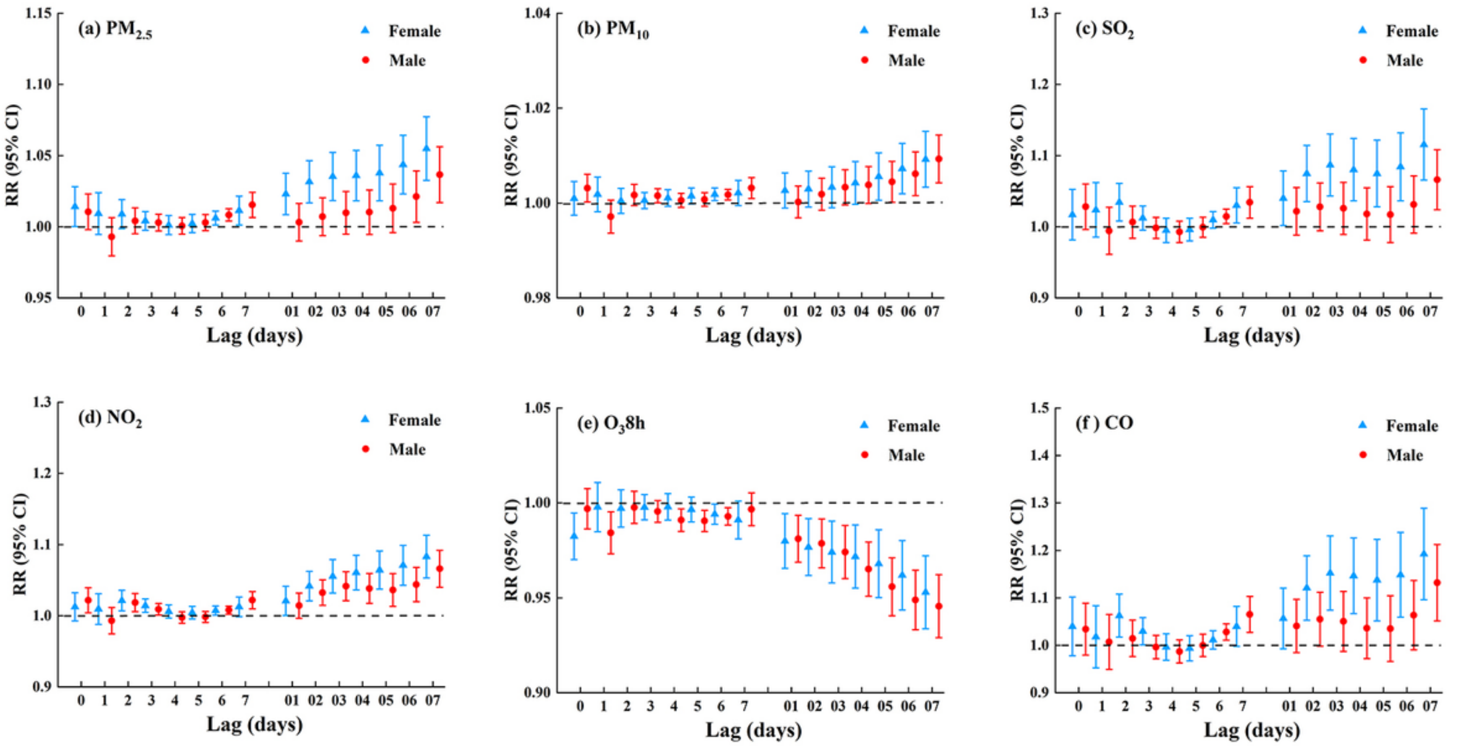

Figure 5

RRs (95% CI) of pneumonia hospital admissions associated with air pollutants (per 10 μg/m^3 increase and 1 mg/m^3 increase in CO) at various lags by gender in single pollutant model.

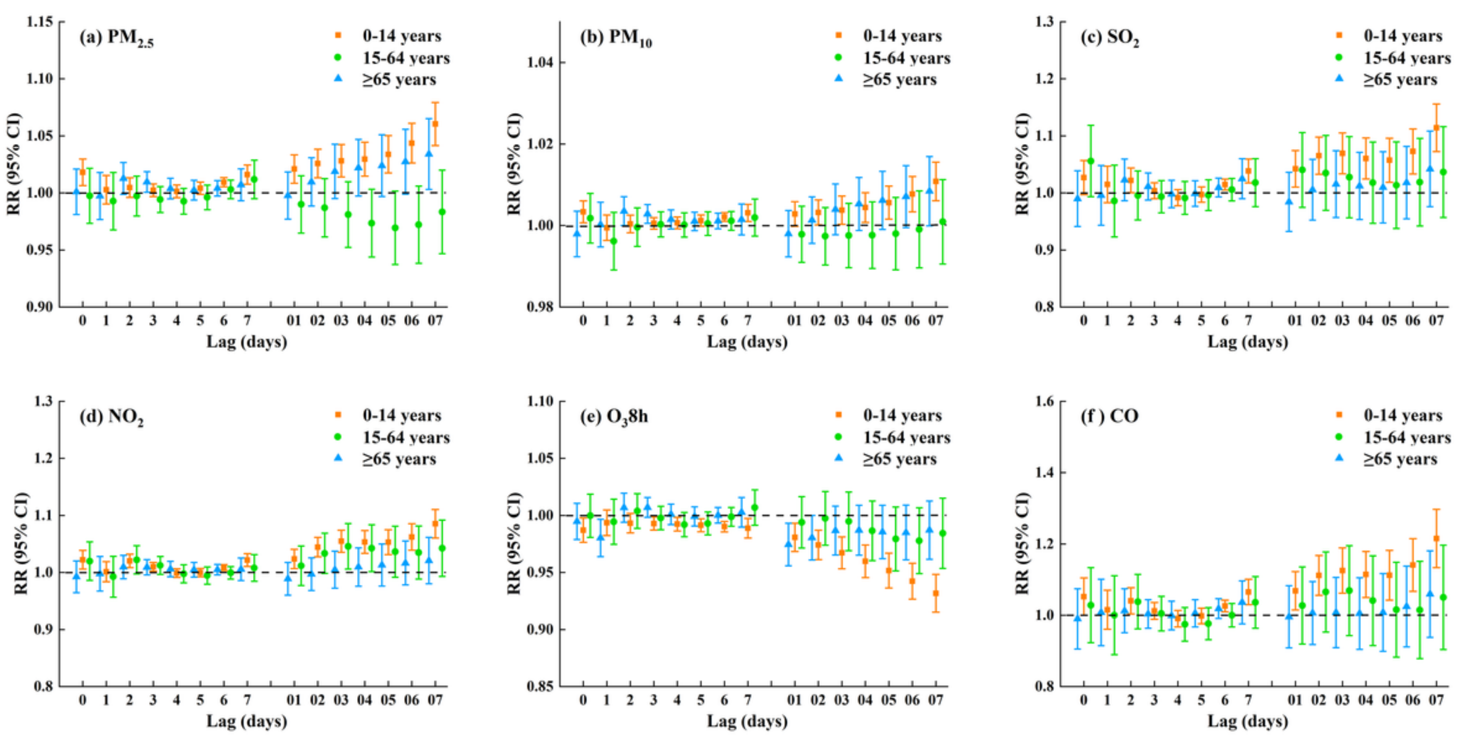

Figure 6

RRs (95% CI) of pneumonia hospital admissions associated stratified by age in single pollutant model.

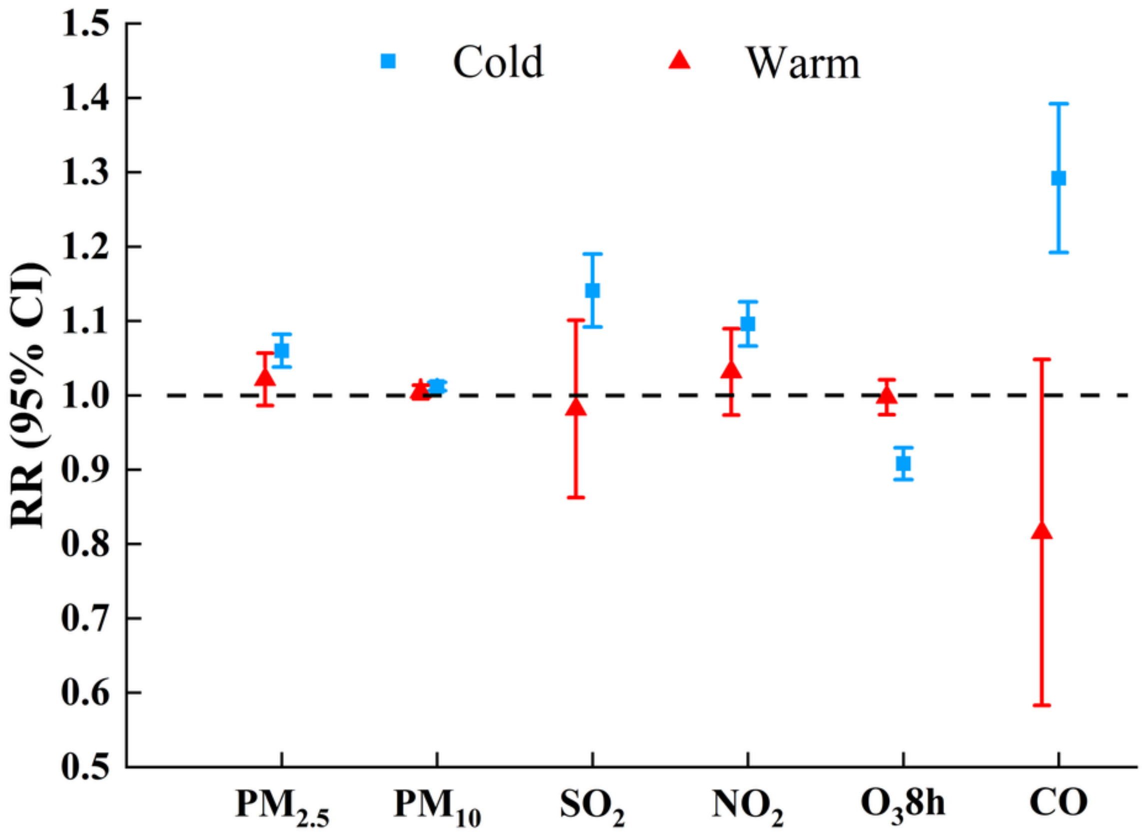

Figure 7

RRs (95% CIs) of pneumonia hospital admissions with an increase of 10μg/m^3 in air pollutants (1 mg/m^3 in CO) at lag07 by season in single pollutant model.

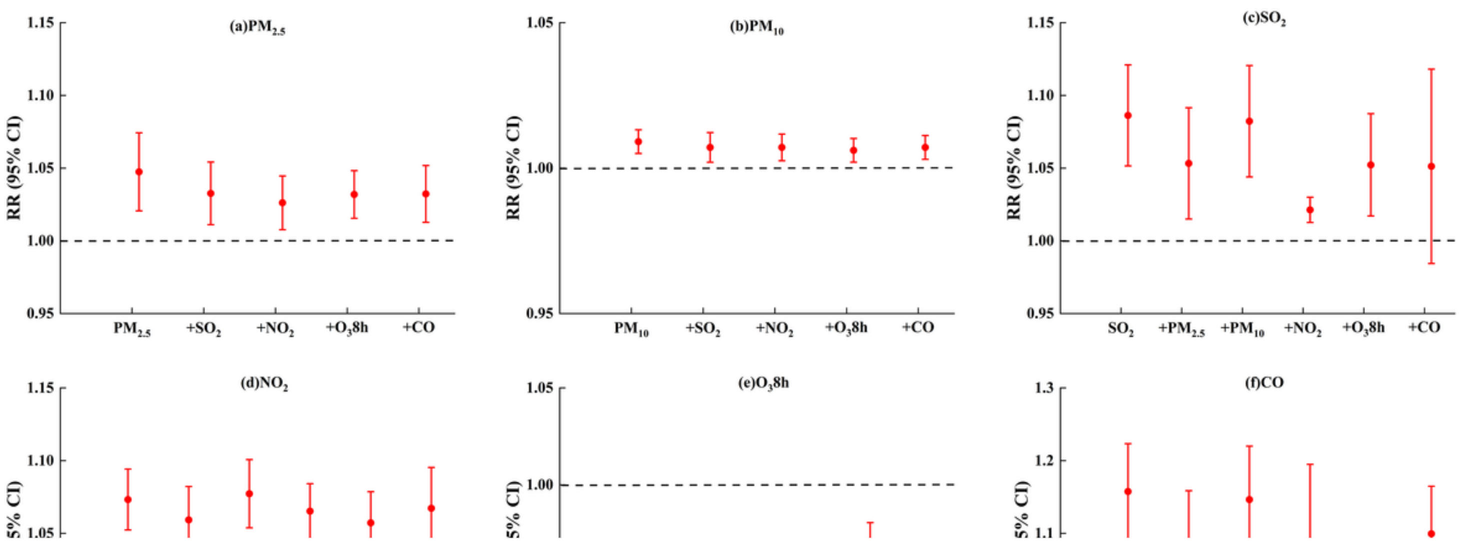

Figure 8

RR (95% CIs) of associations between pneumonia hospital admissions and air pollutants (per 10 μg/m^3 increase and 1 mg/m^3 increase in CO) at lag07 from single-pollutant and two-pollutant models

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementalMaterials.docx