# Effect of Ambient Fine Particulate (PM2.5) on Hospital Admissions for Respiratory and Cardiovascular Diseases in Wuhan, China

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**Research**

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# Abstract

**Background:** The positive associations between ambient $PM_{2.5}$ and cardiorespiratory disease have been well demonstrated during the past decade. However, few studies have examined the adverse effects of $PM_{2.5}$ based on an entire population of megalopolis. In addition, due to the lack of accurate methods of assessing individual $PM_{2.5}$ exposure, further studies are still necessary to be launched in China.

**Methods:** The study was conducted in Wuhan, a megacity in central China with about 10.8929 million population. Daily hospital admission records, from October 2016 to December 2018, were obtained from Wuhan Information center of Health and Family Planning, which administrates all the hospitals in Wuhan. The daily air pollution concentration and weather variable in Wuhan during the study period were collected. We developed Land use regression model (LUR) to assess individual $PM_{2.5}$ exposure. Time-stratified case-crossover design and conditional logistic regression models were adopted to estimate cardiorespiratory hospitalization risks associated with short-term exposures to $PM_{2.5}$. We also conducted stratification analyses by age, sex and season.

**Results:** A total of 2,806,115 hospital admissions records were collected during the study period, from which we identified 332,090 for total cardiovascular diseases and 159,365 for total respiratory diseases. We found short-term $PM_{2.5}$ exposure was associated with increased risk of cardiorespiratory hospital admission in Wuhan. Per 10 $\mu g/m^3$ increase of $PM_{2.5}$ at lag0~2 days was associated with 1.23% (95%CI: 1.01–1.45%) and 1.95% (95%CI: 1.63–2.27%) elevated risk of admission from cardiovascular and respiratory diseases respectively. The elderly were at higher PM-induced risks. The associations appeared to be more evident in the cold season than in the warm season.

**Conclusions:** This study contributed evidence to support the short-term effects of $PM_{2.5}$ on cardiorespiratory hospital admission, which may be helpful for air pollution control and disease prevention in Wuhan.


# Background

Air pollution has remained as an important global health issue [1]. Numerous epidemiology studies have proved that $PM_{2.5}$, particle matter with aerodynamic diameter less than 2.5 μm, is a vital contributor leading to increased mortality and morbidity [2, 3]. According to the analysis of Global Burden of Diseases Study, an approximate of 2.94 million deaths and 10.5 million disability-adjusted life-years (DALYs) globally were attributable to ambient particulate matter pollution, making it the eighth leading risk for deaths [4].

Previous studies have provided strong evidence of the harm effect of $PM_{2.5}$ on cardiorespiratory diseases [5, 6]. Although several large-scale studies, conducted in western developed countries [7, 8], have examined the associations between air pollution and cardiorespiratory hospital admissions. These results may not be applicable to developing countries due to local climate conditions, PM chemical components and population susceptibility. In China, several large-scale analyses have shed light on partial associations [9, 10]. However, the study population of these studies were obtained by specific sampling methods and may not represent the entire population. Some single-center epidemiological studies have been conducted in several large cities in China [11, 12], but the hospital admission data of these studies were collected from a limited number of hospitals, which may introduce selection bias. Therefore, studies that examine the association between $PM_{2.5}$ and cardiorespiratory hospital admissions based on all citizens of specific city are needed to better understand the real impact of ambient fine particulate matter in China.

Exposure assessment methods are crucial for epidemiological studies. Commonly used air pollution assessment methods include monitoring data derived from fixed stations, Dispersion Models (DM), atmospheric Chemical Transport Models (CTMs) and Land Use Regression (LUR) [13, 14]. Most studies estimated individual exposure to air pollution using the ambient concentrations derived from fixed stations, which lacks spatial and temporal resolution. Conventional DM and CTMs require various data with high precision, which makes the simulation process complicated and high-cost [15]. Compared with above methods, LUR model, using land use, geographic, and traffic characteristics to explain spatial variations of air pollution concentrations, has been proven to be a cost-effective method of air pollution exposure assessment. With the development of geographic information system (GIS) technology, LUR has achieved great success mainly in Europe and North America [16, 17]. In China, however, only few studies have applied LUR models in epidemiological studies.

Therefore, this study was conducted based on the admission data of all hospitals in Wuhan, from October 2016 to December 2018. Considering Wuhan's universal access to hospital health care, our study can well represent the real impact of ambient $PM_{2.5}$ among the whole citizen. Furthermore, LUR models were developed to better capture individual $PM_{2.5}$ exposure. The objective of this analysis was to examine the association between $PM_{2.5}$ and cardiorespiratory hospital admissions.

## Methods

# Study area

With a land area of 8569.15 $km^2$ and a population of about 10.8929 million (Wuhan Statistical Yearbook-2018), Wuhan (29.58°N to 31.22°N, 113.41°E to 115.05°E) is the capital city of Hubei Province and the megacity in central China. Due to its subtropical, monsoon climate, Wuhan has a typical weather featuring in distinct seasons and abundant rainfall. The major sources of air pollution in the city are biomass, coal combustion, steel manufacture, smelting, and vehicle emissions [18].

# Case Ascertainment

Daily hospitalization records were obtained from Wuhan Information center of Health and Family Planning (http://wjw.wuhan.gov.cn/) between Oct 1, 2016 and Dec 31, 2018. Wuhan Information center of Health and Family Planning is a hospital authority within the municipal Bureau of Health, to which all the hospitals in Wuhan have to report their information of hospital infrastructure, medical service and management. All of the public hospitals (university affiliated hospital, regional hospital, provincial hospital and so on), a total of 59 municipal hospitals, were included in this study. From each record, we extracted de-identified patients age, sex, home address and primary diagnosis. The diagnoses were made by licensed specialized physicians according to current clinical guidelines. Cardiorespiratory hospital admissions in the present study were identified based on the primary diagnosis according to the International Classification of Diseases, 10th Revision (ICD-10): total cardiovascular disease (CVD, I00–I99), hypertension (I10–I15), coronary heart disease (CHD, I20–I25), stroke (I60–I69), total respiratory disease (I00–I99), and chronic obstructive pulmonary disease (COPD, J41–J44). A total of 2,806,115 hospital admission records were collected during the study period, from which we identified 332,090 for total cardiovascular diseases and 159,365 for total respiratory diseases. Specific inclusion and exclusion process are outlined in Figure S1.

# Air pollutant data

During the study period, the air pollution data were collected from the Wuhan Environmental Protection Bureau (http://hbj.wuhan.gov.cn/), which established 20 ambient air quality monitoring stations in the 13 districts of Wuhan city. To calculate daily 24-h concentrations, ≥75% of the 1-h values must have been available on that particular day; To calculate the annual concentration, there must be at least 324 daily values available. Four stations were excluded if the above criteria was not met. Finally, daily 24-hour average concentration data for $PM_{2.5}$ (unit, μg/$m^3$), $PM_{10}$ (unit, μg/$m^3$), sulfur dioxide ($SO_2$) (unit, μg/$m^3$), nitrogen dioxide ($NO_2$) (unit, μg/$m^3$) and carbon monoxide (CO) (unit, mg/$m^3$) during the study period were collected from 16 air quality monitoring stations (Figure 1). Daily meteorological data including mean temperature (°C) and relative humidity (%) during the study period were collected from the China Meteorological Data Network (http://data.cma.cn/).

# LUR model

In this study, The LUR model was constructed by combining measurements of $PM_{2.5}$ from fixed-site monitors with a range of geographic predictors. The detailed model building process was described in the supplementary material (Table S1).

Final models were represented with 1 km spatial resolution. Kriging interpolation method was used to transform predicted $PM_{2.5}$ data from monitors into concentration maps (Figure 1). We then extrapolated annual-mean $PM_{2.5}$ concentrations from the LUR model to daily levels, following the method described in previous studies [19]. Briefly, we geocoded individual addresses and assigned the annual average $PM_{2.5}$

concentrations from the LUR models to each individual. Daily $PM_{2.5}$ concentration assigned to each subject was adjusted by the ratio of daily-specific $PM_{2.5}$ concentrations to the estimated annual average $PM_{2.5}$ concentrations at the nearest monitor.

# Statistical design

The case-crossover (CCO) design was first proposed by Maclure [20] to study transient effects on the risk of acute events. As each subject serves as his or her own control, this type of study controls for the influence of self-confounding variables that remain constant.

In this study, we performed a time-stratified case-crossover study design to evaluate associations between short-term $PM_{2.5}$ exposures and cardiorespiratory hospital admission in Wuhan. The case day was defined as the day of hospital admission and the control days were identified by matching the day of the week (DOW) within the same year and month. By virtue of this design, the potential confounding effects by long-term trend, seasonality can be well eliminated.

# Analytic model

We used conditional logistic regression (CLR) model to obtain estimates of the odds ratios (ORs) and 95% confidence intervals (CIs) for the effect of $PM_{2.5}$ exposures on cardiorespiratory hospital admission. As controlling covariates, we applied a natural cubic spline (NCS) function with 3 degrees of freedom (df) for both temperature and humidity to eliminate nonlinear confounding effects.

Considering that a single-day lag model might underestimate the association [21], the cumulative effects were estimated using different lag structures, including both single-day (lag0 to lag6) and several days' moving averages (lag0~1 to lag0~6). Linearity for exposure-response relationship between $PM_{2.5}$ and cardiorespiratory admissions was further checked by smoothing the $PM_{2.5}$ terms using NCS function (with 3 df).

Furthermore, we conducted stratification analyses by age (<45, 45–54, 55–64, 65–74, and >74 years), sex (male and female) and season (warm: April to September; cold: October to March of the next year) to explore the potential effect modifiers on the associations between $PM_{2.5}$ and cause-specific hospital admission deriving from the single pollutant model. The Z-test was applied to test the statistical significance of differences by gender or season [22].

# Sensitivity analysis

To check the robustness of our main results, we conducted several sensitivity analyses by: (1) Fitting two-pollutant models by additionally adjusting for air pollutants ($PM_{10}$, $SO_2$, $NO_2$, CO), collected from the monitoring station closest to patients' home; (2) Conducting symmetric CCO design (days: ±7, 14) [23]; (3) Changing degrees of freedom of meteorological variables (2–4 df).

All analyses were conducted using R, version 3.5.1. We used the "survival" package for CLR analysis. Two-sided tests were conducted and effects with $p<0.05$ were considered statistically significant. All results of model estimates were reported as odds ratios (ORs) and 95% confidence intervals (CIs), associated with each 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentrations.

# Results

A total of 491,455 hospital admissions, in which 332,090 for total cardiovascular diseases and 159,365 for total respiratory diseases, were recorded from 1st October 2016 to 31st December 2018 in Wuhan (Table 1). Mean age of cardiovascular diseases admissions was 63.69 years (SD = 17.58) and 68.17 years (SD = 10.42) for respiratory diseases admissions. For both cardiovascular and respiratory admissions, older people over 74 years old accounted for the largest proportion, and the number of male was higher than that of female during the study period.

Table 1
Basic characteristics of cardiovascular disease and respiratory diseases admissions in Wuhan (Oct 1, 2016 to Dec 31, 2018).

| **Characteristic** | **Cardiovascular diseases (n = 332,090)** | **Respiratory diseases (n =159,365 )** |
|---|---|---|
| Age [mean ± SD (years)] | 63.69 ± 17.58 | 68.17 ± 10.42 |
| Age group [n (%)] | | |
| <45 | 20,089 (0.06) | 25,212 (0.16) |
| 45~54 | 41,956 (0.13) | 18,507 (0.12) |
| 55~64 | 79,240 (0.24) | 32,206 (0.20) |
| 65~74 | 85,869 (0.26) | 35,292 (0.22) |
| >74 | 104,936 (0.31) | 48148 (0.30) |
| Sex [n(%)] | | |
| Men | 181,133 (0.55) | 90,961 (0.57) |
| Women | 150,957 (0.45) | 68,404 (0.43) |
| Sub-diagnoses [n(%)] | | |
| COPD | | 41,467 (0.26) |
| Hypertension | 51,790 (0.16) | |
| CHD | 97,846 (0.29) | |
| Stroke | 113,967 (0.34) | |
| Season at admission [n(%)] | | |
| Warm | 163,495 (0.49) | 74,358 (0.47) |
| Cold | 168,595 (0.51) | 85,007 (0.53) |

Note: SD = standard deviation; warm = April to September; cold = October to March of the next year.

During the study period, the mean daily average concentrations were 48.2 μg/m$^3$ for $PM_{2.5}$ and the mean daily average temperature and humidity were 16.3 °C and 80% (Table S2), reflecting the subtropical climate in Wuhan. Figure 2 shows seasonal trends of $PM_{2.5}$ concentration, with high values in winter and low values in summer. The $PM_{2.5}$ exposure of most patients is lower than China AQS, but still higher than WHO AQG.

$PM_{2.5}$ showed similar lag patterns for its impact on total cardiorespiratory hospital admission (Figure 3). Detailed risk estimates were listed in the supplementary material (Table S4). For single-day lags, a weakened lagging effect of $PM_{2.5}$ were observed from lag0 to lag6. Significant harmful effects were shown on lag0-lag2 with respect to the risk of admissions for all cardiorespiratory disease, and the highest risks were found at lag0, except hypertension. For the cumulative lag day effect, we found a significant positive associations in all analyzed hospital admissions, while the greatest effects for all diseases were observed at lag0~2. Thus, in the subsequent analyses, we mainly chose lag0~2 as the exposure period to evaluate the acute effects of ambient particulate matters. The moving average lag model usually had higher estimates than that of single-day exposure. Per 10 μg/m$^3$ increase in $PM_{2.5}$ at lag0~2 was associated with a 1.2% (95% CI: 1.0%–1.4%) increments in daily hospital admissions for total CVD and 2.0% (95% CI: 1.6%–2.3%) increments for total respiratory diseases (Table S4). The effect estimates remained stable in symmetric CCO design (Table S5) and in different degrees of freedom for smoothness of meteorological variables (2–4 df) (Table S6).

For subgroup analysis, we examined the associations between $PM_{2.5}$ and cardiorespiratory hospital admission at lag0~2, classified by age, gender and admission season (Figure 4). In age-specific analyses, positive associations were found in all age groups for respiratory admission. Stronger effects of $PM_{2.5}$ on both cardiovascular and respiratory admission were observed in the elderly (aged above 65 years old). However, the hazard effects among people aged >74 years group were slightly lower than that of the people aged 65~74 years in some cause-specific diseases (COPD, coronary heart disease and stroke). In addition, COPD patients aged 45~54 years old were at the greatest risk, with ORs of 1.042 (95% CI: 1.010 to 1.075) (Table S7). In sex-specific analyses, exposures to $PM_{2.5}$ showed significant effects on both genders, except hypertension, but gender difference of PM-associated risks were statistically insignificant. In season-specific analyses, we found a greater effect of $PM_{2.5}$ for all cardiorespiratory disease in the cold season than in the warm season.

There was a clear dose–response relationship between $PM_{2.5}$ concentration and the hospital admissions for both cardiovascular and respiratory disease (Figure 5). Both results exhibited generally similar patterns. The relationship was approximately linear, with a tiny fluctuation at lower concentrations (<100 μg/m$^3$) and a sharper response at higher concentrations.

For sensitivity analysis, we examined the adverse effects of $PM_{2.5}$ with a three-day moving average (lag0-2) in two-pollutant model, adjusting for other air pollutants ($PM_{10}$, $SO_2$, $NO_2$, CO). Compared with single-pollutant models, the observed associations diminished but remained robust after adding other air pollutants into the model (Table 2).

Table 2
Odds ratio (95% CIs) of hospital admission per 10 μg/m$^3$ increase concentration of $PM_{2.5}$ at lag0~2, with and without adjustment for other pollutants.

| Pollutants | CVD | Respiratory | COPD | Hypertension | CHD | Stroke |
|---|---|---|---|---|---|---|
| $PM_{2.5}$ | 1.012 (1.010, 1.014) | 1.020 (1.016, 1.023) | 1.020 (1.014, 1.026) | 1.011 (1.006, 1.017) | 1.013 (1.009, 1.017) | 1.011 (1.007, 1.015) |
| Adjusted for $PM_{10}$ | 1.005 (1.002, 1.008) | 1.013 (1.008, 1.017) | 1.015 (1.006, 1.024) | 1.001 (0.993, 1.008) | 1.002 (0.996, 1.008) | 1.009 (1.003, 1.014) |
| Adjusted for CO | 1.008 (1.006, 1.011) | 1.013 (1.009, 1.017) | 1.010 (1.003, 1.018) | 1.009 (1.003, 1.016) | 1.006 (1.001, 1.011) | 1.011 (1.006, 1.015) |
| Adjusted for $SO_2$ | 1.009 (1.007, 1.012) | 1.013 (1.010, 1.017) | 1.012 (1.005, 1.018) | 1.009 (1.003, 1.015) | 1.009 (1.004, 1.013) | 1.011 (1.007, 1.015) |
| Adjusted for $NO_2$ | 1.003 (1.001, 1.005) | 1.011 (1.007, 1.015) | 1.012 (1.005, 1.019) | 1.001 (0.994, 1.007) | 0.999 (0.995, 1.005) | 1.006 (1.001, 1.010) |

# Discussion

To the best of our knowledge, this is the first study in China that examined the adverse effects of $PM_{2.5}$ on hospital admission based on an entire population of single city, with the application of LUR model. Evidence gained in this study showed the significant $PM_{2.5}$ associated risk on cardiovascular diseases (including hypertension, CHD and stroke) and respiratory diseases (including COPD), with robust outcomes after the adjustment for other pollutants ($PM_{10}$, CO, $NO_2$ and $SO_2$). These results were stable and consistent across subgroup analyses, which demonstrated that elderly people were more vulnerable to $PM_{2.5}$ and the higher risk in cold season. These findings provided strong evidence of the associations between ambient $PM_{2.5}$ and cardiorespiratory hospital admissions in Wuhan, and might help public agencies to develop the strategies for air pollution control and disease prevention.

Our main findings are broadly consistent with several surveys from populations in other continents although with different health outcomes, and methods [24, 25]. An ecological study evaluated hospital admissions associated risk with $PM_{2.5}$ exposure in 202 US counties with populations ≥ 200,000 from 1999 to 2005 [24]. Each 10 μg/m$^3$ increases in $PM_{2.5}$ were associated with 0.8% and 0.14% percentage increase in hospital admission for cardiovascular and respiratory disease. Another European study observed a strong $PM_{2.5}$-mortality risk at lag0~5 in twelve Mediterranean cities, for a 10 μg/m$^3$ increase in $PM_{2.5}$ associated with a 0.86% and 1.91% increase cardiovascular and respiratory mortality [25].

Lag effects of short-term exposure to air pollution have been of wide interest in air pollution epidemiology. In this study, $PM_{2.5}$ exhibited similarly lagged pattern on overall cardiorespiratory admission as well as in different sub-groups. For single-day lag models, the estimates for $PM_{2.5}$ were the highest at lag0 day and decreased in later lag days, in line with previous studies [10, 26]. This temporal pattern suggested that exposure to $PM_{2.5}$ may increase the risk of hospital admission within hours of exposure. A multi-city study in England and Wales found the elevated risk for myocardial infarction of $PM_{10}$ and $NO_2$ at lag1–6 h, with excess risks of 1.2% (95% CI, 0.3%~2.1%) and 1.1% (95% CI, 0.3%~2.1%) respectively per 10 μg/m$^3$ increase [27]. Another study from Japan also found that hourly changes in particulate matter (0 to <6 h) were positively associated with the risk of cardiovascular and cerebrovascular disease [28]. In the present investigation, we found that moving average lag model usually had higher estimates than that of single-day exposure, with the greatest effects observed at lag0~2. Similar results were also observed in other continents [8, 29]. In New England, a study found that the highest harmful effects of $PM_{2.5}$ exposure were at lag0~5, for each 10 μg/m$^3$ increment associated with an increase of 4.31%, 3.95% and 2.56% percentage change in the hospital admission rate for myocardial infarction, congestive heart failure and ischemic stroke respectively [8]. Another study in Denmark found the highest ultrafine particles–associated risks for stroke at lag0~4 [29]. The variation in days of moving average pattern could be attributed to combined effects of many complex factors such as different type of diseases, individual behavior patterns, air pollution component and the differences in study design. This study, based on the overall residents of the whole city, can reflect the real and precise impact of ambient fine particulate matter in Wuhan. These findings suggested that the effect of increments in air pollution concentration on a single day are distributed across several subsequent days. There is also experimental evidence support for this pattern, a toxicological study reported that the acute lung inflammation, induced by particles instillation, took up to 4 days to resolve [30]. Considering the time scale extends over several days, a moving average lag model might be a better exposure metric than single-day lag in air pollution epidemiologic studies. These results have provided solid evidence about the importance of the timing of air pollution exposure.

This study explored demographic-specific associations between $PM_{2.5}$ and hospital admission for respiratory and cardiovascular diseases. Similar to other studies, a higher susceptibility to $PM_{2.5}$ was found among the elderly (aged above 65 years old). Such elderly-high risk association has been widely accepted for the weaker immune systems and possible more chronic medical conditions [31]. In addition, interesting deviations from this pattern were observed for specific subgroups of disease. The risk of COPD, coronary heart disease and stroke in the study peaked in the middle age group. For cause-specific cardiovascular diseases, CHD and stroke, the adverse effects were slightly higher in the 65–74 years group than group over 74 years old. This result may be the consequence of a “harvesting effect” that susceptible residents might have developed symptoms and died before reaching the age 75 [32]. Notably, for the COPD patients, the stronger associations were found in those aged 45–54 years old, each 10 μg/m$^3$ increase in $PM_{2.5}$ corresponded to 4.25% (95% CI, 1.02%~7.58%) increases in hospital admissions. This finding seemed to be inconsistent to prior study results. In a cohort study conducted in

American, the higher risk of hospital admission for COPD were found in age group ≥76 [33]. More recently, a review of 30 epidemiological studies on air pollution and the morbidity of COPD and asthma found no evidence for the effect of any pollutants on hospital utilization in people aged 15–64 [34]. The variability in these results could be due to possible differences in selection strategy of the study population. As COPD largely encountered in the elderly population, previous studies tended to select people ≥65 years old as the study population, or divided age into categorical variables based on 15 and 65 years old [33, 35], which limited the power to examine the relationship between COPD and air pollutants in specific age groups. Further investigations are still of great need to explore vulnerable populations.

The assessment of gender differences has been of wide interest in air pollution epidemiology. In current study, although the statistical significance of gender difference was not observed in PM-associated risks for hospital admission, there were still slight deviations in the magnitude of the risk estimates in male and female. For total respiratory disease, a slight higher risk estimates were found in female. For specific cardiovascular diseases, coronary heart disease and stroke, it was found that males were at slight higher risk of hospital admission. Being consistent with the results of the present study, a pooled analysis from 33 Chinese communities has reported that the effect of ambient air pollution exposure on prevalence of stroke and CVD was much higher in men than in women [36]. Another multi-counties study in American suggested that women might be more susceptible to $PM_{2.5}$-related hospitalizations for respiratory causes [37]. Although, these difference could be related to factors such as chemical components and exposure pattern of local population. The findings of current study indicated that the tendency of gender differences for PM-associated risk may vary among different diseases. Underlying pathology and mechanism for these discrepancies should be further explored in future investigations, so as to provide scientific knowledge to protect the vulnerable subpopulations to PM pollution.

In this study, the higher short-term effects of $PM_{2.5}$ on cardiorespiratory hospital admission were found during the cold period. This findings may be attributed to the seasonally variation of $PM_{2.5}$ in Wuhan, with high concentration in winter and lower in summer (Figure 2), combined with sharper response at higher concentrations in the exposure–response curve (Figure 5). Relatively low temperature in winter can accelerate the conversion of particles, while low wind speed restricts air pollutants to disperse [38]. The seasonal finding of study echoes with a study in Hong Kong [39], which found an increased risk of respiratory mortality in cold season when $PM_{10}$ concentrations up to 80 μg/m$^3$. Two previous large-scale analyses from America [24, 37] found larger $PM_{2.5}$-induced risks of hospitalizations for cardiovascular and respiratory diseases in cold months (winter or spring) as well.

Compared with previous studies, this study has several strengths. First, we obtained the hospitalization data of a total of 59 hospitals in Wuhan to evaluate the PM-admission relationships. Given Wuhan's universal access to hospital health care, potential for selection bias is minimized and the results could be directly generalized to the whole city. Second, the adoption of LUR model increases the accuracy to assess the spatial variations in individual $PM_{2.5}$ exposure and detect possible associations. This study has some limitations as well. First, we linked $PM_{2.5}$ to cardiorespiratory diseases by date of hospital admission rather than by the date of symptom onset. This may have introduced non-differential error in exposure measurement and underestimate the effect estimates. Second, while the exposure modeling methods employed in this study added new information in comparison with most previous studies, the deficiency of $PM_{2.5}$ exposure from occupation, commuting, and pollution originating in indoor sources may have further attenuated our effect estimates. Third, although the two-pollutant models were fitted to examine the robustness of the association between $PM_{2.5}$ and hospital admissions, the collinearity between pollutants limited the ability to separate the independent effect of $PM_{2.5}$.

# Conclusion

This study provided evidence regarding the short-term health impacts of high $PM_{2.5}$ exposure in Wuhan. The elderly were at higher PM-induced risks. Additionally, the significantly stronger associations between $PM_{2.5}$ and cardiorespiratory hospital admissions were observed during cold season than warm season. These findings have important implications to local public health and environmental strategy and policy.

# Abbreviations

**AQG:** Air Quality Guidelines;

**AQS:** Ambient Air Quality Standards;

**CCO:** case-crossover;

**CHD:** coronary heart disease;

**CI:** confidence interval;

**CO:** carbon monoxide;

**COPD:** chronic obstructive pulmonary disease;

**CTM:** atmospheric Chemical Transport Model;

**CVD:** cardiovascular disease;

**DALYs:** disability-adjusted life-years;

**DOW:** day of the week;

**DF:** degrees of freedom;

**DM:** Dispersion Models;

**GIS:** geographic information system;

**LUR:** land use regression;

**NCS:** natural cubic spline;

**$NO_2$:** nitrogen dioxide;

**OR:** odds ratio;

**$PM_{10}$:** particulate matter with an aerodynamic diameter of 10 μm or less;

**$PM_{2.5}$:** particulate matter with an aerodynamic diameter of 2.5 μm or less;

**SD:** standard deviations;

**$SO_2$:** sulphur dioxide;

**WHO:** World Health Organization.

## Declarations

# Ethics approval and consent to participate

The study was approved by the ethics committee of Wuhan University (no. 2020YF0020), and all data included in the analysis were anonymized.

# Consent for publication

Not applicable

# Availability of data and materials

The data that support the findings of this study are available from Wuhan Information center of Health and Family Planning but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Wuhan Information center of Health and Family Planning.

# Competing interests

The authors declare that there are no conflicts of interest.

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# Authors' contributions

ZR and XL analyzed the data, interpreted the data, and drafted the manuscript; TL collected the data and revised the manuscript; DC conducted statistical analysis, and revised the manuscript. JK, WX, SJ and YH contributed to data collection and manuscript preparation. LJ provided important comments while developing the manuscript; LM took overall responsibility for the design, implementation and analysis of the study. The author(s) read and approved the final manuscript.

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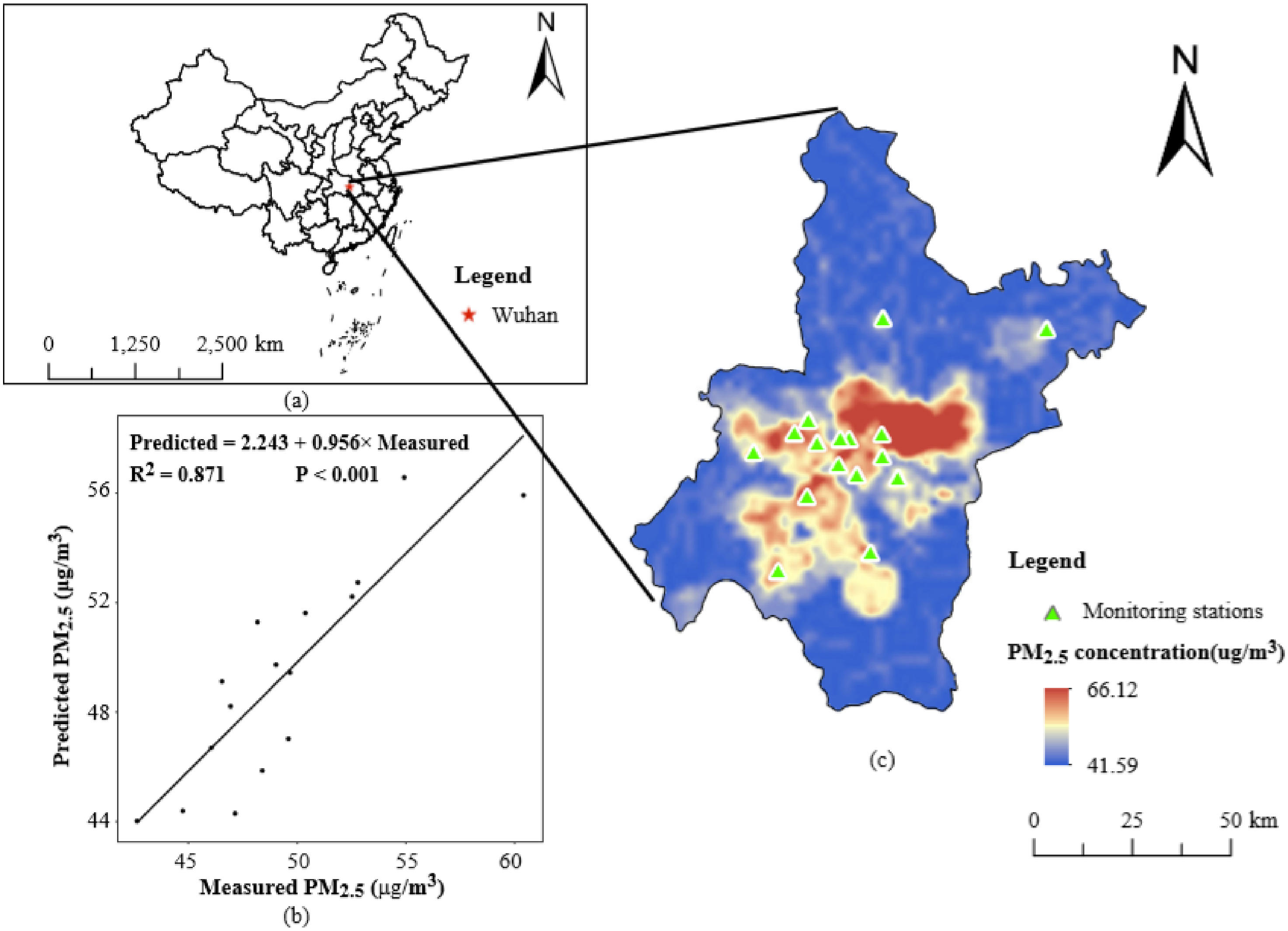
# Figures




## Figure 1

Study area and the results of LUR model. Figure legend: (a) Geographical location of Wuhan in China. (b) Spatial distribution of mean PM2.5 estimations across Wuhan city from October 1, 2016 to December 31, 2018. (c) A scatter plot correlating the measured and predicted PM2.5 values from 16 monitoring stations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

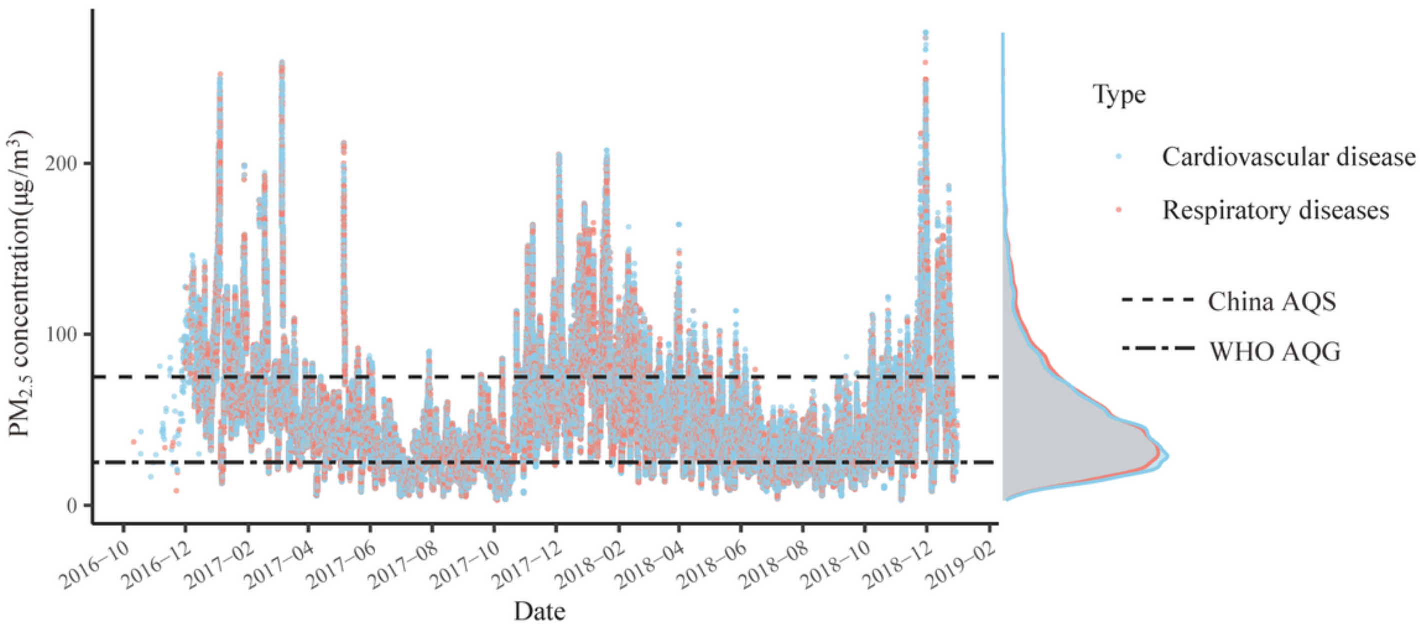
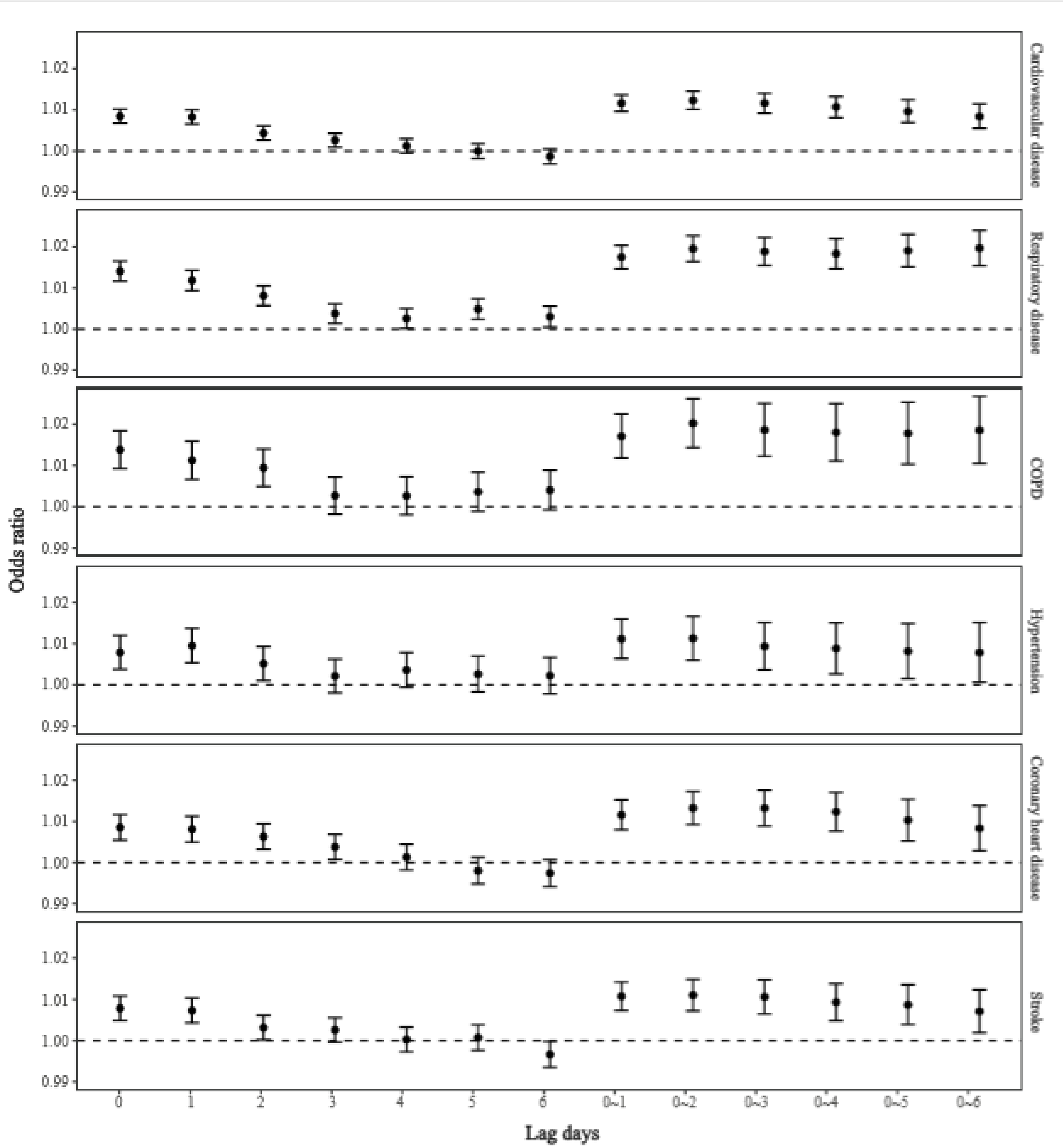


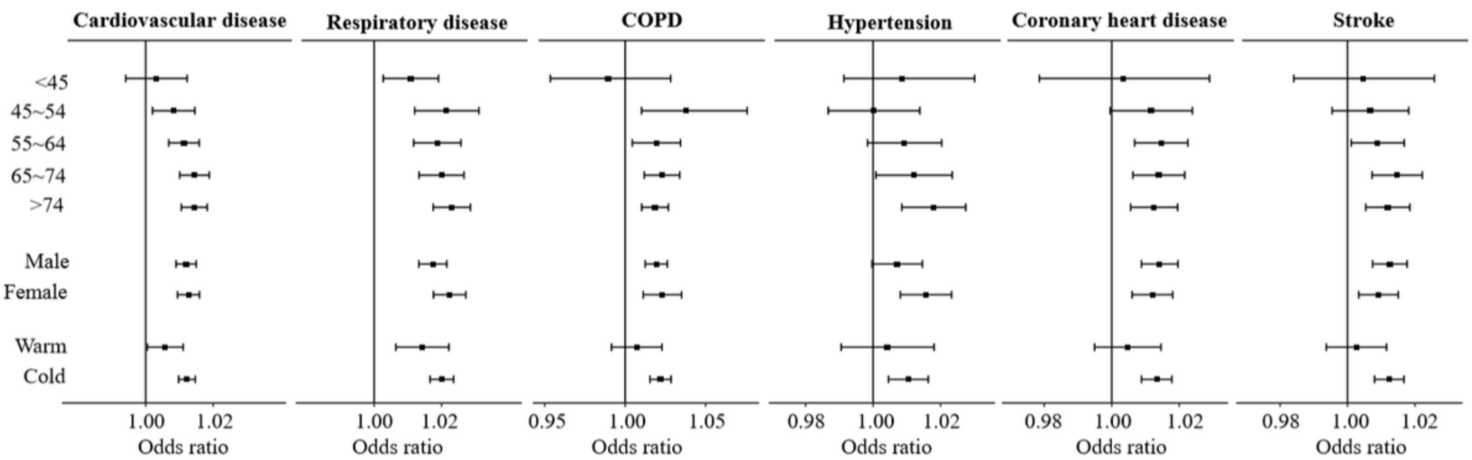

**Figure 2**

Distribution of individuals PM2.5 exposure on the day of admission. Figure legend: The points present the PM2.5 concentration of individuals. The density plot on the right marginal of y-axis visualizes the distribution of the number of subjects over the PM2.5 concentration. The dashed line denotes the Grade II criteria set by the Chinese Ambient Air Quality Standards (AQS, 75 μg/m3) and World Health Organization Air Quality Guidelines (WHO AQG, 25 μg/m3).



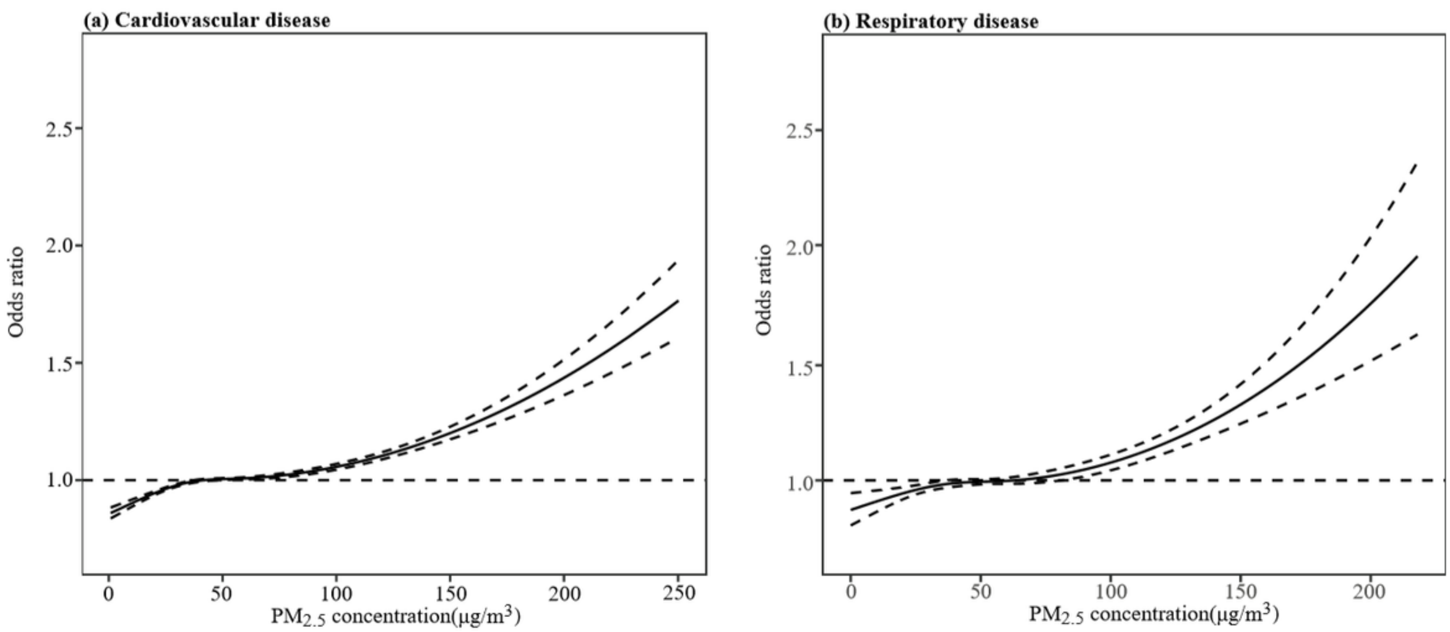

## Figure 3

OR (95% CI) of hospital admission for total and cause-specific cardiorespiratory disease per 10 μg/m³ increase of PM2.5 with different lag patterns in single-pollutant models.




## Figure 4

OR (95% CI) of hospital admission with per 10 μg/m3 increase of PM2.5, stratified by age, gender and season at admissions at lag0~2.




## Figure 5

Concentration–response relationship of PM2.5 concentrations with hospital admissions for cardiorespiratory disease at lag0~2. Figure legend: The solid line represents the predicted Odds ratios (OR), and the dotted lines represent the 95% CI

# Supplementary Files

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