Short-term Effects of Different PM2.5 Thresholds on Daily All-cause Mortality in Jinan, China

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Abstract

To examine the effects of different $PM_{2.5}$ limits on daily all-cause mortality, 8,768 all-cause deaths were recorded in the database of the Jinan Center for Disease Control and Prevention. Data on the levels of air pollutants ($PM_{2.5}$ and O_3) were provided by the Jinan Environment Monitoring Center. The Jinan Bureau of Meteorology provided air temperatures and relative humidity. The relative risk of all-cause mortality was assessed using a quasi-Poisson regression model after adjusting Interference factors. There was a significant positive association between exposure concentrations (35 μg/m³, 75 μg/m³, and 150 μg/m³) and all-cause deaths, with a mortality increase of 1.07 (1.01, 1.13), 1.03 (1.00, 1.05), and 1.05 (1.01, 1.08), respectively. It had a significant correlation between all-cause deaths and a $PM_{2.5}$ limit of 35 μg/m³ in men. All-cause mortality in women and individuals aged ≥ 60 years increased significantly with exposure to $PM_{2.5}$ levels of 75, 115, and 150 μg/m³. There was no significant relationship between $PM_{2.5}$ exposure and all-cause deaths in individuals aged < 60 years. Exposure to $PM_{2.5}$ (35 μg/m³) increased the mortality risk. Women and individuals aged ≥ 60 years were more sensitive to the effects of $PM_{2.5}$ than men and individuals aged < 60 years.

Introduction

The adverse effects of airborne particulate matter ≤ 2.5 μm ($PM_{2.5}$) on public health, especially in the respiratory and cardiovascular systems, have been studied for nearly half a century. The formation of $PM_{2.5}$ and its adverse impact on public health are evident in both developed and developing countries[1–4]. Various studies in Europe, the United States, and developing countries such as China, India, and Korea found that entire populations were affected by short-term exposure to fine particulate matter and that there was a positive correlation between $PM_{2.5}$ levels and mortality[5–9]. In addition, substantial epidemiological evidence demonstrates that ground-level fine particulate matter is linked to various respiratory diseases, including asthma, chronic obstructive pulmonary disease, lung cancer[10,11,12], and cardiovascular mortality[10,13,14].

However, the results of all-cause mortality associated with exposure to $PM_{2.5}$ are inconsistent; therefore, public awareness of the risk of this type of exposure is low [15,16,17]. Moreover, few studies to date investigated the $PM_{2.5}$ limit that poses no health risk. For this reason, a recommended $PM_{2.5}$ concentration is needed to minimize the adverse health effects [18].

The objective of this study is to examine the effects of different $PM_{2.5}$ thresholds on all-cause mortality and provide public health recommendations to avoid exposure of $PM_{2.5}$.

Materials And Methods

Data source

Daily levels of $PM_{2.5}$ in 24-hour intervals and ozone (O_3) in 1-hour intervals averaged from 14 permanent monitoring stations in urban areas of Jinan, China, from 2013 to 2015 were provided by the Jinan Environment Monitoring Center. Daily mean air temperatures and relative humidity in the corresponding period were provided by the Jinan Bureau of Meteorology.

Data on the daily mortality of the registered population of Jinan for the period 2013–2015 were recorded in the database of the Jinan Center for Disease Control and Prevention. Detailed demographic information, including age, gender, date of hospital admission, date of hospital discharge, admission diagnosis, discharge diagnosis codes, and current residence were extracted from the Jinan Qilu Hospital registry. Mortality data on total non-accidental causes (codes A00–R99), cardiovascular disease (codes I00–I99), and respiratory disease (codes J00–J98) were classified according to Diseases Revision 10 (ICD-10). The data on all-cause mortality were stratified by gender (male and female) and age (< 60 and ≥ 60 years).

Data analysis

$PM_{2.5}$ concentrations were classified into four thresholds—35 μg/m³, 75 μg/m³, 115 μg/m³, and 150 μg/m³—based on the Chinese new air quality index (AQI) (GB3095-2012) released by the Ministry of Environmental Protection (MEP).

A quasi-Poisson regression model with natural splines was used to assess the impact of different $PM_{2.5}$ limits on daily all-cause mortality because the daily death counts in Jinan approximately followed a Poisson distribution. This regression model is used to adjust inference for overdispersion [19]. The natural cubic spline for mean temperatures with 5 degrees of freedom and relative air humidity with 3 degrees of freedom (*df*) was controlled to analyze all-cause mortality based on Akaike's Information Criterion (AIC) for lag effects of up to 3 days [20]. Confounding factors such as day of the week and holidays were included as dummy variables.

The natural cubic spline smoothing function degree of freedom for mean temperature and relative air humidity is determined as follows:

$$Log[E(Yt)] = \alpha + ns(Temp, df) + \beta_1 factor(DOW) + \beta_2 factor(Holiday)$$
$$Log[E(Yt)] = \alpha + ns(RH, df) + \beta_1 factor(DOW) + \beta_2 factor(Holiday)$$

Yt represents the death counts on day t. *E(Yt)* represents the expected death counts on day t, *ns* stands for the natural cubic spline smoothing function, *Temp* represents the mean temperature, *RH* represents the relative air humidity, *DOW* and *Holiday* stands for the day of the week effect and legal holidays respectively, β_1 and β_2 is the coefficient of *DOW* and *Holiday* respectively. The degree of freedom of the mean temperature factor is N (N = 2,3,...6). Obtain the magnitude of the corresponding AIC of the equation when N is different, and the minimum value of AIC is the optimal degree of freedom.

Different $PM_{2.5}$ limits were added into the above basic model to establish a single-pollutant model. O_3 was included in the single-pollutant models of $PM_{2.5}$ with multi-day moving average lag structures [from a lag of 0 to 1 day (mean) to a lag of 0 to 3 days (mean)] were used for sensitivity analysis to determine the stability of the model.

The relative risk (RR) and corresponding 95% confidence interval (CI) were estimated to assess the impact of different $PM_{2.5}$ limits on daily counts of all-cause mortality. P-values smaller than 0.05 were considered statistically significant.

Stratified analyses of exposure to different $PM_{2.5}$ limits based on gender (male or female) and age (< 60 years and ≥ 60 years) were performed to find associations with daily all-cause mortality.

Results

Distribution of ambient pollutants and weather data

The mean daily concentrations of $PM_{2.5}$ and O_3 from 2013 to 2015 were 96 μg/m³, and these values are 1.28- and 0.64-fold higher than those reported by the new Chinese ambient air quality standards (GB3095-2013). The levels of $PM_{2.5}$ in 625 of 1095 days exceeded the annual secondary national 24-hour ambient air quality standards (75 μg/m³). The frequency distribution of daily ambient pollutant levels and temperatures is shown in Fig. 1.

Data description

A total of 8,768 all-cause deaths (5,462 men and 3,306 women) for the period 2013–2015 were recorded in the database of the Jinan Center for Disease Control and Prevention. The percentage of individuals aged < 60 and ≥ 60 years was 38.79% (3401/8768) and 61.21% (5367/8768), respectively. The distribution of the daily concentration on air pollutants, weather parameters, and deaths is shown in Table 1.

Table 1
Daily distribution of air pollutant levels, weather parameters, and deaths in Jinan, China, from 2013 to 2015.

Variable	X ± S	Min	P25	P50	P75	Max	IQR
Pollutants							
$PM_{2.5}$ (μg/m³)	96 ± 58	22	59	82	116	443	57
O_3 (μg/m³)	96 ± 57	8	48	86	134	283	87
Meteorological data							
Temperature (°C)	15.2 ± 10.3	−9.4	5.8	16.6	24.1	33.7	18.3
Relative air humidity (%)	56 ± 20	15	41	55	70	100	29
Daily deaths							
From all causes	8 ± 3	1	4	6	10	15	20
Gender							
Male	5 ± 1	0	1	4	6	8	11
Female	3 ± 1	0	1	3	4	6	12
Age							
< 60	3 ± 1	0	1	3	5	6	3
≥ 60	5 ± 1	1	1	5	7	11	19

According to MEP, air quality was good (green category) in 4.11% of the days, moderate (yellow category) in 38.36% of the days, poor for sensitive groups (orange category) in 32.24% of the days, poor (yellow category) in 12.42% of the days, and very poor (red category) in 12.88% of the days for all populations. PM_{25} concentration and air quality index values in the study period are shown in Table 2.

Table 2
$PM_{2.5}$ levels and air quality index values in Jiang, China, from 2013 to 2015.

$PM_{2.5}$ levels (μg/m³)	2013		2014		2015		Air quality index values	MEP air quality	Category
	N	(%)	N	(%)	N	(%)			
≤ 35	12	3.3	9	2.5	24	6.6	≤ 50	Good	Green
36–75	116	31.8	150	41.1	154	42.2	51–100	Moderate	Yellow
76–115	119	32.6	125	34.2	109	29.9	101–150	Poor for sensitive groups	Orange
116–150	48	13.1	44	12.1	44	12.0	151–200	Poor	Red
> 150	70	19.2	37	10.1	34	9.3	> 200	Very poor	Purple

Daily all-cause mortality

There was a strong association between the lag day of exposure to three $PM_{2.5}$ concentrations (35 μg/m³, 75 μg/m³, and 150 μg/m³), and the relative risk (RR) with 95% confidence interval (CI) for daily all-cause mortality from exposure to the three $PM_{2.5}$ thresholds for lag 1, lag 0, and lag 01 was 1.07 (1.01, 1.13), 1.03 (1.00, 1.05), and 1.05 (1.01, 1.08), respectively. For moving average lag structures, RR (95% CI) for daily all-cause mortality from exposure to 35 μg/m³, 75 μg/m³, and 150 μg/m³ of $PM_{2.5}$ was 1.10 (1.02, 1.18), 1.04 (1.01, 1.07), and 1.06 (1.02, 1.11) in lag 01, respectively. Furthermore, RR (95% CI) for daily all-cause mortality from exposure to 150 μg/m³ of $PM_{2.5}$ was 1.06 (1.01, 1.11) in lag 02 (Table 3).

Table 3
Relative risk (RR) with 95% confidence interval (CI) for daily all-cause mortality from exposure to different $PM_{2.5}$ thresholds in Jinan, China, from 2013 to 2015.

All-cause	35 μg/m³ [RR, (95% CI)]	75 μg/m³ [RR, (95% CI)]	115 μg/m³ [RR, (95% CI)]	150 μg/m³ [RR, (95% CI)]
Lag 0	1.03 (0.98–1.09)	1.03 (1.00–1.05)*	1.02 (0.99–1.05)	1.05 (1.01–1.08)*
Lag 1	1.07 (1.01-–1.13)*	1.02 (1.00–1.04)	1.01 (0.99–1.04)	1.03 (1.00–1.07)
Lag 2	0.95 (0.91–1.00)	0.99 (0.97–1.01)	1.00 (0.97–1.02)	1.00 (0.97–1.04)
Lag 3	0.96 (0.92–1.01)	0.97 (0.95–0.99)	0.98 (0.96–1.01)	0.99 (0.96–1.03)
Lag 01	1.10 (1.02–1.18)*	1.04 (1.01–1.07)*	1.03 (1.00–1.07)	1.06 (1.02–1.11)*
Lag 02	1.04 (0.95–1.14)	1.03 (0.99–1.06)	1.02 (0.98–1.07)	1.06 (1.01–1.11)*
Lag 03	1.00 (0.91–1.11)	1.00 (0.96–1.04)	1.01 (0.96–1.06)	1.05 (0.99–1.11)
*p < 0.05				

Stratified analysis based on gender and age indicated that there was a significant relationship between all-cause mortality and a $PM_{2.5}$ threshold of 35 μg/m³ in men in lags 1 and 01. All-cause deaths in women significantly increased with exposure to 75 μg/m³, 115 μg/m³, and 150 μg/m³ in lag 1; lags 0 and 01; and lags 0, 1, 01, 02, and 03, respectively. There were no significant associations between $PM_{2.5}$ exposure and all-cause mortality in individuals aged < 60 years. All-cause deaths in individuals aged ≥ 60 years were significantly correlated with exposure to 75 μg/m³, 115 μg/m³, and 150 μg/m³ in lags 1 and 01; lags 1 and 01; and lags 0 and 01, respectively (Fig. 2).

The results of sensitivity analysis indicated that there were no significant changes in the RR at different $PM_{2.5}$ limits for daily all-cause mortality after including O_3 in the multi-day moving average lag structures. Therefore, the effect of this single-pollutant model was robust (Fig. 3).

Discussion

To our knowledge, this epidemiologic study is the first to examine the association of $PM_{2.5}$ limits with all-cause mortality in Asia. The results indicated that, except for the $PM_{2.5}$ threshold of 115 μg/m³, the concentrations of 35 μg/m³, 75 μg/m³, and 150 μg/m³ were significantly associated with mortality from all causes, and the effects of $PM_{2.5}$ were stronger as the levels increased. In addition, consistent with other studies, there was no evidence of a limit at which $PM_{2.5}$ exposure does not affect mortality, even for concentrations lower than 35 μg/m³, demonstrating that $PM_{2.5}$ is a significant risk factor for all-cause mortality, and the adverse impacts on public health do not decrease as pollutant levels decrease [21–23].

The association between all-cause deaths and $PM_{2.5}$ exposure was statistically significant at 35 μg/m³, 75 μg/m³, and 150 μg/m³, and this result maybe because of the relatively fewer deaths between 75 μg/m³ and 115 μg/m³. Furthermore, the daily temperature corresponding to each of these concentrations was higher than that of other thresholds. The impact of different $PM_{2.5}$ limits on mortality may be due to high temperatures [24, 25].

The results of a previous study on the gender-specific effects of particulate matter were inconsistent [26]. The results of the gender-stratified analysis demonstrated that female patients were more sensitive to the $PM_{2.5}$ levels of 75 μg/m³, 115 μg/m³, and 150 μg/m³, whereas male patients were more sensitive to a concentration of 35 μg/m³, indicating that men are more susceptible to lower $PM_{2.5}$ concentrations than women. Smoking is a critical environmental risk factor, and one study suggested that the estimated impact of air pollution might be stronger in nonsmokers than smokers [27]. A potential reason for this difference may be that women have slightly stronger airway reactivity and smaller airways than men [28]. Moreover, the adverse impacts of additional exposure to $PM_{2.5}$ may be overcome by the oxidative and inflammatory effects of smoking [29].

Older individuals had increased susceptibility to $PM_{2.5}$ levels of 75 μg/m³, 115 μg/m³, and 150 μg/m³ compared with younger individuals, possibly because the former group has a weaker immune system and higher sensitivity to these particles [30, 31]. However, there was no significant association between $PM_{2.5}$ exposure and all-cause mortality in individuals aged < 60 years, indicating that the general population should avoid high levels of $PM_{2.5}$ (≥75 μg/m³).

This study has some limitations. First, the study selected the mean air pollutant concentration from each monitoring site in Jinan as the exposure concentration; nonetheless, individual exposure may depend on other factors, including the type of outdoor activity, physical fitness, and living habits, potentially causing exposure measurement errors or underestimating the impact of air pollution. In addition, this study belongs to the field of ecological research, and the conclusions cannot prove causality but merely indicate the relationship between air pollutants and all-cause mortality.

Conclusions

For all-cause mortality, $PM_{2.5}$ presented adverse effects on health even at a low concentration (35 μg/m³), and the impact of $PM_{2.5}$ on mortality was higher as the concentration was increased. Women and individuals aged ≥ 60 years were more sensitive to the effects of $PM_{2.5}$ than men and individuals aged < 60 years.

Declarations

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Conflict of Interest: The authors declare that they have no conflict of interest.

Authors' contributions: Ma Zhixiang designed/performed most of the investigation, data analysis and wrote the manuscript; Chen Cai and Meng Xiangwei contributed to scoping and structuring the paper and guided method development. Li Wei provided pathological assistance; Zhang Chuanzhen contributed to the interpretation of the data and analyses. All of the authors have read and approved the manuscript

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Figures

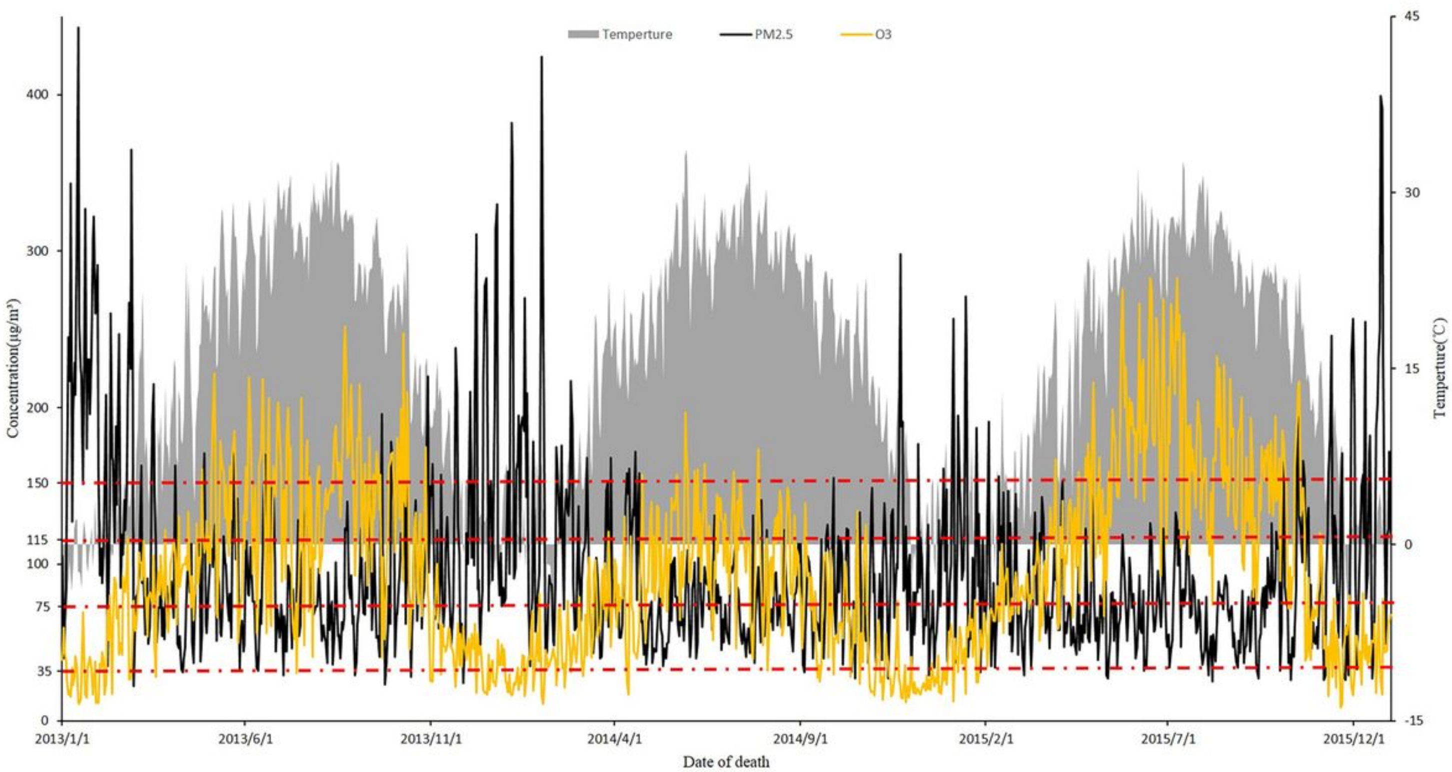

Figure 1

Distribution of daily ambient pollutant concentrations and temperature in Jinan, China, from 2013 to 2015.

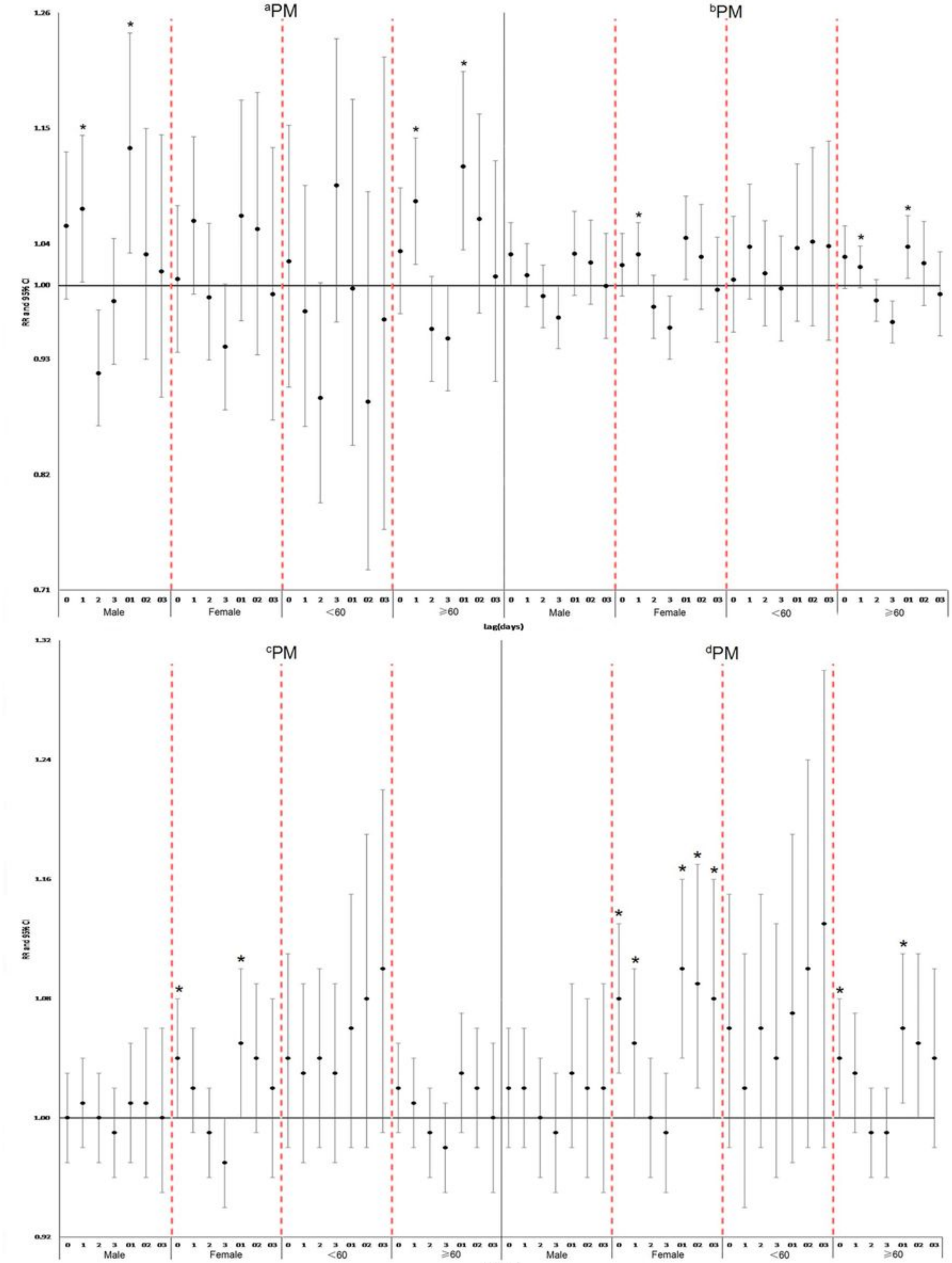

Figure 2

Lag structures of age and gender-specific relative risk (RR) of daily mortality from exposure to different PM2.5 thresholds. a35 μg/m3, b75 μg/m3, c115 μg/m3, d150 μg/m3. *p<0.05

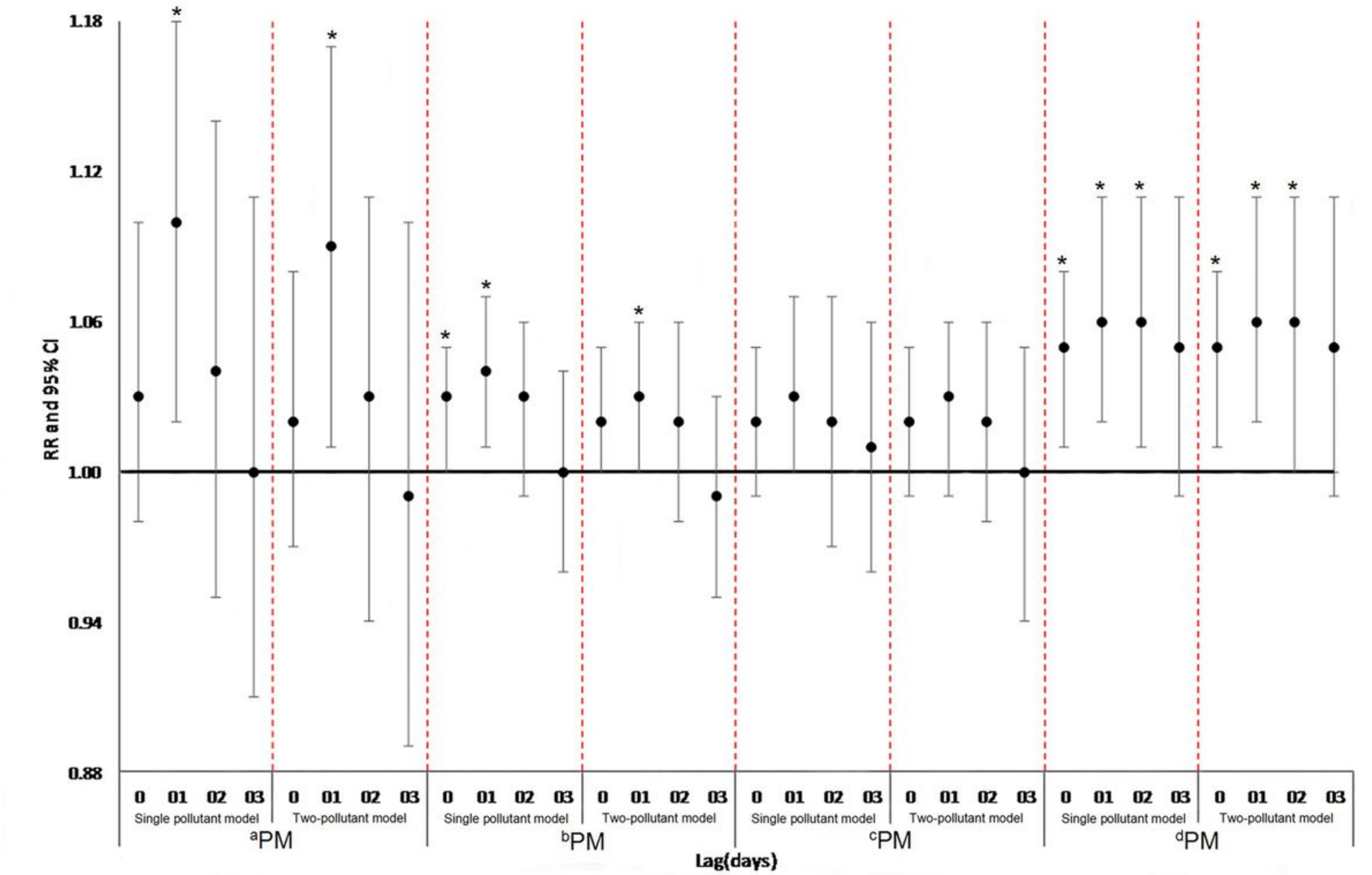

Figure 3

Lag structures of relative risk (RR) and 95% confidence interval (CI) between single pollutant models and two-pollutant models for different PM2.5 thresholds in lag 0 to lag 03. a35 μg/m3, b75 μg/m3, c115 μg/m3, d150 μg/m3. *p<0.05