Original Contribution

Association of Particulate Air Pollution With Daily Mortality

The China Air Pollution and Health Effects Study

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China is one of the few countries with some of the highest particulate matter levels in the world. However, only a small number of particulate matter health studies have been conducted in China. The study objective was to examine the association of particulate matter with an aerodynamic diameter of less than 10 μm (PM$_{10}$) with daily mortality in 16 Chinese cities between 1996 and 2008. Two-stage Bayesian hierarchical models were applied to obtain city-specific and national average estimates. Poisson regression models incorporating natural spline smoothing functions were used to adjust for long-term and seasonal trends of mortality, as well as other time-varying covariates. The averaged daily concentrations of PM$_{10}$ in the 16 Chinese cities ranged from 52 μg/m$^3$ to 156 μg/m$^3$.

The 16-city combined analysis showed significant associations of PM$_{10}$ with mortality: A 10-μg/m$^3$ increase in 2-day moving-average PM$_{10}$ was associated with a 0.35% (95% posterior interval (PI): 0.18, 0.52) increase of total mortality, 0.44% (95% PI: 0.23, 0.64) increase of cardiovascular mortality, and 0.56% (95% PI: 0.31, 0.81) increase of respiratory mortality. Females, older people, and residents with low educational attainment appeared to be more vulnerable to PM$_{10}$ exposure. Conclusively, this largest epidemiologic study of particulate air pollution in China suggests that short-term exposure to PM$_{10}$ is associated with increased mortality risk.

Abbreviations: CAPES, China Air Pollution and Health Effects Study; CI, confidence interval; ICD-10, International Classification of Diseases, Tenth Revision; PACF, partial autocorrelation function; PAPA, Public Health and Air Pollution in Asia; PI, posterior interval; PM$_{10}$, particulate matter with an aerodynamic diameter of less than 10 μm.

Ambient air pollution is a complex mixture composed of both solid particles and gaseous pollutants. Among the various air pollutants, particulate matter shows the strongest evidence for adverse health effects (1). Short-term exposure to particulate matter has been linked to adverse health effects, including increased mortality, increased rates of hospital admissions and emergency department visits, exacerbation of chronic respiratory conditions, and decreased lung function (2). Recent multicity analyses conducted in North America and Europe provide further evidence supporting the coherence and plausibility of short-term association of particulate matter with cardiorespiratory disorders (3–5). Most of these studies were conducted in developed countries; to our knowledge, only 1 multicity study, the Public Health and Air Pollution in Asia (PAPA) project, has examined the acute health effects of particulate matter in Asian developing countries (6).

China is one of the few countries with highest particulate matter levels in the world (7). However, only a small number of health studies of particulate matter have been conducted in China (8). The PAPA project includes only 2 mainland Chinese cities—Shanghai and Wuhan. There remains a need for the multicity analysis of particulate matter in China, where the characteristics of particulate matter (e.g., level and components) and sociodemographic status of local residents (e.g., age structure, disease pattern, and socioeconomic status) are
different from those of developed countries. Also, little attention has been paid in Chinese studies to the assessment of possible modifiers of the health impact of particulate matter. These modifiers include preexisting health status (9), population demographic characteristics (e.g., gender and age) (9–11), and socioeconomic status (10–13).

The objective of this paper is to examine the association of particulate matter with an aerodynamic diameter of less than \(10 \mu m\) (\(PM_{10}\)) with daily mortality in 16 Chinese cities. We considered \(PM_{10}\) because the current Chinese Air Quality Standard includes only \(PM_{10}\) among the various particulate matter metrics. We also examined the modifying effects of gender, age, and education on the associations between \(PM_{10}\) and daily mortality. This analysis is a component of the China Air Pollution and Health Effects Study (CAPES).

MATERIALS AND METHODS

Data

The CAPES project includes 16 Chinese cities: Anshan, Beijing, Fuzhou, Guangzhou, Hangzhou, Hong Kong, Lanzhou, Shanghai, Shenyang, Suzhou, Taiyuan, Tangshan, Tianjin, Urumqi, Wuhan, and Xi’an (Figure 1). Our study areas were restricted to the urban areas of these cities, because of inadequate air pollution monitoring stations in the suburban areas.

The daily mortality data of urban residents were obtained from the Municipal Center for Disease Control and Prevention in each city. The causes of death were coded according to the International Classification of Diseases, Tenth Revision (ICD-10). The mortality data were classified as deaths due to total nonaccidental causes (ICD-10 codes A00–R99), cardiovascular disease (ICD-10 codes I00–I99), and respiratory disease (ICD-10 codes J00–J98). For total mortality, the data were classified by gender (female and male), age (0–4, 5–64, ≥65 years), and educational attainment (low: illiterate or primary school; high: middle school or above). Education has been used as a surrogate indicator of socioeconomic status in air pollution epidemiologic studies (10–13). Cause-specific mortality data were not available in Lanzhou.

The air pollution data were collected from the National Air Pollution Monitoring System that was part of the air-monitoring network, China National Quality Control (14). In each city, there were from 2 to approximately 13 monitoring stations (Table 1). The daily (24-hour) average concentrations of \(PM_{10}\) were measured by using the method of tapered element oscillating microbalance. To control the confounding effects of gaseous co-pollutants, we collected the daily concentrations for sulfur dioxide and nitrogen dioxide. The methods based on ultraviolet fluorescence and chemiluminescence were used for the measurement of sulfur dioxide and nitrogen dioxide, respectively. For the calculation of 24-hour mean concentrations, at least 75% of the 1-hour values must be available on that particular day. If a station had more than 25% of the values missing for the whole period of analysis, the entire station was excluded from the analysis. The location of monitoring stations is mandated not to be in the direct vicinity of traffic or of industrial sources and not to be influenced by local pollution sources, thus also avoiding buildings or housing and large emitters such as coal-, waste-, or oil-burning boilers; furnaces; and incinerators. In each city, the daily air pollutants’ concentrations were averaged from the available monitoring results across various stations (6).
To allow adjustment for the effect of weather conditions on mortality, meteorologic data (daily mean temperature and relative humidity) were obtained in each city.

**Statistical analysis**

We applied 2-stage Bayesian hierarchical statistical models to estimate city-specific and national average associations of PM$_{10}$ with daily mortality.

In the first stage, we used the same analytical protocol as the PAPA project to obtain the city-specific estimates (6). Specifically, the protocol comprises specification for selection of monitoring stations and quality assurance or quality control for the data collection, health outcomes, and air pollutants to be included in the analysis. The protocol also included the methods to standardize data management, including compilation of daily data.

To control long-term and seasonal trends of daily mortality and weather conditions, we used generalized linear modeling with natural spline smoothers to model daily mortality (15). The partial autocorrelation function (PACF) was used to guide the selection of degrees of freedom (df) for time trend in the core models. Specifically, 4–6 df per year were used for the time trend. When the absolute magnitude of the PACF plot was less than 0.1 for the first 2 lag days, the core models were regarded as adequate (16). If this criterion was not met, autoregression terms were used to reduce autocorrelation (17). The day of the week was included as a dummy variable in the models. Residuals of the core models were examined to check whether there were discernible patterns and autocorrelation by means of residual plots and PACF plots.

After establishing the basic model, we introduced the air pollutants’ concentrations and weather conditions into the model. Based on the previous literature (6), 3 df (whole period of study) for current-day temperature and humidity (lag 0) and 2 df for lag 1 could control well for their associations with mortality and therefore were used in the model.

Briefly, we fitted the following model to obtain the estimated PM$_{10}$ log-relative rate $\beta$:

$$
\log E(Y_t) = \beta Z_t + \text{DOW} + \text{ns(time, df)} + \text{ns(temperature/humidity, 3)}.
$$

Here, $E(Y_t)$ represents the expected number of deaths at day $t$; $\beta$ represents the log-relative rate of mortality associated with a unit increase of PM$_{10}$; $Z_t$ indicates the PM$_{10}$ concentrations at day $t$; “DOW” is the dummy variable for day of the week; ns(time, df) is the natural spline function of calendar time; and ns(temperature/humidity, 3) is the natural spline function of temperature and humidity with 3 df.

At the second stage, we used Bayesian hierarchical models to obtain the national average estimates of the association of PM$_{10}$ with mortality (18, 19). This approach provides a flexible tool to pool risk estimates while accounting for within-city statistical error and between-city variability (heterogeneity) of the “true” risks. The model produced a posterior probability distribution of the pooled mean estimates, from which we reported the combined log-relative risks as the posterior mean and 95% posterior interval. We performed the chi-square test to examine heterogeneity of the city-specified risks (Cochran’s $Q$ test) (20).

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**Table 1.** Descriptive Data on the Study Period, Population, Outcome (Daily Death Number), Exposure (PM$_{10}$), and Temperature in the CAPES Cities, 1996–2008

<table>
<thead>
<tr>
<th>City</th>
<th>Study Period</th>
<th>Population (Millions)</th>
<th>Mean No. of Deaths per Day</th>
<th>Daily PM$_{10}$ Concentration, $\mu$g/m$^3$</th>
<th>No. of Air Monitors</th>
<th>Mean Temperature ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Cardiovascular Respiratory</td>
<td>Minimum 25th Percentile Mean 75th Percentile Maximum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anshan</td>
<td>2001–2004</td>
<td>2.4</td>
<td>28 14</td>
<td>20 69 111 139 469 2</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>Beijing</td>
<td>2007–2008</td>
<td>12.3</td>
<td>118 54 14</td>
<td>12 78 139 176 600 12</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td>Fuzhou</td>
<td>2004–2006</td>
<td>1.8</td>
<td>16 7 2</td>
<td>9 45 72 91 234 4</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>Guangzhou</td>
<td>2007–2008</td>
<td>6.5</td>
<td>79 29 15</td>
<td>11 44 74 91 236 9</td>
<td>22.8</td>
<td></td>
</tr>
<tr>
<td>Hangzhou</td>
<td>2002–2004</td>
<td>2.5</td>
<td>20 7 4</td>
<td>14 80 121 145 476 10</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1996–2002</td>
<td>6.7</td>
<td>84 24 16</td>
<td>14 32 52 67 189 7</td>
<td>23.7</td>
<td></td>
</tr>
<tr>
<td>Lanzhou</td>
<td>2004–2008</td>
<td>1.9</td>
<td>19</td>
<td>12 88 156 186 1,860 5</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>Shanghai</td>
<td>2001–2004</td>
<td>8.5</td>
<td>119 44 14</td>
<td>14 56 102 128 567 9</td>
<td>17.7</td>
<td></td>
</tr>
<tr>
<td>Shenyang</td>
<td>2005–2008</td>
<td>6.4</td>
<td>67 32 6</td>
<td>20 83 114 134 474 2</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Suzhou</td>
<td>2005–2008</td>
<td>4.1</td>
<td>34 13 5</td>
<td>10 56 90 113 428 8</td>
<td>17.2</td>
<td></td>
</tr>
<tr>
<td>Taiyuan</td>
<td>2004–2006</td>
<td>2.6</td>
<td>24 9 2</td>
<td>15 90 132 159 508 9</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>Tangshan</td>
<td>2006–2008</td>
<td>1.9</td>
<td>19 8 3</td>
<td>19 66 98 117 347 6</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>Tianjin</td>
<td>2005–2008</td>
<td>1.2</td>
<td>11 6 1</td>
<td>10 63 101 124 480 13</td>
<td>13.3</td>
<td></td>
</tr>
<tr>
<td>Urumqi</td>
<td>2006–2007</td>
<td>2.3</td>
<td>17 7 2</td>
<td>23 59 144 174 882 3</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>Wuhan</td>
<td>2003–2005</td>
<td>4.5</td>
<td>58 33 7</td>
<td>25 88 130 165 370 10</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td>Xi’an</td>
<td>2004–2008</td>
<td>3.4</td>
<td>26 12 7</td>
<td>31 94 132 150 2,061 7</td>
<td>13.4</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: CAPES, China Air Pollution and Health Effects Study; PM$_{10}$, particulate matter with an aerodynamic diameter of less than 10 $\mu$m.

* Cause-specific mortality data were not available in Lanzhou.
Single-day lag models might underestimate the cumulative association of \( \text{PM}_{10} \) with mortality (15); therefore, we used the 2-day moving average of current and previous day’s concentrations (lag 01) of \( \text{PM}_{10} \) for our main analyses. As a sensitivity analysis, we also examined the associations with different lag structures, including both single-day lag (from lag 0 to lag 7) and multiday lag (lag 01, lag 04, and lag 07). In single-day lag models, a lag of 0 days (lag 0) corresponds to the current-day \( \text{PM}_{10} \) concentration, and a lag of 1 day (lag 1) refers to the previous day’s concentration; in multiday lag models, lag 07 corresponds to an 8-day moving average of \( \text{PM}_{10} \) concentration of the current and previous 7 days. We fitted both single-pollutant and 2-pollutant models to assess the stability of the associations. In the single-pollutant models, \( \text{PM}_{10} \) was included alone in the model; in the 2-pollutant models, \( \text{PM}_{10} \) and sulfur dioxide (or nitrogen dioxide) were included jointly at the same lag. We also conducted stratified analyses by gender, age, and education for total mortality. We tested the statistical significance of differences between effect estimates of the strata of a potential effect modifier (e.g., the difference between females and males) by calculating the 95% confidence interval as

\[
(\hat{Q}_1 - \hat{Q}_2) \pm 1.96 \sqrt{SE_1^2 + SE_2^2},
\]

where \( \hat{Q}_1 \) and \( \hat{Q}_2 \) are the estimates for the 2 categories, and \( SE_1 \) and \( SE_2 \) are their respective standard errors (11). Regardless of significance, we considered modification of effect by a factor of 2 or more to be important and worthy of attention (11). Considering that \( \text{PM}_{10} \) health effects may vary by pollution levels (3), we divided these Chinese cities into 3 groups based on their \( \text{PM}_{10} \) levels and analyzed the association of \( \text{PM}_{10} \) with mortality in each group. Finally, given that it is not easy to determine the optimal values of df for time trend, we did sensitivity analyses to test the impact of alternative df values on the association of \( \text{PM}_{10} \) with mortality.

The first- and second-stage analyses were conducted in R, version 2.13.1, using the \textit{MGCV} and \textit{TLNISE} packages, respectively (21). The results are presented as the percentage change in daily mortality per 10-\( \mu \)g/m\(^3\) increase of \( \text{PM}_{10} \) concentrations.

**RESULTS**

Table 1 summarizes the population, mortality, \( \text{PM}_{10} \), and temperature data in the 16 Chinese cities. The daily mean numbers of total, cardiovascular, and respiratory deaths varied according to the size of the city and ranged from 11 to 119, from 6 to 54, and from 1 to 16, respectively. On average, cardiorespiratory diseases accounted for 49% of the total nonaccidental deaths in these cities. The averaged daily concentrations of \( \text{PM}_{10} \) in the Chinese cities ranged from 52 \( \mu \)g/m\(^3\) to 156 \( \mu \)g/m\(^3\), which were much higher than those reported in developed countries (3–5). Generally, \( \text{PM}_{10} \) levels in northern Chinese cities were higher than those in southern Chinese cities. The averaged temperature ranged from 7.4°C to 23.7°C.

The correlation coefficient among \( \text{PM}_{10} \), sulfur dioxide, and nitrogen dioxide differed across cities, ranging from 0.51 to 0.87. \( \text{PM}_{10} \) was weakly correlated with temperature and relative humidity (data not shown).

In the single-pollutant models, the associations of \( \text{PM}_{10} \) (lag 01) with daily mortality varied by cities and causes of deaths (Figure 2). We observed statistically significant associations of \( \text{PM}_{10} \) with total, cardiovascular, and respiratory mortality in most of the cities we examined. Chi-square tests showed that the heterogeneity was significant for total (\( P < 0.01 \)), cardiovascular (\( P < 0.01 \)), and respiratory (\( P < 0.05 \)) mortality. When considering the national average association of \( \text{PM}_{10} \), we estimated an increase of 0.35% (95% posterior interval (PI): 0.18, 0.52) of total mortality, 0.44% (95% PI: 0.23, 0.64) of cardiovascular mortality, and 0.56% (95% PI: 0.31, 0.81) of respiratory mortality associated with a 10-\( \mu \)g/m\(^3\) increase of \( \text{PM}_{10} \).

In the 2-pollutant model, the associations of \( \text{PM}_{10} \) with total and cardiopulmonary mortality decreased but remained statistically significant after sulfur dioxide or nitrogen dioxide was added in the models (Table 2). For example, after adjustment for sulfur dioxide and nitrogen dioxide, a 10-\( \mu \)g/m\(^3\) increase in 2-day moving averaged \( \text{PM}_{10} \) was associated with a 0.24% (95% PI: 0.01, 0.47) and 0.16% (95% PI: 0.00, 0.32) increase of total mortality, respectively. The associations of sulfur dioxide and nitrogen dioxide with daily mortality were summarized in Appendix Table 1.

\( \text{PM}_{10} \) showed similar lag patterns for its association with total and cardiopulmonary mortality (Figure 3). For single-day lags, the risks of total and cardiovascular mortality decreased from lag-day 0 to 7 and became negative after lag-day 4, suggesting that some “harvesting” effect may exist (22); the risk of respiratory mortality remained positive but became statistically insignificant after lag-day 3. Multiday (lag 01 and lag 04) exposures usually have larger effect estimates than single-day exposures; however, the associations of multiday (lag 07) exposure were significant for respiratory mortality only.

The associations between \( \text{PM}_{10} \) and total mortality varied by gender, age group, and educational attainment (Table 3). The effect estimate of \( \text{PM}_{10} \) among females was higher than that among males, although their between-gender difference was statistically insignificant. Deaths under age 5 were too few and therefore were excluded from our analysis. We did not observe a significant association of \( \text{PM}_{10} \) among residents aged 5–64 years. Among the elderly aged 65 years or more, the effect estimate was significant and approximately 3 times higher than that among people aged 5–64 years, and the between-age difference was statistically significant. The effect estimate of \( \text{PM}_{10} \) among residents with low educational attainment (illiterate or primary school) was approximately twice that among those with high educational attainment (middle school or above), although the between-education difference was not significant.

The associations of \( \text{PM}_{10} \) with mortality also varied by the cities’ pollution level (Table 4). The Chinese cities with low \( \text{PM}_{10} \) levels (from 52 to approximately 98 \( \mu \)g/m\(^3\)) reported approximately 2–3 times higher estimates, per 10 \( \mu \)g/m\(^3\) increase in \( \text{PM}_{10} \), than the cities with middle (from 101 to approximately 121 \( \mu \)g/m\(^3\)) or high (130 to approximately 144 \( \mu \)g/m\(^3\)) \( \text{PM}_{10} \) level. The differences between high- and low-level cities were significant for both total and cause-specific mortality.

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Within the range of 3–12, the change of df/year for time trend did not substantially affect the association of PM$_{10}$ with mortality (data not shown), suggesting that our findings are relatively robust in this aspect.

**DISCUSSION**

Our multicity analysis in 16 Chinese cities showed that PM$_{10}$ was significantly associated with mortality from all causes and from cardiopulmonary diseases. The associations of PM$_{10}$ remained statistically significant after adjustment for gaseous co-pollutants. Our findings were generally insensitive to alternative model specifications, such as lag structures of PM$_{10}$ and df for time trend. Our analysis also provided preliminary, but not conclusive, evidence that females, older people, and residents with low educational attainment might be more vulnerable to PM$_{10}$ than males, younger people, and residents with high educational attainment. The increased

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**Table 2.** Pooled Estimates (Mean and 95% PI) for the Increase in Mortality Associated With an Increase of 10 $\mu$g/m$^3$ in PM$_{10}$ in the CAPES Cities, 1996–2008

<table>
<thead>
<tr>
<th>Model Choice</th>
<th>Total Mortality</th>
<th>Cardiovascular Mortality</th>
<th>Respiratory Mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% PI</td>
<td>Mean</td>
</tr>
<tr>
<td>Single-pollutant model</td>
<td>0.35</td>
<td>0.18, 0.52</td>
<td>0.44</td>
</tr>
<tr>
<td>Multipollutant model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Sulfur dioxide</td>
<td>0.24</td>
<td>0.01, 0.47</td>
<td>0.35</td>
</tr>
<tr>
<td>+ Nitrogen dioxide</td>
<td>0.16</td>
<td>0.00, 0.32</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Abbreviations: CAPES, China Air Pollution and Health Effects Study; PI, posterior interval; PM$_{10}$, particulate matter with an aerodynamic diameter of less than 10 $\mu$m.

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Figure 2. Percentage increase of mortality associated with a 10-$\mu$g/m$^3$ increase of 2-day moving average PM$_{10}$ concentrations in the CAPES cities, China, 1996–2008. Effect estimates of individual cities (mean and 95% confidence interval) and national average values (mean and 95% posterior intervals) are shown. A, total mortality; B, cardiovascular mortality; C, respiratory mortality (cause-specific mortality data were not available in Lanzhou). CAPES, China Air Pollution and Health Effects Study; PM$_{10}$, particulate matter with an aerodynamic diameter of less than 10 $\mu$m.
mortality risks per amount of PM$_{10}$ may vary by the cities’ pollution levels. To our knowledge, this is the largest epidemiologic study to date in China to examine the association of PM$_{10}$ with daily mortality.

In the present analysis, an increase of 10 $\mu$g/m$^3$ of 2-day moving average concentrations of PM$_{10}$ corresponds to 0.35%, 0.44%, and 0.56% increase of total, cardiovascular, and respiratory mortality, respectively. Generally, the magnitudes of our estimates for PM$_{10}$ in China are comparable with previous multicity and meta analyses world-wide. For example, a recent large-scale multicity air pollution time-series analysis, the APHENA (Air Pollution and Health: A Combined European and North American Approach) study, estimated that a 10-$\mu$g/m$^3$ increase of 2-day moving averaged PM$_{10}$ (lag 01) corresponded to a 0.29% (95% confidence interval (CI): 0.14, 0.45) increase of total mortality in Europe and a 0.14% (95% CI: −0.12, 0.40) increase in the United States (5). In a previous meta-analysis of 109 time-series studies of PM$_{10}$ and daily mortality, most of which were conducted in North America and Europe, Stieb et al. (23, 24) estimated that the excess all-causes mortality change (single-pollutant models) associated with a change in pollutant concentration was 0.64% (95% CI: 0.48, 0.77) per 10-$\mu$g/m$^3$ increase of PM$_{10}$. Moreover, a new meta-analysis of Asian literature indicated that a 10-$\mu$g/m$^3$ increase of PM$_{10}$ was associated with a 0.33% (95% CI: 0.16, 0.51) increase of total mortality (25). Another meta-analysis of PM$_{10}$ based on Chinese studies estimated that a 10-$\mu$g/m$^3$ increase of PM$_{10}$ corresponded to a 0.44% (95% CI: 0.13, 0.76) increase of total mortality (26). The broad consistency in the literature suggests that the association of particulate air pollution with mortality is not likely to be changed substantially by such characteristics as geography, climate, and population nor by publication bias and model specifications.

We observed heterogeneity of the association of PM$_{10}$ in various Chinese cities (Figure 2). This difference may be explained by the characteristics of the study sites, such as indoor air pollution, weather patterns, sensitivity of local residents to PM$_{10}$ (e.g., socioeconomic status, age, smoking rate), PM$_{10}$ levels, and especially components of PM$_{10}$ (27). Our study found that the cities with higher PM$_{10}$ levels generally reported lower effect estimates, per unit increase of PM$_{10}$ concentrations, compared with the cities with low PM$_{10}$ levels (Table 4).

![Figure 3. Percentage increase (mean and 95% posterior intervals) of daily mortality associated with a 10-$\mu$g/m$^3$ increase of pollutant concentrations, using different lag structures of PM$_{10}$, in the CAPES cities, China, 1996–2008. CAPES, China Air Pollution and Health Effects Study; PM$_{10}$, particulate matter with an aerodynamic diameter of less than 10 $\mu$m.](image-url)
One study suggested that the exposure-response curves of particulate matter often tend to become flat at higher concentrations (28). Another potential explanation for heterogeneity in the associations of PM$_{10}$ is that the toxic components of PM$_{10}$ may vary by cities (29). Different research periods in each city may also contribute to the heterogeneity that we observed (30).

We found a larger effect estimate of PM$_{10}$ on total mortality in females than in males. Results of prior studies on the gender-specific effects of particulate matter were inconsistent (31). The reasons for our gender-specific observations are unclear and deserve further investigation. In China, females have a much lower smoking rate than males (32). One study suggested that the effect estimate of air pollution might be stronger in nonsmokers compared with smokers (33). The oxidative and inflammatory effects of smoking may dominate to such an extent that the additional exposure to PM$_{10}$ may not further enhance effects along the same pathways in males. In addition, females have slightly greater airway reactivity than males as well as smaller airways (34); therefore, dose-response relations might be detected more easily in females than in males.

Like a few other studies (9–11), our study found higher susceptibility to PM$_{10}$ among the elderly. Preexisting cardiopulmonary disorders in the elderly are more prevalent than in younger age groups; thus, there is some overlap between potentially susceptible groups of the elderly and people with heart or lung diseases. Consistent with previous reports (11, 17), our study found that residents with low educational attainment were more sensitive to PM$_{10}$ than those with high educational attainment, suggesting that lower socioeconomic status may comprise a risk factor for PM$_{10}$-related health impact. The modifying effect of education observed in our study may be due to varying exposures, differing prevalence of comorbid conditions, or other systematic differences related to degree of education that were not fully elucidated with the study designs we used.

Not surprisingly, we found statistically significant associations of PM$_{10}$ after we adjusted for gaseous pollutants, suggesting that PM$_{10}$ is important for the air pollution mixture in China. The biologic mechanism by which exposure to PM$_{10}$ may increase mortality is not well understood but has received considerable attention (35). For example, particulate matter has been associated with increased plasma viscosity (36); changes in the characteristics of the blood (37); and anomaly indicators of autonomic function of the heart including increased heart rate, decreased heart rate variability, and increased cardiac arrhythmias (38). These findings provide possible pathways by which particulate matter affects the cardiopulmonary system. Our study confirmed previous findings that the association between particulate matter and the mortality risks of cardiopulmonary diseases was stronger than all-cause mortality risk (9). Interestingly, our study also showed that the association of PM$_{10}$ with respiratory mortality risk was stronger than that with cardiovascular death risk, which is consistent with previous meta-analyses (23, 24).

Although the increased mortality risks found in these Chinese cities are similar in magnitude, per amount of PM$_{10}$ concentrations, to the risks found in other parts of the world, the importance of this increased risk for mortality is greater in China than that in North America or Europe, because the PM$_{10}$ level in China is much higher. Therefore, particulate air pollution may represent a major and growing public health problem in Chinese cities.

Our analysis has strengths and limitations. These 16 Chinese cities offer advantages for the study of the particulate matter–mortality relation in that they are generally very densely populated. As in most previous time-series studies, we simply averaged the monitoring results across various stations as the proxy for population exposure level to particulate matter. The simple averaging method may raise a number of issues given that pollutant measurements can differ from monitoring location to monitoring location and that ambient monitoring results differ from personal exposure level to particulate matter (39). Numerous factors, such as air conditioning and ventilation rate between indoor and outdoor air, may affect the monitoring results from fixed stations as surrogates of personal exposure to air pollutants (40). Because we were unable to measure the true population exposures of particulate matter in these Chinese cities, we could...
not determine the direction of the bias and its impact on our conclusions.

In summary, we found significant association of PM\(_{10}\) with mortality in 16 Chinese cities. The associations were generally independent of sulfur dioxide and nitrogen dioxide. Sociodemographic factors, such as gender, age, and socioeconomic status, may modify the association of PM\(_{10}\) with mortality. Our findings suggest that the role of outdoor exposure to PM\(_{10}\), especially the ambient-personal associations, should be investigated further in the country.

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### Appendix Table 1. Pooled Estimates for the Increase in Mortality Associated With an Increase of 10 μg/m³ in Sulfur Dioxide and Nitrogen Dioxide in the CAPES Cities, 1996–2008a

<table>
<thead>
<tr>
<th>Pollutant and Model</th>
<th>Total Mortality</th>
<th>Cardiovascular Mortality</th>
<th>Respiratory Mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate, %</td>
<td>95% PI</td>
<td>Estimate, %</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-pollutant model</td>
<td>0.77</td>
<td>0.47, 1.06</td>
<td>0.83</td>
</tr>
<tr>
<td>Multipollutant model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ PM10</td>
<td>0.40</td>
<td>0.14, 0.67</td>
<td>0.34</td>
</tr>
<tr>
<td>+ Nitrogen dioxide</td>
<td>0.17</td>
<td>−0.07, 0.41</td>
<td>0.21</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
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<td></td>
<td></td>
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<tr>
<td>Single-pollutant model</td>
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<td>1.09, 2.17</td>
<td>1.80</td>
</tr>
<tr>
<td>Multipollutant model</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>+ PM10</td>
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<td>0.68, 1.89</td>
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<tr>
<td>+ Sulfur dioxide</td>
<td>1.38</td>
<td>0.80, 1.95</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Abbreviations: CAPES, China Air Pollution and Health Effects Study; PI, posterior interval; PM10, particulate matter with an aerodynamic diameter of less than 10 μm.

*a Average of lag 0 and lag 1 of the 24-hour average concentrations.