Acute Effect of Ambient Air Pollution on Stroke Mortality in the China Air Pollution and Health Effects Study

Renjie Chen, MD*; Yuhao Zhang, MD*; Chunxue Yang, MPH; Zhuohui Zhao, PhD; Xiaohui Xu, PhD; Haidong Kan, PhD

**Background and Purpose**—There have been no multicity studies on the acute effects of air pollution on stroke mortality in China. This study was undertaken to examine the associations between daily stroke mortality and outdoor air pollution (particulate matter <10 μm in aerodynamic diameter, sulfur dioxide, and nitrogen dioxide) in 8 Chinese cities.

**Methods**—We used Poisson regression models with natural spline-smoothing functions to adjust for long-term and seasonal trends, as well as other time-varying covariates. We applied 2-stage Bayesian hierarchical statistical models to estimate city-specific and national average associations of air pollution with daily stroke mortality.

**Results**—Air pollution was associated with daily stroke mortality in 8 Chinese cities. In the combined analysis, an increase of 10 μg/m³ of 2-day moving average concentrations of particulate matter <10 μm in aerodynamic diameter, sulfur dioxide, and nitrogen dioxide corresponded to 0.54% (95% posterior intervals, 0.28–0.81), 0.88% (95% posterior intervals, 0.54–1.22), and 1.47% (95% posterior intervals, 0.88–2.06) increase of stroke mortality, respectively. The concentration–response curves indicated linear nonthreshold associations between air pollution and risk of stroke mortality.

**Conclusions**—To our knowledge, this is the first multicity study in China, or even in other developing countries, to report the acute effect of air pollution on stroke mortality. Our results contribute to very limited data on the effect of air pollution on stroke for high-exposure settings typical in developing countries. *(Stroke. 2013;44:954-960.)*

**Key Words:** air pollution ■ China ■ mortality ■ stroke
The Chinese Government has mandated detailed quality assurance and quality control programs at each monitoring station providing air pollution data. The daily (24-hour) average concentrations of PM10, SO2, and NO2 were collected from the National Air Pollution Monitoring System, which is certified by the Ministry of Environmental Protection of China. Each city had between 2 and 12 monitoring stations (Table 1). The Chinese Government has mandated detailed quality assurance and quality control programs at each monitoring station providing air pollution data. The daily (24-hour) average concentrations of PM10, SO2, and NO2 were measured using tapered element oscillating microbalance, ultraviolet fluorescence, and chemiluminescence methods, respectively. For the calculation of 24-hour mean concentrations, at least 75% of the 1-hour values had to be available on that particular day. If a station had >25% of the values missing for the whole period of analysis, the entire station was excluded. Per Chinese Government rules, the location of monitoring stations are mandated to not be in the direct vicinity of traffic or of industrial sources, and not be influenced by local pollution sources, and to avoid buildings, or those housing 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.14

To allow adjustment for the effect of weather conditions on stroke mortality, meteorologic data (daily mean temperature and relative humidity) were obtained from each city.

Statistical Analysis
We applied 2-stage Bayesian hierarchical statistical models to estimate city-specific and national average associations of air pollution, with daily stroke mortality.15

In the first stage, we applied the generalized additive models with quasi-Poisson regression to examine the association between air pollution and stroke mortality. We incorporated natural cubic smooth functions of calendar time with 8 degrees of freedom (df) per year in the generalized additive models to control for the long-term and seasonal trends of daily stroke mortality. We also included day of the week as an indicator variable. To control for the confounding effects of weather conditions, we applied natural smooth functions with 6 df for temperature and 3 df for humidity. After we established the basic models, we introduced the pollutant variables and analyzed their effects on stroke mortality. We fitted single-pollutant models and used 2-day moving average of current and previous day concentrations of air pollutants (lag 01) for our main analyses.

In the second stage, we used Bayesian hierarchical models to obtain the national average estimates of the association between air pollution and daily stroke mortality.16 This approach provides a flexible tool to pool risk estimates, whereas accounting for within-city statistical error and between-city variability (heterogeneity) of the true risks. The model generated 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 (PI). We performed a χ² test to examine heterogeneity of the city-specified risks (Cochran Q test).17

Because the assumption of the linearity between the log of stroke mortality and air pollution level may not be justified, we used the same approach as the Air Pollution and Health—A European Approach project to combine the city-specific concentration–response relationship curves to get overall associations between air pollution and stroke mortality.18 We compared the linear and spline models by computing the difference between the deviances of the 2 fitted models.19

We performed 3 sensitivity analyses to examine the robustness of our findings. First, we fitted 2-pollutant models to assess the stability of the pollutants' effect. Second, we estimated air pollution's effects on stroke mortality using different lag structures, including both single-day lags (from lag 0 to lag 4) and multiday lags (lag 01 and lag 04). In single-day lag models, a lag of 0 days (lag 0) corresponded to the current-day air pollutants concentration, and a lag of 1 day (lag 1) referred to the previous-day concentration; in multiday lag models, lag 04 meant the 5-day moving average concentrations of current day and the previous 4 days. Third, we tested the impact of alternative df values for time trend on the association between air pollution and stroke mortality.

The first- and second-stage analyses were conducted in R 2.15.1 using the mixed GAM computation vehicle with GCV/AIC/REML smoothness estimation and two-level normal independent sampling estimation packages, respectively. All statistical tests were 2-sided and probability values of <0.05 were considered statistically significant. The results are presented as the percentage change in daily stroke mortality per 10 μg/m³ increase of air pollutants’ concentrations.

Results
Table 1 summarizes the study period, population, exposure (PM10, SO2, and NO2), outcome (daily stroke mortality), and
mean temperature in 8 Chinese cities. The population size at each city varied from 1.8 to 12.3 millions, with a total population of 48.2 million. The daily mean number of stroke deaths varied according to the size of the city and ranged from 4 (Tangshan) to 26 (Shanghai). There were no missing data for the air pollution measurements. The averaged daily concentrations ranged from 52 μg/m$^3$ (Hong Kong) to 139 μg/m$^3$ (Beijing) for PM$_{10}$, from 16 μg/m$^3$ (Fuzhou) to 84 μg/m$^3$ (Tangshan) for SO$_2$, and from 37 μg/m$^3$ (Shenyang) to 67 μg/m$^3$ (Shanghai) for NO$_2$. Generally, the reported air pollution levels in these Chinese cities were much higher than those reported in developed countries.\textsuperscript{20,21} The mean temperature ranged from 8.2°C (Shenyang) to 23.7°C (Hong Kong). The correlation coefficients between PM$_{10}$, SO$_2$, and NO$_2$ differed across cities, ranging from 0.51 to 0.87 (data not shown).

In the single-pollutant models, the associations of daily stroke mortality with air pollutants (lag 01) varied between cities (Figure 2). We observed statistically significant associations of daily stroke mortality with PM$_{10}$, SO$_2$, and NO$_2$ in most of the cities we examined. $\chi^2$ tests showed the heterogeneity was

Table 1. Descriptive Statistics in This Study

<table>
<thead>
<tr>
<th>City</th>
<th>Study Period</th>
<th>Population (Million)</th>
<th>No. of Air Monitors</th>
<th>Stroke Deaths Per Day</th>
<th>Air Pollutants' Concentrations (Mean and Standard Deviation, μg/m$^3$)</th>
<th>Mean Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>2007–2008</td>
<td>12.3</td>
<td>12</td>
<td>23</td>
<td>PM$_{10}$: 139 (87); SO$_2$: 41 (43); NO$_2$: 58 (25)</td>
<td>14.8</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>2004–2006</td>
<td>1.8</td>
<td>4</td>
<td>4</td>
<td>PM$_{10}$: 72 (37); SO$_2$: 16 (7); NO$_2$: 45 (9)</td>
<td>20.7</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>2007–2008</td>
<td>6.5</td>
<td>9</td>
<td>10</td>
<td>PM$_{10}$: 74 (40); SO$_2$: 50 (33); NO$_2$: 66 (32)</td>
<td>22.8</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1996–2002</td>
<td>6.7</td>
<td>7</td>
<td>9</td>
<td>PM$_{10}$: 52 (25); SO$_2$: 18 (12); NO$_2$: 56 (20)</td>
<td>23.7</td>
</tr>
<tr>
<td>Shanghai</td>
<td>2001–2004</td>
<td>8.5</td>
<td>9</td>
<td>26</td>
<td>PM$_{10}$: 102 (65); SO$_2$: 45 (24); NO$_2$: 67 (25)</td>
<td>17.7</td>
</tr>
<tr>
<td>Shenyang</td>
<td>2005–2008</td>
<td>6.4</td>
<td>2</td>
<td>15</td>
<td>PM$_{10}$: 114 (50); SO$_2$: 55 (44); NO$_2$: 37 (15)</td>
<td>8.2</td>
</tr>
<tr>
<td>Suzhou</td>
<td>2005–2008</td>
<td>4.1</td>
<td>8</td>
<td>7</td>
<td>PM$_{10}$: 90 (48); SO$_2$: 45 (21); NO$_2$: 45 (21)</td>
<td>17.2</td>
</tr>
<tr>
<td>Tangshan</td>
<td>2006–2008</td>
<td>1.9</td>
<td>6</td>
<td>4</td>
<td>PM$_{10}$: 98 (47); SO$_2$: 84 (60); NO$_2$: 41 (18)</td>
<td>12.6</td>
</tr>
</tbody>
</table>

PM$_{10}$ indicates particulate matter <10 μm in aerodynamic diameter; and SO$_2$, sulfur dioxide.

Figure 2. Percentage increase of stroke mortality associated with 10 μg/m$^3$ increase of 2-day moving average air pollutant concentrations in 8 Chinese cities—effect estimates of individual cities (mean and 95% confidence intervals) and national average (mean and 95% posterior intervals; A, PM$_{10}$; B, SO$_2$; C, NO$_2$). NO$_2$ indicates nitrogen dioxide; PM$_{10}$, particulate matter <10 μm in aerodynamic diameter; and SO$_2$, sulfur dioxide.
significant for all 3 pollutants (P<0.05). When considering the national average associations, we estimated an increase of 0.54% (95% PI, 0.28–0.81), 0.88% (95% PI, 0.54–1.22), and 1.47% (95% PI, 0.88–2.06) in stroke mortality associated with a 10 μg/m³ increase of PM₁₀, SO₂, and NO₂, respectively.

Figure 3 shows the combined concentration–response curves of stroke mortality with air pollution. For all 3 pollutants, we observed almost linear relationships. The differences in the deviance between the linear and spline models did not indicate a statistically significant improvement in the fit of the spline versus linear models.

PM₁₀, SO₂, and NO₂ showed similar lag patterns for their effects on stroke mortality (Figure 4). For single-day lags, the risks of stroke mortality decreased between 0 and 4 days lag. Multiday exposures (lag 01 and lag 04) generally presented larger effect estimates than single-day exposure.

In the 2-pollutant model, the association of PM₁₀ with stroke mortality decreased but remained statistically significant by adding SO₂ into the models; however, adjustment for NO₂ lessened the association and rendered it statistically insignificant (Table 2). Similarly, adjustment for NO₂ rendered the association for SO₂ insignificant. In contrast, the effects of NO₂ remained statistically significant, after controlling for PM₁₀ or SO₂ in the models. For example, a 10 μg/m³ increase in the 2-day moving average of NO₂, after adjustment for PM₁₀ and SO₂, was associated with a 1.17% (95% PI, 0.47–1.88) and 1.35% (95% PI, 0.55–2.15) increase of stroke mortality, respectively.

Within the range of 4 to 10 df per year, changing its value for time trend control did not substantially affect the association of air pollution with stroke mortality (data not shown), suggesting that our findings are relatively robust in this aspect.

Discussion

Our multicity analysis found significant associations between major air pollutants (PM₁₀, SO₂, and NO₂) and increased risk of death from stroke in 8 Chinese cities. The combined concentration–response curves indicated linear associations between air pollution and risk of stroke mortality. We found significant effects of air pollution even below the latest Air Quality Standard in China (24-hour average: 150 μg/m³ for PM₁₀, 150 μg/m³ for SO₂, and 120 μg/m³ for NO₂). To our knowledge, this is the first multicity study in China, or even in other developing countries, to report the acute effects of air pollution on stroke mortality. Our findings may have implications for primary prevention of stroke in China.

In the current analysis, a 10 μg/m³ increase of PM₁₀, SO₂, and NO₂ was associated with a 0.54%, 0.88%, and 1.47% increase of stroke mortality, respectively. These estimates were similar to our previous estimates on cardiovascular mortality, suggesting that air pollution may have comparable hazards on cardiac and cerebrovascular health. Generally, the magnitude of our estimates was comparable with previous findings worldwide.22 In the Netherlands, for example, Hoek et al reported that a 10 μg/m³ increase of PM₁₀, SO₂, and NO₂ was associated with 0.4%, 1.3%, and 1.6% increase of stroke mortality, though the associations were significant for SO₂ only.23 In another study in Seoul, Korea, Hong et al estimated a 0.7% (95% confidence interval, 0.6–0.9) increase in stroke mortality per 10 μg/m³ of PM₁₀.7 In Hong Kong, however, Wong et al did not find statistically significant association between air pollution and stroke mortality.24 The heterogeneity of various findings may reflect differences in the analytic techniques used, aside from the different characteristics of the study sites. For instance, various statistical models, as well as the parameter setting in these models (eg, df selection and convergence criteria) can affect the effect estimates of time-series studies.25 In addition, characteristics of the study sites,
such as indoor air pollution, weather patterns, sensitivity of local residents to air pollution, outdoor air pollution levels, and especially components of pollution mixture, may affect the magnitudes of exposure–response relationships.26

We reported similar acute mortality risk of stroke as found in other parts of the world; however, the importance of this increased risk for stroke mortality is greater than in developed countries, not only because stroke burden is disproportionately high in China, but also because the air pollution level is much higher. It should be noted that we may have underestimated the stroke mortality burden from outdoor air pollution because we accounted only for the short-term effects.27 Future research should focus on the long-term effects of outdoor air pollution on cerebrovascular health (eg, individual-level cohort study) in China.

We observed heterogeneity of the association between air pollution and stroke mortality 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, housing types, sensitivity of local residents to air pollution (eg, socioeconomic status, age, and smoking rate), air pollution levels, and components of ambient particles. Different research periods in each city may also contribute to the heterogeneity we observed.

Among the pollutants we examined in the 8 Chinese cities, only NO₂ remained significantly associated with stroke mortality after adjustment for copollutants (Table 2). Our findings for NO₂ are robust and consistent with a recent multicity analysis in Europe (Air Pollution and Health—A European Approach).28 However, in the analysis of 20 US cities within the National Morbidity, Mortality and Air Pollution Study, no consistent pattern of association between stroke mortality and NO₂ was found.29 The difference between National Morbidity, Mortality and Air Pollution Study and Air Pollution and Health—A European Approach findings may be attributed to the varying air pollution sources and mixture in the United States and Europe.29 Most air pollution epidemiologic studies, including ours, use ambient pollutant concentrations as surrogates of personal exposure. Therefore, the observed health effects attributed to NO₂ might actually be a result of exposures to fine particles or traffic-related emissions.30 For example, Seaton et al suggested NO₂ is a surrogate for ultrafine particle measures;31 therefore, there is a possibility that the effect of NO₂ we observed might be because of other unmeasured pollutant such as ultrafine particle. In Europe and North America, NO₂ is typically a traffic-related pollutant; in China, however, both vehicles and coal-fired plants are major sources of NO₂. At present, we cannot conclude that NO₂ is a suitable proxy of particulate pollutant, or that it has direct effects on stroke mortality. The role of outdoor exposure to NO₂ should be investigated further.

The shape of exposure–response relationships is crucial for public health assessment, and there has been growing demand for studies to provide relevant curves. Previous multicity studies in the United States and Europe have explored the exposure–response relationship between air pollution and mortality, and generally supported a linear association without a threshold.32 In our study, we found significant effects of air pollution on stroke mortality, even below the current Air Quality Standard levels in China (Figure 3). Therefore, the current standards might not be sufficient to protect individuals from the negative cerebrovascular health effects in the country. Thus, further control of air pollution is likely to result in health benefits. A reduction in stroke morbidity and mortality after the implementation of an intervention program would add evidence to the hypothesis of a causal link between air pollution and cerebrovascular health.

The mechanisms by which air pollution affects the stroke deaths is still not clear, although some biological mechanisms have been proposed.33 For example, air pollution has been associated with increased plasma viscosity, changes in the

Table 2. Pooled Estimates (Mean and 95% PI) for the Increase in Stroke Mortality Associated With an Increase of 10 μg/m³ in 2-Day Moving Average Air Pollutant Concentrations, Using the Single- and Two-Pollutant Models

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Mean</th>
<th>95% PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM_{10}</td>
<td>0.54</td>
<td>0.28, 0.81</td>
</tr>
<tr>
<td>Adjusted for SO₂</td>
<td>0.38</td>
<td>0.10, 0.67</td>
</tr>
<tr>
<td>Adjusted for NO₂</td>
<td>0.14</td>
<td>-0.04, 0.31</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.88</td>
<td>0.54, 1.22</td>
</tr>
<tr>
<td>Adjusted for PM_{10}</td>
<td>0.54</td>
<td>0.06, 1.01</td>
</tr>
<tr>
<td>Adjusted for NO₂</td>
<td>0.16</td>
<td>-0.41, 0.72</td>
</tr>
<tr>
<td>NO₂</td>
<td>1.47</td>
<td>0.88, 2.06</td>
</tr>
<tr>
<td>Adjusted for PM_{10}</td>
<td>1.17</td>
<td>0.47, 1.88</td>
</tr>
<tr>
<td>Adjusted for SO₂</td>
<td>1.35</td>
<td>0.55, 2.15</td>
</tr>
</tbody>
</table>

NO₂ indicates nitrogen dioxide; PI, posterior intervals; PM_{10}, particulate matter <10 μm in aerodynamic diameter; and SO₂, sulfur dioxide.
characteristics of the blood, and indicators of abnormal autonomic function of the cerebrovascular system. These findings provide possible pathways in which air pollution affects stroke deaths.

Our analysis has limitations. First, we were not able to differentiate the subtypes (ischemic versus hemorrhagic) of stroke because of data limitations. Second, as in most previous time-series studies, we simply averaged the results across various monitoring stations as the proxy for population exposure levels. This simple averaging method may raise a number of issues, given that pollutant measurements can differ from monitoring location to monitoring location, and these differ from personal air pollutant exposure levels. Third, high correlation between PM$_{10}$, SO$_2$, and NO$_2$ in China limited our ability to separate the independent effect for each pollutant. Further research will be needed to disentangle the effects of the various pollutants on cerebrovascular health. Finally, we were not able to obtain the sex-, age-, and socioeconomic status-specific stroke mortality in these Chinese cities, which has limited our ability to examine potential modifiers of the association between air pollution and stroke mortality.

Conclusions

In summary, we found that short-term exposure to outdoor air pollution was associated with increased risk of death from stroke in China. To our knowledge, this is the first multicity study conducted in China, or in other even developing countries, to report the acute effect of air pollution on stroke mortality. Our results contribute to very limited data on the effect of air pollution on stroke for high-exposure settings typical in developing countries.

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Disclosures

None.

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