PM_{10} Exposure, Gaseous Pollutants, and Daily Mortality in Inchon, South Korea

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To evaluate the relative importance of various measures of particulate and gaseous air pollution as predictors of daily mortality in Inchon, South Korea, the association between total daily mortality and air pollution was investigated for a 20-month period (January 1995 through August 1996). Poisson regression was used to regress daily death counts on each air pollutant, controlling for time trends, season, and meteorologic influences such as temperature and relative humidity. Regression coefficients of a 5-day moving average of particulate matter ≤ 10 µm in aerodynamic diameter (PM_{10}) on total mortality were positively significant when considered separately and simultaneously with other pollutants in the model. PM_{10} remained significant when the models were confined to cardiovascular or respiratory mortality. Sulfur dioxide (SO_2) and carbon monoxide (CO) were significantly related to respiratory mortality in the single-pollutant model. Ozone exposure was not statistically significant with regard to mortality in the above models, and graphic analysis showed that the relationship was nonlinear. A combined index of PM_{10}, nitrogen dioxide, SO_2, and CO seemed to better explain the exposure–response relationship with total mortality than an individual air pollutant. Pollutants should be considered together in the risk assessment of air pollution, as opposed to measuring the risk of individual pollutants.

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The most acute air pollution episode in history occurred in London in 1952, when 4,000 excess deaths were attributed to air inversion. Other acute episodes have been reported in Donora, Pennsylvania, in 1948 and Los Angeles, California, in 1963. Since these episodes, investigations into the relationship between air pollution and mortality have demonstrated a positive association between air pollution levels and mortality, even at lower air pollution levels. A number of daily time–series studies have demonstrated an association between short-term exposure and increased mortality in air pollution areas when confounders were controlled (*1,2*). Daily mortality has been associated with total suspended particulates in Steubenville, Ohio (*3*); Philadelphia, Pennsylvania (*4*); and Mexico City, Mexico (*5*); and with particulate matter of ≤ 10 µm (PM_{10}) in Utah Valley, Utah (*2*); Birmingham, Alabama (*6*); St. Louis, Missouri, and Kingston, New York (*7*); and Amsterdam, The Netherlands (*8*). Most published U.S. studies show that particulate matter is the pollutant which exhibits this relationship most clearly (*2,3,9–13*), even though most of these studies have not considered multiple pollutants. The relationship between particulate air pollutants and mortality seems to continue well below current ambient air quality standards, and the exposure–response relationship is linear with no evidence of a threshold (*14–16*). Investigations have been carried out in Europe, although they yielded more diverse results in terms of the pollutant with the strongest associations. In most of the European studies there were significant relationships between mortality and either sulfur dioxide (SO_2) or particulate matter (*17–22*). Different areas of the world have different mixtures and levels of pollutants. Thus, it is unclear whether the same pollutants and mortality relationships found in the United States or Europe would apply to Inchon, an industrial city in South Korea.

Particulate matter levels in Inchon are much higher than in most developed countries; however, SO_2 levels have recently been decreasing rapidly. The combined effects of dust particles and other pollutants may play more important roles in the damaging process than dust particles alone. Combination indices of PM_{10} and gaseous pollutants can be useful tools to evaluate the relationship of pollutants with mortality; single or multiple pollutant models cannot analyze pollutant effects accurately when the pollutants are highly correlated with each other. Few studies have described the association between present levels of air pollution in East Asia and mortality. The objective of our study was to report on the association between daily mortality and ambient air pollution in Inchon, South Korea.

Materials and Methods

Daily mortality, weather, and air pollution data. Daily deaths for the Inchon area were read from the annual detail mortality tapes of the National Statistical Office (Taejon, Korea) for the period from 1 January 1995 to 31 August 1996. Cause-specific categories included in our analysis were total deaths, respiratory deaths, and cardiovascular deaths. The deaths due to accidents or violence were excluded from the total counts. Codes from the *International Classification of Diseases, 10th revision* (World Health Organization, Geneva) were used to define these categories.

The city of Inchon is located on the western side of the Korean peninsula, with a sea to the west and metropolitan Seoul to the east. It is the third largest city in the country. The 1996 census indicated that the population of Inchon was 2.4 million. Inchon has a four-season climate and low-level temperature inversions are common during the winter months. Data on 24-hr mean temperature and relative humidity were obtained from a centrally located Inchon weather station.

Air pollution data were obtained from the Department of the Environment (Seoul, Korea). Two monitoring sites for 24-hr measurements of PM_{10} and gaseous pollutants—SO_2, nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO)—were established in residential areas. Concentrations of these pollutants were measured hourly, and 24-hr averages were constructed between measurement sites. For O_3, a daytime 8-hr average was used instead of a 24-hr average.

Statistical analysis. The associations between daily mortality and air pollutants, as well as weather variables, were analyzed with a generalized additive model (GAM) estimating Poisson distribution. The relationship between pollution and mortality was complicated by the fact that periods with the highest pollution levels occurred during the winter months (with the exception of O_3), and the higher incidence of death may be at least partially due to cold winter weather. Seasonal change or time trends also could confound the pollutant effects. Daily mortality was fit

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to the GAM, which included loess function of temperature, relative humidity, time trends, and indicator variables of the season. Once these models were established, the association of each air pollutant and multiple pollutants in predicting daily mortality was evaluated separately. Air pollutants may affect mortality with some time lags, and the appropriate averaging time for exposure may exceed 24 hr. Therefore, single-day exposure and multiple-day moving averages of up to 6 days were examined. To consider the correlation between the pollutants, and to evaluate the combined effects of pollutants, we introduced indices of combination of primary gaseous pollutants with PM_{10} using a 5-day moving average of pollutant levels.

- Index of all pollutants = PM_{10} m^5/mean (PM_{10}) + NO_2 m^5/mean (NO^2) + SO_2 m^5/mean (SO_2) + CO m^5/mean (CO)
- Index of PM_{10} + NO_2 = PM_{10} m^5/mean (PM_{10}) + NO_2 m^5/mean (NO_2)
- Index of PM_{10} + SO_2 = PM_{10} m^5/mean (PM_{10}) + $SO_2$$m^5$/mean ($SO_2$)
- Index of PM_{10} + CO = PM_{10} m^5/mean (PM_{10}) + CO m^5/mean (CO)

A pollutant divided by the mean value reflects the relative variations and may be used when comparing it to other pollutants. Using these indices, we can evaluate the combined effects of pollutants that reflect real environments, and thus better predict the mortality risk. To graphically analyze the dose–response relationships, the relative risks of mortality for pollutants and the combined indices were plotted using the GAM.

Results

Table 1 shows the distribution of mortality, meteorologic measurements, and air pollution between 1 January 1995 and 31 August 1996 for Inchon. An average of 22 persons died in the city each day. The Pearson correlations between the variables and total mortality are presented in Table 2. Correlations between mortality and primary pollutants were small but significantly positive: They ranged from 0.05 to 0.19. A negative correlation between the daily mortality and O_3 was noticeable. There was also a negative correlation between the daily mortality and temperature or relative humidity. Correlations between exposure variables showed that there was a problem of collinearity among pollutants. PM_{10} was correlated significantly with other air pollutants, positively with NO_2, SO_2, and CO, and negatively with O_3.

A greater association with mortality was seen with the 5-day moving averages and the previous day's exposure than with other exposure variables. Tables 3–5 show the Poisson regression model, which includes time trends, season, and weather variables for temperature and relative humidity. In the models that included a 5-day moving average of one pollutant or multiple pollutants, PM_{10} was a significant predictor of total mortality, whereas gaseous pollutants remained insignificant. An increase in the 5-day moving average of PM_{10}, equal to 10 µg/m^3, was associated with an increase in the relative risk of mortality to 0.8%. When the previous day's concentrations were considered, PM_{10} and NO_2 were significant pollutants in the single-pollutant models. PM_{10} remained significant when the models were confined to cardiovascular or respiratory mortality. The association with PM_{10}, as measured by regression coefficients, was greatest for respiratory mortality. SO_2 and CO were significantly related to respiratory mortality in the single-pollutant model using the previous day's concentrations. However, O_3 was not statistically significant

Table 1. Mean values of variables related to daily mortality in Inchon.

Variables	No.	Mean ± SD	Range
Mortality (deaths/day)			
Total	609	22.1 ± 4.9	10–37
Cardiovascular	609	6.7 ± 2.7	1–18
Respiratory	609	1.2 ± 1.1	0–6
Meteorology			
Temperature (°C)	608	11.9 ± 10.1	-8.7–28.8
Relative humidity (%)	608	68.3 ± 15.8	26.1–96.8
Particulate pollution			
PM_{10} (µg/m^3)	583	71.2 ± 34.3	15.0–267.4
Gaseous pollution			
SO_2 (ppb)	601	18.0 ± 9.7	2.4–52.8
NO_2 (ppb)	600	24.1 ± 10.1	4.9–64.3
O_3 (ppb)	600	15.4 ± 7.4	2.1–49.0
CO (100 ppb)	589	15.2 ± 7.1	2.9–51.2

PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter.

Table 2. Pearson correlation coefficients between meteorologic and air pollutant variables and daily mortality.

Variables	Current exposure	5-day moving average	Previous day's exposure
Temperature	-0.21**	-0.22**	-0.20**
Relative humidity	-0.07	-0.15**	-0.08*
PM_{10}	0.06	0.12**	0.13**
NO_2	0.12**	0.18**	0.19**
SO_2	0.05	0.09*	0.10*
CO	0.08	0.11**	0.12**
O_3	-0.13**	-0.17**	-0.17**

PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter.
*$p < 0.05$. **$p < 0.01$.

Table 3. Regression coefficients and standard errors when 5-day moving averages and the previous day's concentrations of one pollutant and multiple pollutants are considered in the Poisson regression for total mortality.

	5-day moving average		Previous day	
Pollutants	Separately	Simultaneously	Separately	Simultaneously
PM_{10}	0.0008* (0.0004)	0.0027** (0.0010)	0.0007* (0.0003)	0.0005 (0.0003)
NO_2	0.0023 (0.0013)	0.0022 (0.0037)	0.0026** (0.0010)	0.0012 (0.0013)
SO_2	0.0017 (0.0021)	-0.0011 (0.0042)	0.0023 (0.0014)	-0.0005 (0.0019)
CO	0.0024 (0.0041)	-0.0018 (0.0043)	0.0019 (0.0015)	-0.0009 (0.0019)
O_3	-0.0027 (0.0031)	0.0002 (0.0060)	-0.0049* (0.0022)	-0.0038 (0.0025)

PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter.
*$p < 0.05$. **$p < 0.01$.

Table 4. Regression coefficients and standard errors when 5-day moving averages and the previous day's concentrations of one pollutant and multiple pollutants are considered in the Poisson regression for cardiovascular mortality.

	5-day moving average		Previous day	
Pollutants	Separately	Simultaneously	Separately	Simultaneously
PM_{10}	0.0010* (0.0005)	0.0010 (0.0007)	0.0007(0.0007)	0.0036* (0.0017)
NO_2	0.0016 (0.0018)	-0.0006 (0.0023)	0.0012 (0.0024)	0.0009 (0.0067)
SO_2	0.0044 (0.0025)	0.0029 (0.0034)	0.0058 (0.0038)	0.0031 (0.0074)
CO	-0.0008 (0.0028)	-0.0037 (0.0033)	0.0019 (0.0073)	-0.0053 (0.0078)
O_3	-0.0005 (0.0040)	-0.0003 (0.0045)	-0.0018 (0.0057)	0.0042 (0.0110)

PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter.
*$p < 0.05$.

Table 5. Regression coefficients and standard errors when 5-day moving averages and the previous day's concentrations of one pollutant and multiple pollutants are considered in the Poisson regression for respiratory mortality.

	5-day moving average		Previous day	
Pollutants	Separately	Simultaneously	Separately	Simultaneously
PM_{10}	0.0027 (0.0017)	0.0118* (0.0040)	0.0015 (0.0011)	-0.0001 (0.0016)
NO_2	0.0024 (0.0057)	-0.0075 (0.0160)	0.0044 (0.0042)	-0.0004 (0.0053)
SO_2	0.0052 (0.0090)	-0.0247 (0.0179)	0.0116* (0.0059)	-0.0068 (0.0078)
CO	0.0063 (0.0171)	-0.0034 (0.0183)	0.0148* (0.0065)	0.0121 (0.0079)
O_3	0.0066 (0.0135)	0.0170 (0.0261)	0.0001 (0.0093)	0.0084 (0.0103)

PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter.
*$p < 0.05$.

when related to mortality except for the previous day's concentrations in the single-pollutant model of total mortality. The direction of the coefficient was negative in its relationship with total and cardiovascular mortality and positive with respiratory mortality.

A loess function of 5-day moving averages of PM_{10}, NO_2, SO_2, and CO levels was used in the GAM to graphically analyze the dose–response relationship between pollutants and daily mortality. Figures 1 and 2 show the relative risks of total mortality by 5-day moving averages of pollutants and the combination indices of PM_{10} and primary gaseous pollutants. Excess mortality risk is clearly evident in the higher range of PM_{10} levels and the increase is dose responsive. When using combined indices of the pollutants, the exposure–response relationship for the index of overall pollutants was better than that of single pollutants or other combination indices. The index of PM_{10} + SO_2 also showed a near-linear increase of relative risk, which suggests that the joint effect model of PM_{10} and SO_2 is a better predictor of mortality risk than effect models of individual pollutants. Contour analysis illustrated this joint effect well, showing that when concentrations of the two pollutants were high, the mortality rate peaked (Figure 3).

Outputs from GAMs using a 5-day moving average and the previous day's concentrations were analyzed graphically to clarify the contradictory relationship between O_3 and daily mortality (Figure 4). There was a clear change of direction in the relationship at approximately 23 ppb O_3 concentration, suggesting that there is a threshold for the effects of O_3 on mortality.

Discussion

This study documents a strong association between mortality and particulate air pollution in Inchon during the period of January 1995 to August 1996. This association was statistically significant in a model controlling other variables, and exhibited an exposure–response relationship. The increase in mortality risk with a 10-µg/m^3 increase in PM_{10} was 0.8%. Results of most of the previous studies have suggested that a 10-µg/m^3 increase in PM_{10} is associated with an increase in daily mortality equal to 0.5–1.5% (*1*). The mortality studies in Utah Valley (*2*) and Philadelphia (*4*) show that deaths due to respiratory disease were most strongly associated with particulate pollution levels, and statistical associations were also observed for deaths due to cardiovascular disease. In our study the highest regression coefficients were in the model for respiratory mortality. However, they did not reach statistical significance except when using multiple models with a 5-day moving average because of the low frequency of nonmalignant respiratory death. We also found PM_{10} to be significantly related to cardiovascular mortality, but the regression coefficients were lower than those for respiratory mortality.

The sources and levels of ambient air pollution, as well as population characteristics and habits, vary widely among the

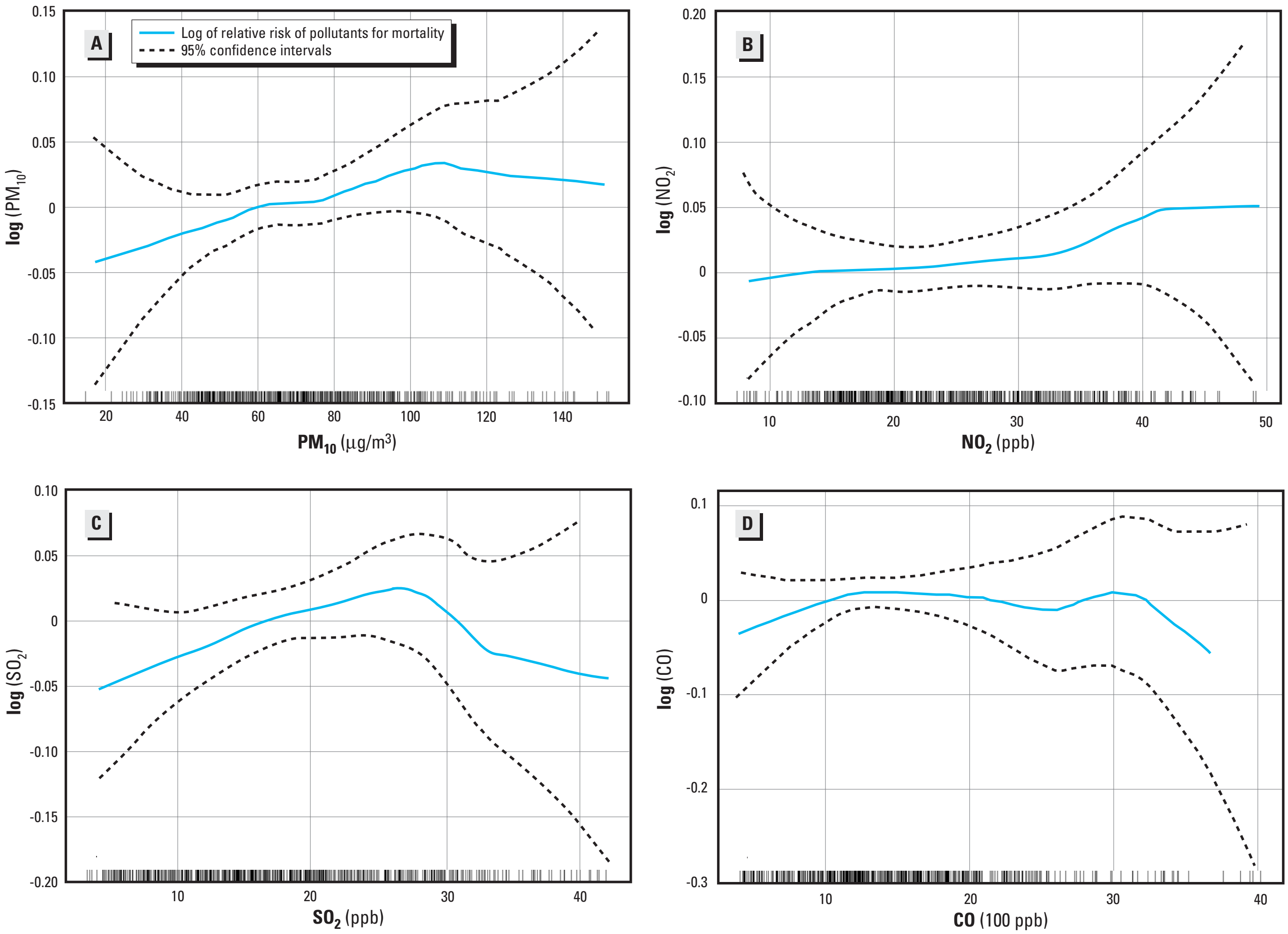

Figure 1. Graphic analysis of relationship of the primary pollutants [(*A*) PM_{10}, (*B*) nitrogen dioxide, (*C*) sulfur dioxide, and (*D*) carbon monoxide] with daily mortality by generalized additive model using loess function after controlling time trends, season, and weather variables. PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter. The 5-day moving average of pollutant concentrations is along the x-axis.

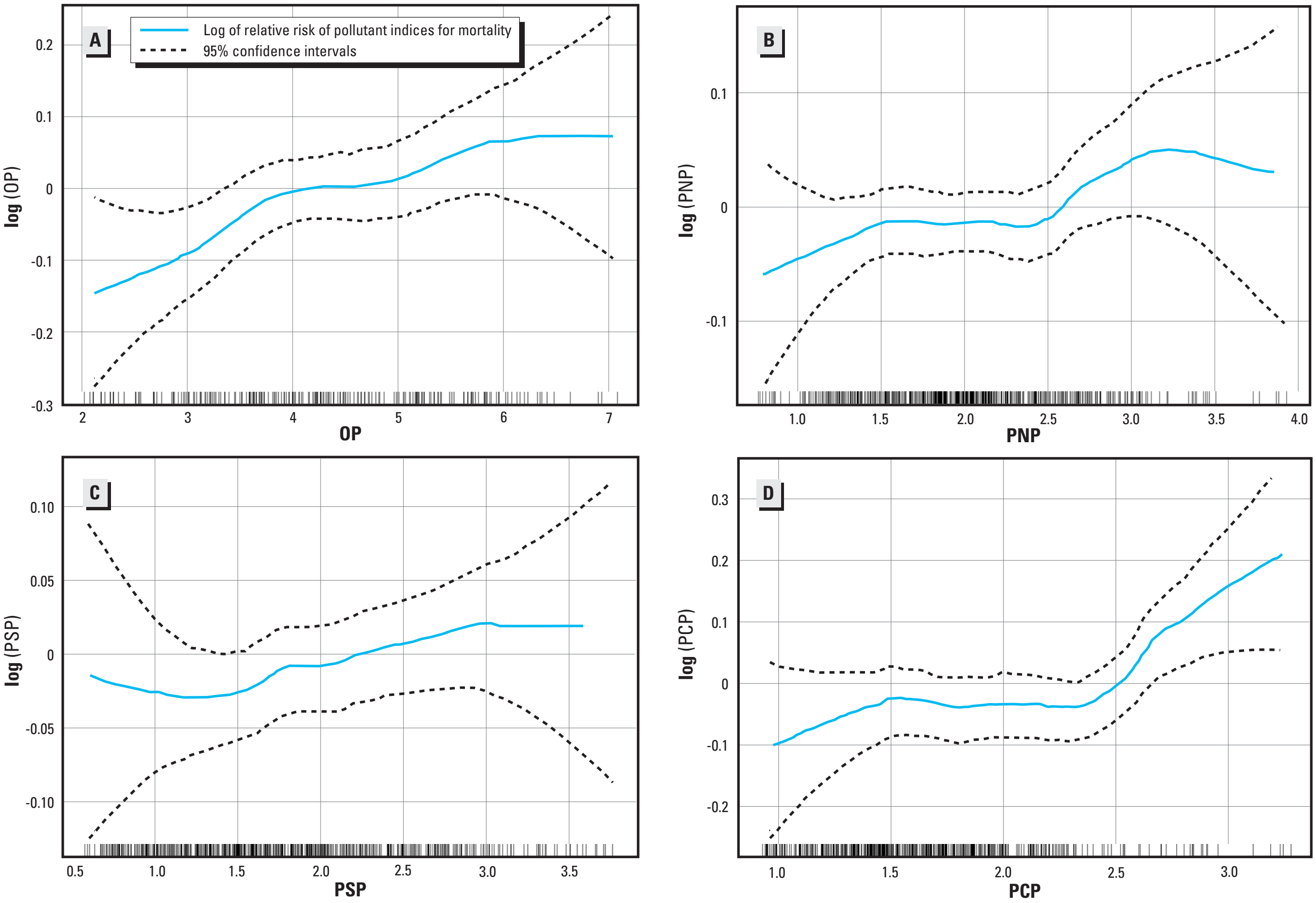

Figure 2. Graphic analysis of relationship of the pollutant indices [(*A*) OP, (*B*) PNP, (*C*) PSP, and (*D*) PCP] with daily mortality by generalized additive model using loess function after controlling time trends, season, and weather variables. Abbreviations: OP, index of overall pollutants; PCP, index of PM_{10} + CO; PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter; PNP, index of PM_{10} + NO_2; PSP, index of PM_{10} + SO_2.

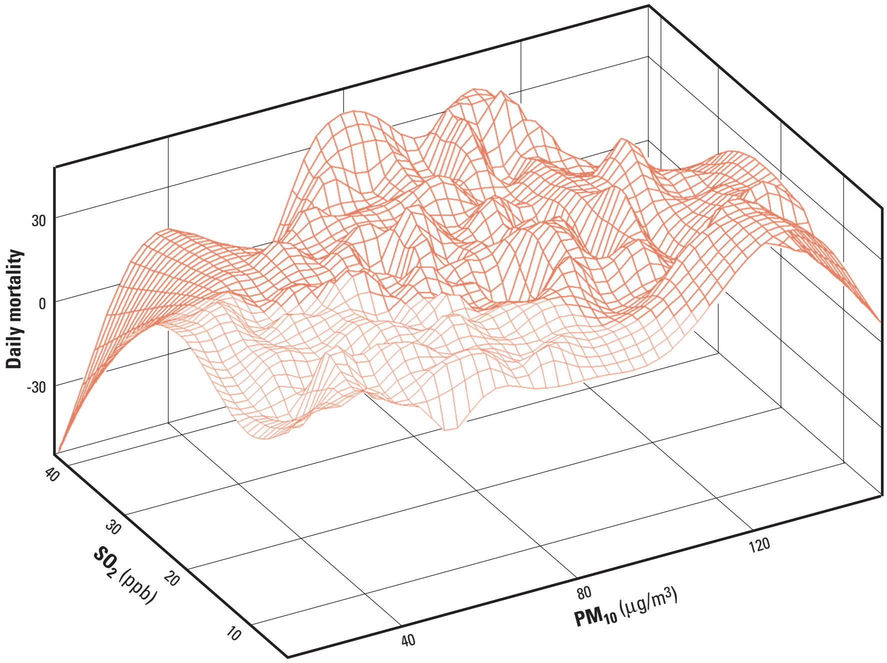

Figure 3. Contour analysis of PM_{10} and SO_2 with daily mortality shows interaction of the two pollutants. PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter. When concentrations of both pollutants are in the high range, mortality is higher than in any other combination.

United States, Europe, and Korea. However, the results of this study suggest that these differences do not exhibit a large influence on the relationship with mortality. It is highly unlikely that concordant results across so many locations could have occurred because of confounding or by chance. The highest particulate concentrations in Inchon occur during cold winter weather. There are substantial differences in the coincident weather patterns that accompany particulate exposure in different locations in the world. However, observed associations between particulate pollution and mortality are similar in many locations around the world. It is also unlikely that confounding weather effects are the source of the apparent pollution effects.

The most likely confounder that could be responsible for the effects observed is another pollutant or combination of pollutants which are highly correlated with particulate pollution (*1*). The high degree of correlation between air pollutants makes it difficult to analyze the single or multiple pollutant models appropriately. The fact that SO_2 and

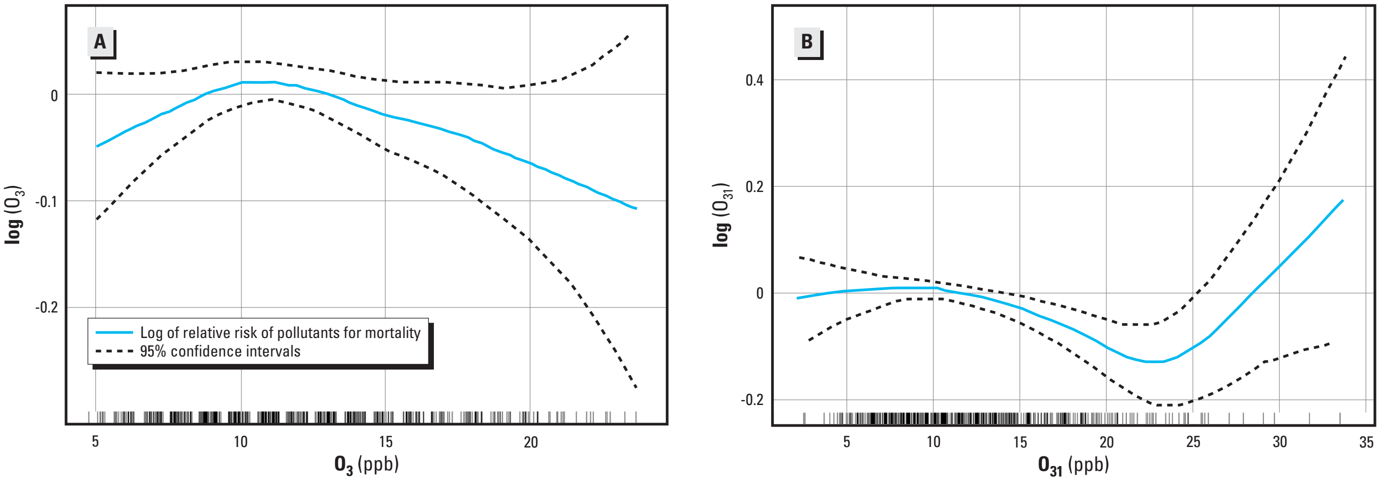

Figure 4. Graphic analysis of relationship of ozone concentrations for (*A*) the 5-day moving average of ozone concentrations (O_3) and (*B*) the previous day's ozone concentrations (O_{31}) with daily mortality by generalized additive model using loess function after controlling time trends, season, and weather variables.

NO_2 are converted to sulfates and nitrates, thus contributing to the fine particles, makes the individual effects of the gaseous pollutants more difficult to explain (*23*). Therefore, indices of pollutants can more accurately represent the effects of complex air pollutants in spite of the different modes of action of the pollutants and can also be better predictors of mortality risk. When using combined indices of pollutants, the dose–response relationship of the index of overall pollutants is better than that of a single pollutant alone or of other combination indices. This index of overall pollutants can be useful to predict mortality risk and to manage air pollution policies.

Our analysis shows no specific particulate pollution threshold. Mortality risk increased with PM_{10} levels in an exposure–response fashion. However, there seems to be a threshold for mortality for O_3. The negative direction of the O_3 relationship in the Poisson regression model was due to low O_3 concentrations; therefore, results from higher O_3 areas may differ.

The mechanism of the relationship between daily mortality and particulate air pollution is not obvious. Some studies have provided evidence that PM_{10} has free radical activity and causes lung inflammation (*24,25*). Heavy metals, transition metals, and polycyclic aromatic hydrocarbons in particulate pollutants may also cause harmful effects (*26,27*). However, specific mechanisms remain unclear. This epidemiologic study cannot explain the toxicologic mechanism for particulate pollution-induced mortality. However, the relationship of the combined indices suggests that there is a mutual interaction between particles and gaseous pollutants.

This study is limited by its use of environmental monitoring data alone to represent ambient concentrations, which do not necessarily represent individual exposures. This can result in nondirectional misclassification of exposure and bias toward the null. Therefore, it is likely that our positive results underestimate the magnitude of the association. Some studies have found that PM_{10} levels are highly correlated between indoor and outdoor air (*28*). Therefore, outdoor measurements of pollutants can also represent indoor environments, and thus be used as a proxy in the analysis.

In summary, the association of particulate air pollution with daily mortality in Inchon is similar in magnitude to the results in other communities in the United States and in Europe. These associations are still observed when weather variables and other pollutants are accounted for. The association between particulate air pollution and mortality was largest for respiratory deaths. Increased cardiovascular mortality associated with particulate air pollution was also observed. Further, there is no evidence to support a threshold for particulate air pollution. However, there appears to be an O_3 threshold level for adverse health effects and mortality. Additional studies will be needed to confirm this threshold in communities with varying concentrations of O_3. A combined index of overall pollutants, a variable more accurately reflecting real environments, can be a better predictor of acute mortality. Future studies should be directed at evaluating the mutual interaction of pollutants and their chemical composition.

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