

Childhood Asthma Hospitalizations and Ambient Air Sulfur Dioxide Concentrations in Bronx County, New York

SHAO LIN

SYNI-AN HWANG

CRISTIAN PANTEA

CHRISTINE KIELB

EDWARD FITZGERALD

Bureau of Environmental and Occupational

Epidemiology

Center for Environmental Health

New York State Department of Health

Troy, New York

ABSTRACT. The association between asthma hospitalizations and ambient sulfur dioxide (SO₂) concentrations was examined in a case-control study in Bronx County, New York. Cases comprised 2629 children aged 0–14 yr who were admitted to hospitals for asthma. There were 2236 controls who were admitted for reasons other than asthma. Daily ambient SO₂ concentrations were categorized into quartiles of both average and maximum levels and various exposure windows (i.e., day of admission and 1-, 2-, and 3-d lags). Cases were exposed to higher daily average concentrations of SO₂ than controls. The authors compared the highest exposure quartile with the lowest, and the odds ratios were 1.66, 1.90, 2.05, and 2.21 (all $p < 0.01$ for same-day, 1-, 2-, and 3-d lags, respectively), with a similar finding for daily SO₂ maximum exposure. The results suggest a consistent positive association between SO₂ exposure and hospitalizations for childhood asthma.

<Key words: ambient air pollutants, asthma, childhood asthma, hospitalization, sulfur dioxide>

ASTHMA is a chronic inflammatory disease of the bronchial airways that causes variable—and often reversible—airflow obstruction and associated episodes of wheezing, coughing, and breathlessness.¹ The effects of asthma are substantial—both in terms of health and monetary costs. In 1995 an estimated 14.9 million people suffered from asthma in the United States, which resulted in approximately 1.5 million visits to emergency rooms, 500,000 hospitalizations, more than 5500 deaths, and \$11.3 billion in direct and indirect costs.²

The prevalence of asthma has been increasing in the United States during the past 2 decades. Although this trend is evident in all age groups, asthma prevalence has risen most sharply in children under the age of 5 yr: from 22.2/1000 in 1980 to 57.8/1000 in 1994 (i.e., an increase of 160%). In children 5–14 yr of age, asthma prevalence has risen by 74%—from 42.8/1000 to 74.4/1000 during

the same aforementioned time period. The asthma prevalences for these 2 age groups were higher than for any other age group.² The hospitalization rate for asthma has also been steadily increasing, both in New York State³ and in the United States as a whole.⁴

Sulfur dioxide (SO₂) is one of many air pollutants considered to be a potential asthmagene. It is produced primarily when fossil fuels (e.g., oil, coal) are combusted, as well as by various engineering or industrial processes (e.g., metal smelting). Although both SO₂ emissions and ambient levels in the United States have generally declined since the time period 1986–1995, officials at the United States Environmental Protection Agency (EPA) remain concerned about health effects of short-term peak SO₂ concentrations.⁵ More important, in 1995, New York City had a daily maximum SO₂ concentration of 0.053 ppm, one of the highest among all

the metropolitan statistical areas in the United States, and Bronx County, one of the 5 boroughs of New York City, had the highest daily maximum SO₂ level (138 µg/m³) of all counties in New York State.⁵

In experimental chamber studies, investigators found evidence that SO₂ can exacerbate asthma. Levels of SO₂ that range from 100 to 1000 parts per billion (ppb) caused bronchoconstriction or reductions in lung function in exercising adult asthmatics.^{6–13} In 1 study of asthmatics who were 14–18 yr of age, Koenig et al.¹⁴ found that exposure to 500 ppb of SO₂ was associated with the stated endpoints.

Although in many epidemiologic studies, researchers investigating the association between ambient SO₂ concentrations and childhood asthma hospitalization and/or emergency room visits found statistically significant associations,^{15–23} others reported no association^{24–34} or findings of marginal statistical significance.³⁵ These mixed results could have been caused by the generally lower ambient SO₂ levels studied relative to the experimental studies, but perhaps they could be traced to the relative insensitivity of hospitalizations and emergency room use relative to symptoms of asthma.

Much of the existing epidemiologic research has significant limitations. In most of the studies noted previously, investigators examined aggregate hospital admissions or emergency room visits, which also included multiple admissions. Consequently, the results could have been subject to the confounding effects of readmission, and the demographic variables could be correlated with multiple admissions. Additionally, in two of the studies,^{19,21} researchers used health care data from only 1 hospital; therefore, the children in those studies who experienced acute asthma exacerbations may not have been truly representative of pediatric asthma exacerbations in the geographic area from which the ambient SO₂ concentration data were obtained. Finally, in most studies, investigators did not control for sociodemographic factors (e.g., race, ethnicity), which are strongly related to hospital admissions for asthma.^{4,36–41} Given these limitations and lack of consistency in results, additional epidemiologic research is needed to examine the association between SO₂ concentrations and asthma hospitalizations.

In the current study, we used asthmatic *patients*, rather than asthma *admissions*, thus eliminating the biases and confounding effects associated with multiple admissions. In our study, we also used data from all hospitals—rather than a single hospital—in New York State that admitted residents who resided in Bronx County, and we controlled for race and ethnicity.

Method

We conducted a case-control study to test the main hypothesis that the risk of hospitalization for asthma among children is associated with an increased daily

concentration of SO₂ in Bronx County, New York. Bronx County was chosen for several reasons. First, it is an urban area with a population that exceeds 1.2 million and it has the potential for high ambient levels of air pollutants (e.g., SO₂). Second, the prevalence of asthma among children who are 0–17 yr of age in Bronx County is 8.6%, which is substantially higher than in other low-income urban areas of the United States (i.e., 4.3%).⁴² This higher rate of asthma is apparent across age groups, gender, and racial and ethnic groups. The Bronx County hospitalization rate for asthma among 5- to 14-yr-olds is also high (i.e., 1102 per 100,000 population), compared with the rate for New York State in its entirety (357/100,000 population).⁴³ In addition, compared with New York State, Bronx County has a substantially lower median income, higher poverty rate, and higher proportions of African Americans and Hispanics,⁴⁴ all of which are risk factors for asthma hospitalization in children.^{4,36–41,45,46}

The case group comprised residents of Bronx County who were 0–14 yr of age who had been admitted to any hospitals located in New York State from June 1991 through December 1993 with a primary diagnosis of asthma (International Classification of Diseases [ICD-9-CM {hereinafter “ICD”}]: 493.0–493.9). The control group consisted of nonasthmatic admissions during the same period for gastroenteritis (ICD: 009.0–009.3), non-traffic-related injuries (ICD: E849), accidents resulting from poisoning (ICD: E850–E869), accidental falls (ICD: E880–E888), and other accidents (ICD: E920, E924–E925). These diagnoses were chosen because they are unlikely to be associated with air pollution. For a child who had been admitted more than once with asthma ($n = 702$), we included data relative to the most recent admission. If a child had been admitted with asthma (i.e., ≥ 1 times) and with non-asthma-related conditions during the study period ($n = 14$), we selected the admissions for asthma only. All admissions for whom addresses were unknown or individuals who were not residents of Bronx County were eliminated from the study ($n = 462$).

Data sources and collection. Hospital discharge data for residents of Bronx County between 1990 and 1993 were identified from the Statewide Planning and Research Cooperative System (SPARCS) in the New York State Department of Health. SPARCS is a legislatively mandated discharge database and contains discharge data abstracts for at least 95% of all New York State acute care hospitalizations, excluding hospitalizations at psychiatric and federal hospitals. We obtained approval from the Internal Review Board of the New York State Department of Health for access to and use of these confidential data because they contain personal information, such as unique patient identification numbers, detailed residential addresses, and dates of birth. Other discharge information from SPARCS used in the

current study included race, ethnicity, gender, and principal diagnosis at time of admission.

Ambient air pollutant information was obtained from the New York State Department of Environmental Conservation (NYSDEC). The Bureau of Air Quality Surveillance, New York State's ambient air-monitoring system, provided hourly SO₂ values for each calendar day. In this study, a running average of 24-h SO₂ values for each calendar day was used as an index of daily average SO₂ level. The highest value of SO₂ for each calendar day was defined as the daily SO₂ maximum value. The method used for measuring SO₂ by New York State's continuous air-monitoring network was pulsed fluorescent (Thermo Electron model 43 SO₂ Pulsed Fluorescent Analyzer, EPA No. EQSA-0276-009, Thermo Electron Company, Franklin, MA). The Thermo Electron model measures SO₂ by absorption of ultraviolet light. This method was designated as the standard by the EPA. All SO₂ monitors in New York State have used this method since 1980. Throughout the study period, standardized procedures were in place for quality assurance for ambient air monitoring. For example, a total of 103 audits were conducted statewide to estimate accuracy. In addition, NYSDEC performed precision checks for all monitoring sites, including a total of 641 checks on SO₂ monitoring sites. The validity of the results has been examined routinely.

Exposure assessment. There are 2 SO₂ monitoring sites operated by the NYSDEC in Bronx County. Both sites are located in the center of the borough and represent population exposures: site 709403 is in a residential area, and site 709405 is in a commercial area. Given that the correlation coefficient of SO₂ levels between the 2 sites is quite high ($r = .87$), we pooled information from them and averaged them to produce 2 overall estimates of exposure to SO₂: (1) the daily average and (2) the daily maximum concentration.

The daily average and daily maximum SO₂ concentrations were each measured in accordance with the following exposure timing windows: (a) the same day as the day of admission (same-day lag); (b) 1 day prior to the day of admission (1-d lag); (c) 2 d prior to the day of admission (2-d lag); and (d) 3 d prior to the day of admission (3-d lag). Each of the 2 measures of exposure was divided into 4 categories on the basis of the quartiles of their respective distributions. The lowest quartile of SO₂ exposure was used as the reference group for the 3 higher quartiles. To estimate the cumulative effects of SO₂ exposures, we calculated moving average values by averaging SO₂ concentrations for 2 d (i.e., the same day and the day prior to the hospitalization), 3 d (the same day and 2 d prior to hospitalization), and 4 d (the same day and 3 d prior to hospitalization). To assess these cumulative effects, the range of these moving averages was divided into 10 groups. Groups 7–10 were categorized into 1 group because the number of subjects was small. We then compared the final groups (i.e., groups 2–7)

with the lowest exposure group (group 1 [2.9–9.2 ppb]) to compute odds ratios (ORs), as well as by using different moving-average days.

Covariates. African American and Hispanic populations have higher risks of asthma hospitalizations than whites, as determined in studies conducted previously.^{4,36–41} Therefore, race and ethnicity were considered as potential confounders in the current study and were controlled in the multivariate analysis. A race variable, defined as African Americans vs. other, was created, as was an ethnicity variable, which was defined as Hispanic vs. non-Hispanic.

Given that the asthma admission rate among younger children (0–4 yr old) is typically higher than the rate among older children,^{3,47} age was a potential confounding factor in the current study. The children in this study were grouped into 3 age categories: (1) 0–4 yr, (2) 5–10 yr, and (3) 11–14 yr. In previous literature, the asthma rate was reportedly higher among boys than girls³; therefore, in the current study, we checked for the potential confounding effects of gender.

An increased rate of asthma hospitalization in northern climates occurs in the fall^{34,48} versus other seasons. Therefore, to control for this seasonal trend, we created a dummy seasonal variable by comparing fall with other seasons.

Statistical analysis. Bivariate analysis, in which demographic characteristics, such as age, gender, race, and ethnicity, were compared between cases and controls, was performed with chi-square analysis to assess their potential confounding effects. The mean, standard error, and median of daily average SO₂ levels during different lag periods were calculated, and the ranges of these levels were described.

We then used logistic-regression to examine the association between childhood asthma hospitalizations and ambient SO₂ levels, after adjustment was made for the potential confounding effects of gender, age, race, ethnicity, and seasonality. In the logistic-regression model, the dependent variable was asthma status (i.e., asthma cases or controls). The exposure variables were daily average and maximum SO₂ levels during the 4 different lag periods. These measures were treated as both categorical and continuous variables in the logistic-regression analyses. For each of the 4 different lag periods, we calculated adjusted ORs by comparing the highest exposure quartile (very high exposure group) with the lowest quartile (low-exposure group). We calculated 95% confidence intervals (CIs) to evaluate the precision of the point estimates. The cutoff points for each quartile of the daily average SO₂ concentrations (same day as admission) were 20.21 ppb ($\geq 75\%$), 13.38 ppb (50–74%), 9.37 ppb (25–49%), and 2.88 ppb (0–24%, reference group), respectively. For the daily maximum SO₂ levels, the cutoff points for each quartile (same day as admission) were 42.50 ppb ($\geq 75\%$), 28.00 ppb (50–74%), 19.00 ppb (25–49%), and 6.00 ppb (0–24%, reference group), respectively. For both the daily average and daily maximum SO₂ levels, the cutoff points

for each quartile in the 1-d lag, 2-d lag, and 3-d lag were almost identical to the cutoff points for same day as admission. Finally, we used the Cochran-Armitage trend test for the comparison of the dose response relationships between asthma admissions and SO₂ exposure by comparing the ORs of each quartile group (i.e., ≥75%, 50–74%, and 25–49%) with the low-exposure group (0–24%, the reference group) in the different lag periods.

Results

During the study period (1990–1993), 2629 children were hospitalized for asthma (asthma cases), and 2641 children were admitted to hospitals for gastroenteritis, injury, or accidents (i.e., control group described earlier) in Bronx County, New York. When demographic characteristics were compared between cases and controls (Table 1), the case group contained a significantly higher percentage of young children (i.e., 58.1% for 0 to 4-yr-olds) and African Americans (34.6%) than the control group (48.5% for 0 to 4-yr-olds, and 32.4% for African Americans). There were no significant differences with respect to ethnicity or gender distribution between cases and controls.

Among all asthma cases defined by ICD code 493.0, 77.7% were diagnosed as having unspecified asthma (ICD: 493.9), 22% had extrinsic asthma (ICD: 493.0), and 0.2% were defined as having intrinsic asthma (ICD: 493.1). There was a strong seasonal variation for asthma cases: fall was the seasonal peak (41.19%), followed by winter (26.25%) and spring (21.41%) (data not shown). The season during which there were the lowest number of asthma cases was summer (11.14%). There was, however, no significant seasonal fluctuation for the controls.

Table 1.—Demographic Characteristics of Asthma Cases and Controls in Bronx County, New York

Variable	Case group		Control group	
	<i>n</i>	%	<i>n</i>	%
Age (yr)*				
0–4	1528	58.1	1280	48.5
5–9	687	26.1	671	25.4
10–14	414	15.7	690	26.1
Gender				
Female	986	37.5	982	37.2
Male	1643	62.5	1659	62.8
Race*				
White	103	3.9	243	9.2
Black	909	34.6	856	32.4
Other	1613	61.4	1535	58.1
Ethnicity				
Hispanic	1611	61.3	1484	56.2
Other	990	37.7	1091	41.3
Unknown	28	1.1	66	2.5

**p* < 0.01, general chi-square test.

We examined the overall distributions of the daily average and daily maximum SO₂ concentrations during the study period, with and without specifying lags. The median of the daily average SO₂ concentrations without lags was 13.4 ppb (mean = 16.2 ppb), and the range was 2.9–66.4 ppb. The median and mean of this measure did not change appreciably with differing lags (data not shown). During the same study period, the median of daily maximum levels of SO₂ was 28 ppb (mean = 33 ppb), and the range was from 6 ppb to 126.5 ppb (data not shown).

The means and medians of daily average SO₂ levels for both cases and controls during different lag periods are shown in Table 2. Because SO₂ concentrations were not distributed normally, we performed the Kruskal-Wallis test to compare the medians between cases and controls. As shown in Table 2, the case group had both statistically significantly higher mean and median values of SO₂ than the control group during each lag period. Similarly, daily maximum values of SO₂ (i.e., same day and different lag periods) were significantly higher among cases than controls (data not shown).

When we compared the highest quartiles with the lowest quartiles of the daily average SO₂ levels (Table 3), cases were more likely to have been exposed to SO₂ levels in the highest quartile than controls (exposure ORs from 1.48 to 2.16), after controlling for race, ethnicity, age, and season. These differences were statistically significant (*p* < 0.05). We also found that the ORs increased as the lag time increased from the same day to day 3, but the ORs began to drop after 3 lag days (data not shown). Similar trends were found when we compared the

Table 2.—Comparison of Mean and Median of Daily Average Sulfur Dioxide (SO₂) Levels (ppb) of Asthma Cases and Controls

Study participants	SO ₂			
	Mean (ppb)	Standard error	Median (ppb)*	Range (ppb)
<i>Same day</i>				
Cases	16.78	0.24	13.72	2.88–66.35
Controls	15.57	0.23	13.08	2.88–66.35
<i>1-d lag</i>				
Cases	16.80	0.24	14.15	3.52–66.35
Controls	15.22	0.21	13.04	2.88–66.35
<i>2-d lag</i>				
Cases	16.93	0.24	13.92	2.88–66.35
Controls	15.25	0.22	12.74	2.88–66.35
<i>3-d lag</i>				
Cases	16.93	0.23	14.17	3.77–66.35
Controls	15.03	0.22	12.43	2.88–66.35

**p* < 0.01 for all median comparisons between cases and controls.

highest quartiles with the lowest quartiles of the daily maximum SO₂ levels. When we treated SO₂ levels as a continuous variable in the logistic-regression analysis, the OR of asthma admission for every 10 units (ppb) of increase in daily average SO₂ levels was 1.19 (95% CI = 1.11, 1.29), a result that comports with the positive findings described previously.

To examine the potential dose-response relationship, we compared the rates of admission on the days in different quartiles of daily average SO₂ levels (i.e., ≥75%, 50–74%, and 25–49%) with those on the days in the lowest quartile of daily average SO₂ exposure

(0–24%), respectively, between cases and controls. As indicated in Figure 1, a significant dose-response relationship was evident for asthma admissions (i.e., the daily average exposure ORs increased as the concentrations of SO₂ increased [$p > 0.001$ for all trend tests]). A similar dose-response relationship for daily maximum SO₂ level was also found. Cumulative exposure to high levels of SO₂ may have been associated with increased risk of asthma admissions (Fig. 2), as was demonstrated by the higher ORs that occurred at higher levels of 4-d moving average levels of SO₂, followed by 3-d and 2-d moving averages, compared with the same-day level of SO₂.

Table 3.—Adjusted Odds Ratios (ORs) of Highest vs. Lowest Sulfur Dioxide (SO₂) Exposures on Childhood Asthma Admissions

Lag	Odds ratio	95% CI
<i>Daily average SO₂</i>		
Same day	1.48	(1.21, 1.82)
1 d	1.78	(1.45, 2.19)
2 d	1.92	(1.57, 2.34)
3 d	2.16	(1.77, 2.65)
<i>Daily maximum SO₂</i>		
Same day	1.55	(1.27, 1.89)
1 d	1.64	(1.34, 2.01)
2 d	1.78	(1.46, 2.17)
3 d	1.86	(1.52, 2.27)

Notes: Odds ratios adjusted for race, ethnicity, age, and season. CI = confidence interval.

Discussion

In the current study, we found that children hospitalized for asthma had increased proportions of exposure to higher daily concentrations of SO₂ (both average and maximum levels), compared with children hospitalized for other reasons. This statistically significant positive association occurred on the same day, and on 1-d, 2-d, and 3-d lags (from the date of admission) of daily average and maximum SO₂ levels, but it disappeared at d 4. The ORs increased as the lag period increased, which might imply that people tend to wait and enter the hospital when asthma becomes severe, or it might indicate a possible cumulative effect of SO₂ exposure, as has been found in 2 previous occupational studies.^{49,50}

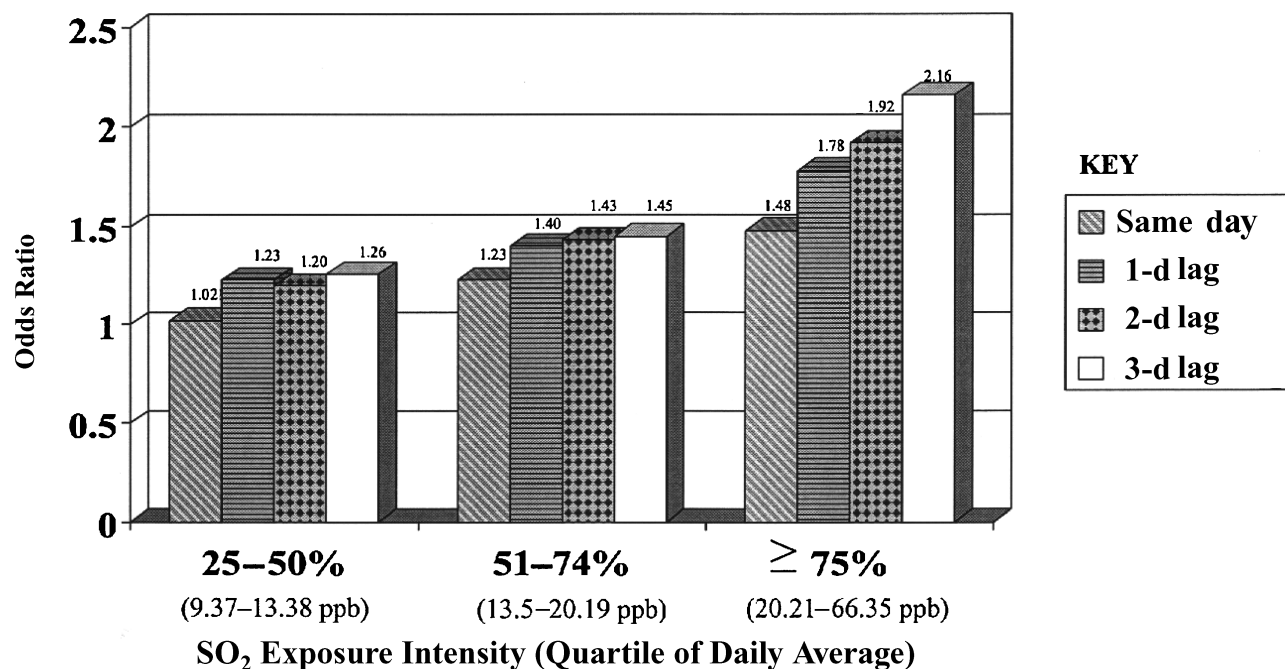
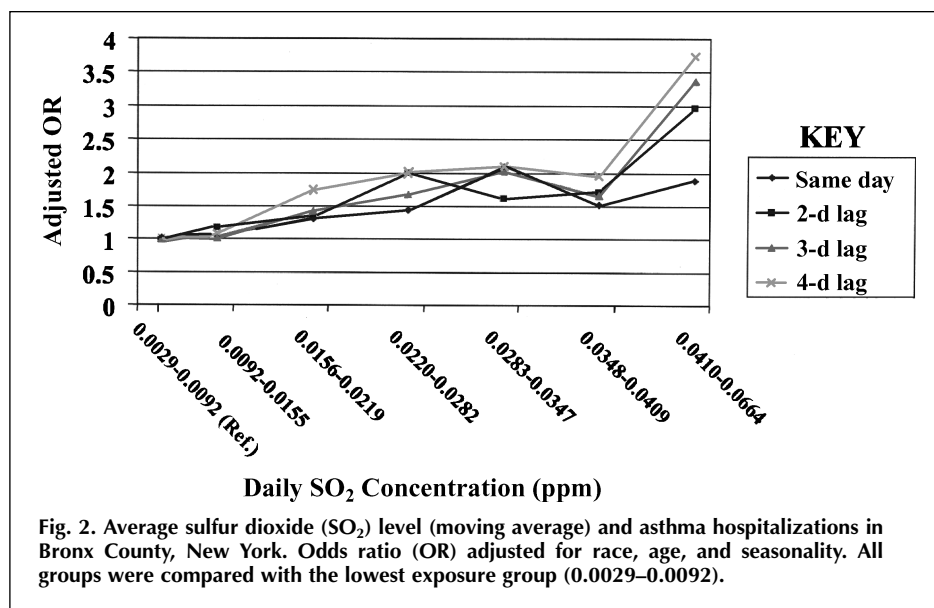


Fig. 1. Sulfur dioxide (SO₂) exposure intensity (daily average) and adjusted risk of childhood asthma admissions in Bronx County, New York. Note: Adjusted risk is compared with the lowest exposure (2.88–9.37 ppb), adjusted for race, ethnicity, age, and season.



Osterman et al.⁵⁰ evaluated the relationship between pulmonary symptoms and exposure to respiratory dust and SO₂ among 145 silicon carbide production workers who had an average of 13.9 yr of experience in that industry. The authors found that cumulative and long-term exposure to SO₂ at levels of 1.5 ppm or less was associated with significantly increased rates of wheezing in silicon workers. We also found that the higher the SO₂ daily value (both average or maximum), the higher the rate of childhood asthma hospitalizations, indicating a possible dose-response relationship. Although the data used in the current study were from 1990–1993, these findings can nonetheless be applied to current years because (a) there have been no substantial changes in ambient air SO₂ levels over time in Bronx County, (b) the NYSDEC standard for SO₂ has remained the same, and (c) Bronx County has consistently had one of the highest levels of SO₂ among all New York counties.^{5,51}

There is a postulated mechanism for the effects of SO₂ on asthma exacerbation that supports these findings. SO₂ is a gas that is highly water soluble at ambient room temperatures,⁵² and it is absorbed primarily in the upper airways of the lung in subjects at rest.⁵³ Hydration in the mucous membrane produces ions capable of causing irritation, and these irritants most likely produce bronchoconstriction by acting on the smooth muscle via afferent neurons.⁵⁴ Results from experimental studies in which SO₂ has been administered to exercising adolescent asthmatics indicates that short-term exposure to concentrations as low as 500 ppb can induce bronchoconstriction.¹⁴ Although this level is well above those found in our current study, the levels we found are representative of chronic, long-term, daily exposures. However, the cumulative effects of residential exposure or latency of SO₂ on asthma are unknown or have not

been studied adequately, inasmuch as most studies of SO₂ exposure have focused on acute effects only.

The results of additional epidemiologic studies of the association between SO₂ and asthma exacerbations in children have been mixed. In some of these studies, emergency room visits were studied, whereas in other studies hospital admissions were examined.^{15–35} In 1 study, the authors used Poisson regression models to assess the effect of SO₂ levels on emergency room visits separately for cases and controls.²¹ A significant, though modest, association was found between the daily average concentration of SO₂ and emergency room visits for acute wheeze episodes at a single hospital, after controlling for lag, season, and temperature (relative risk [RR] for each standard deviation increase in SO₂ levels = 1.12 [95% CI = 1.06, 1.19]). The mean daily average level of SO₂ measured in the aforementioned study²¹ was 8.4 ppb—which was approximately half the average level of 16.2 ppb found in the current study.

Romieu et al.³⁵ accounted for socioeconomic status by measuring emergency room visits at a children's hospital that served a primarily low-income population in Mexico City. The authors used Poisson regression analysis, and daily average SO₂ levels were associated only marginally with asthma exacerbations when other variables (e.g., ozone levels, day of week, period, temperature, sex, age, lag) were included in the model (RR = 1.05; 95% CI = 0.99, 1.11, for each 50-ppb increase in SO₂ level). However, Romieu et al.³⁵ measured asthma morbidity for the first half of the year only; therefore, the effects of SO₂ during the other seasons could not be assessed. The average level of SO₂ in their study was 77 ppb, which was considerably higher than levels found in the current—and other—studies.

Stieb et al.³⁰ looked at daily 1-h maximum levels of SO₂ and found no association with daily emergency room visits for childhood asthma in St. John, New Brunswick, Canada, after they accounted for weather variables and other pollutants. In the study by Stieb et al., the investigators looked at admissions during the summer season only; however, the effects of SO₂ may be different during other seasons in the year. The average 1-h maximum SO₂ level in that study was approximately 38 ppb, which was somewhat higher than 33.6 ppb found in the current study.

A large multicenter study was conducted in Europe by Sunyer et al.,²⁰ who evaluated childhood hospital admissions for asthma and visits to the emergency room. The results from Helsinki, London, and Paris were combined, and statistically significant—although weak—positive associations were identified between daily average SO₂ levels and asthma exacerbations (RR for each 19-ppb increase in SO₂ levels = 1.08; 95% CI = 1.03, 1.13), after controlling for trend, season, day of week, temperature, humidity, influenza epidemics, and lag. The medians of the daily average SO₂ levels ranged from 6.1 to 11.8 ppb (collective range = 0.38–83.57 ppb) in the 3 cities noted; these levels were a bit lower than our median value of 13.4 ppb.

Studies were also conducted separately in London¹⁸ and Paris,²² and in both studies, investigators found that hospital admissions were associated with increases in SO₂ levels. In London, a 10- $\mu\text{g}/\text{m}^3$ (3.82 ppb) increase in daily average SO₂ levels was associated with a 1.64% increase in daily hospital admissions for childhood asthma (95% CI = 0.29, 3.01), corresponding to a relative risk (RR) of approximately 1.66. In the current study, the RR of hospital admissions for asthma for each 4-ppb increase in daily average SO₂ levels was 1.07 (95% CI = 1.04, 1.11). The mean of the daily average SO₂ level in London was 12.2 ppb, which was somewhat less than the 16.2 ppb identified in our current study. In Paris, the RR for asthma hospital admissions was 1.07 (95% CI = 1.00, 1.14)—for an increase of 38 ppb in average SO₂ levels. The mean of the daily average level of SO₂ in the Paris study was 11.3 ppb (range = 0.4–83.6 ppb), which was also lower than in the current study (16.2 ppb).

In a study in Helsinki, Ponka and Virtanen²⁸ used Poisson regression to assess the effect of SO₂ levels on hospital admissions separately for cases and controls, and they found no association between daily average SO₂ values and admissions for childhood asthma, after they controlled for various factors, including lag, temperature, humidity, season, influenza epidemics, day of week, and holidays. The average daily level of SO₂ measured in the aforementioned study was 7.25 ppb—which was approximately half of the average level of 16 ppb identified in our current study.

In summary, compared with most of the previous research conducted in Europe, SO₂ levels found in Bronx

County were higher. In the 4 studies for which authors reported positive associations between SO₂ levels and either emergency room asthma-related visits or hospital admissions,^{18,20–22} they also reported mean or median daily average SO₂ levels that were lower than levels found in our current study. Among the 3 studies for which no association with asthma was reported,^{28,30,35} SO₂ data was used only during the first half of the year or in the summer in the studies by Romieu et al.³⁵ and Stieb et al.,³⁰ thus making comparison of their studies with ours (entire-year data used) difficult. On the basis of the observations from our current study, SO₂ levels began to increase in September, peaked in December, and declined thereafter, with the lowest levels occurring in July. Finally, Ponka and Virtanen²⁸ found no association between daily SO₂ levels and asthma hospital admissions, but the SO₂ levels measured in their study were less than half the levels measured in our current study.

Unlike many previous studies, in the current study we deleted multiple admissions and used unique asthma patients. This approach eliminated potential skewing of effects caused by persons with repeated hospitalizations and the analytical problems introduced by statistical dependence. In addition, demographic confounders (e.g., age, race, ethnicity) could be incorporated into the analysis. In our study were included all hospital admissions in the study area, whereas in some previous studies, admissions or emergency room visits from only a single hospital were examined. In addition, in our study we estimated the duration of exposure windows by comparing different lag times from the date of hospitalization. We also controlled for seasonality of asthma admissions.

The results of our study, however, must be interpreted with caution. This study merely demonstrated a positive statistical association between ambient SO₂ levels and hospitalizations for asthma, rather than a causal association. We did not control for some important risk factors for asthma (e.g., parental or child smoking history, family history of asthma, indoor exposures) because this information was unavailable to us. However, there is no compelling reason to believe that these risk factors are likely to be related to ambient SO₂ levels and therefore they may not have been confounders in this study. Also, in the current study, we did not control for temperature, wind direction, long-term autocorrelation, and other ambient pollutants (e.g., particulates, ozone, nitrogen dioxide), which are potential triggers of asthma. Given that air pollutants are highly interrelated and are very season-dependent, controlling for these variables would have required a multivariate time-series analysis, which was beyond the scope of this study. In addition, we found it difficult to incorporate other pollutants into our data because some, such as particulate matter, were recorded weekly, not daily. However, in a recent study in South Bronx and lower Manhattan, the NYSDOH is examining the association between multiple air pollutants and

emergency department visits for asthma. This study is simultaneously controlling for the confounding effects of other pollutants, which could minimize the limitations of our study as discussed earlier. In this study, 5-d mean SO₂ levels were statistically significantly associated with emergency department visits for asthma, after controlling for ambient ozone, particulate matter with diameters less than or equal to 2.5 µm, and nitrogen dioxide levels in Bronx County (unpublished data). Among all the pollutants examined in this study, SO₂ was associated with the highest RR for asthma morbidity, and it was the only one that remained statistically significant after the other pollutants were controlled for. Daily levels of SO₂ also correlated well with daily concentrations of other pollutants, including ozone, particulate matter with diameters of less than or equal to 2.5 µm, and nitrogen dioxide. In some other studies, investigators found high correlations between SO₂ and nitrogen dioxide (*r* ranged from .45 to .54^{29,34,55}) and between SO₂ and ozone (*r* = .60).³⁴ In a study in Ottawa, Canada, the authors found that SO₂ correlated well with carbon monoxide and particulate matter with diameters less than or equal to 2.5 µm.⁵⁵ Therefore, SO₂ might serve as an important surrogate index of a combustion-related pollutant mixture.

Another concern is whether the 2 air pollution monitors used in our study were representative measurement tools of ambient SO₂ for the study population. Research conducted between 1969 and 1971 indicated that the correlations between SO₂ readings at different monitors in New York City were generally low (i.e., averaging *r* = .40), and that these low correlations did not improve as the distance between pairs of monitors decreased or when monitor height or wind direction were considered.⁵⁶ Nonetheless, comparison of daily SO₂ levels reported by the 2 Bronx County air monitoring sites in the current study yielded correlation coefficients of .87 for daily average levels and .76 for daily maximum levels (1990–1993 available data used), indicating consistency between the 2 monitors in describing changes in these levels.

Current health-related ambient air quality regulations for SO₂ concentrations include a national standard of 30 ppb for the annual arithmetic mean concentrations⁵⁷ and an identical statewide standard.⁵⁸ Although all SO₂ monitoring sites in New York State indicated compliance with these standards in 1993, the highest annual average level (i.e., 18 ppb), as well as the highest 24-h concentrations in New York State, were recorded at the Morrisania site in Bronx County. During 7% of the study period days, daily average SO₂ levels in Bronx County exceeded the annual standards (i.e., 30 ppb), and in 1% of the days, maximum daily SO₂ levels exceeded the daily maximum standard of 140 ppb.^{57,58} Indeed, children's actual exposure to SO₂ in Bronx County is probably lower than that indicated by the NYSDEC monitoring sites, inasmuch as children spend only a portion of the

day outdoors, and SO₂ penetrates indoor environments inefficiently. A statistically significant positive effect was found nonetheless—even with low SO₂ exposure.

In conclusion, in the current study, we found a consistent association between childhood asthma hospitalizations and ambient SO₂ exposure. This positive association prevailed in same-day, 1-d, 2-d, and 3-d lags (from the date of admission) of daily concentrations. In addition, a potential dose-response relationship was found. Given that we were unable to control for many potential confounders in this study, replication of our results in other studies is essential before possible causal relationships or definite conclusions can be drawn with respect to the association between childhood asthma and ambient SO₂ exposure in residential areas. In addition to acute responses, cumulative responses to SO₂ are unknown. New studies using a time-series study design—in which both acute and cumulative effects are examined—and incorporation of adjustment for other potential confounders (e.g., other ambient pollutants, indoor exposures, meteorological data) are needed. The results of such studies will assist in the understanding of health results associated with exposure to air pollution and the possible need for reexamination of existing standards.

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Requests for reprints should be sent to Shao Lin, Center for Environmental Health, New York State Department of Health, Flanigan Square, 547 River St., Troy, NY 12180.

E-mail: SXL05@health.state.ny.us

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