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Particulate Air Pollution and Hospital Emergency Room Visits for Asthma in Seattle

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Recent studies have associated short-term exposure to respirable particulate matter (PM_{10}) exposure with peak flow decrements, increased symptoms of respiratory irritation, increased use of asthma medications, and increased hospitalization for asthma. Increased mortality from chronic respiratory disease has also been reported. To help confirm whether PM_{10} exposure is a risk factor for the exacerbation of asthma, we compiled daily records of asthma emergency room visits from eight hospitals in the Seattle area. In Poisson regressions controlling for weather, season, time trends, age, hospital, and day of the week, the daily counts of emergency room visits for persons under age 65 were significantly associated with PM_{10} exposure on the previous day. The mean of the previous 4 days' PM_{10} was a better predictor ($p < 0.005$). The relative risk for a 30 μg/m³ increase in PM_{10} was 1.12 (95% confidence interval 1.20 to 1.04). Daily PM_{10} concentrations never exceeded 70% of the current ambient air quality standards during the period. The consistency of investigations of the health effects of PM_{10} suggest that increased attention should be given to the control of particulate matter air pollution.

Asthma morbidity has been growing rapidly in certain subpopulations and different areas of the world in the past few years. The causes of this increase have eluded many researchers who have tried to discover factors influencing this complex disease. In addition to the increasing morbidity, there has been an accompanying increase in mortality due to asthma (1). As a lower respiratory illness, it is natural to hypothesize that there is a relationship between asthma and air pollution (2). There is some evidence that air pollution episodes aggravate respiratory disease, especially asthma (3, 4).

Relatively low concentrations of inhalable particulate matter (PM_{15}) have been associated with increased risk of acute bronchitis in children (5). The rate of bronchitis in children was approximately twice as high in communities with airborne particle concentrations at the U.S. Environmental Protection Agency annual average air quality standard (50 μg/m³ of particles with an aerodynamic diameter of 10 μg or less, abbreviated PM_{10}) as in communities having near background concentrations of particles (5). Subjects with a history of wheeze appeared to be particularly sensitive to the impact of airborne particles. A recent study by Pope and coworkers reported that short-term PM_{10} exposure was associated with approximately 3 to 6% decreases in peak expiratory flow in mildly asthmatic school children (6). PM_{10} also was associated with increased reports of symptoms in a diary and increased use of medication (6). For example, a 24-h PM_{10} concentration of 150 μg/m³ (which is the current 24-h ambient air quality standard) was estimated to be associated with a 26% increase in upper respiratory symptoms, a 50% increase in lower respiratory symptoms, and a 217% increase in the use of regular asthma medication compared to the number of cases at 50 μg/m³. PM_{10} has also been associated with lower respiratory symptoms in a diary study of schoolchildren in six communities (7).

Bates and Sizto (8) reported sulfate particulate matter and ozone were associated with hospital admissions for asthma in Ontario. A more recent study in Vancouver (9), where sulfate concentrations were considerably lower and less acid, found a significant association between asthma emergency visits in the summer and the previous day's sulfate concentration in both the 0- to 14-yr and 15- to 60-yr age group. The magnitude of the correlation was essentially identical in these age groups. A similar association was not seen in persons over age 60. A strong peak in asthma emergency visits in September was also seen in the lower ages but not in persons over age 60. This peak did not appear to be related to air pollution. Pope recently reported an association between inhalable particles and hospital admissions for asthma in Utah Valley, Utah (10) and Salt Lake City (11). The Utah Valley study was notable because there was little pollution in the valley except particles, and the particles were not acid (6). The effect also was more pronounced in the younger age groups.

Airborne particles also have been associated with increased daily mortality, particularly from respiratory illness, again at concentrations commonly observed in U.S. communities today (12–15).

To further delineate the association between PM_{10} exposure and asthmatic response, we examined the association between hospital emergency room visits for asthma and PM_{10} concentrations in eight hospitals in the Seattle metropolitan area. Exposure periods of a week or less were identified as the most relevant in the majority of the preceding studies.

METHODS

Emergency room visits for asthma and gastroenteritis symptoms from eight

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hospitals in the Seattle metropolitan area (University, Ballard, Children's, Harborview, Northwest, Overlake, Providence, and Swedish) were abstracted by a graduate student during the period September 1, 1989 through September 30, 1990 (16) (see figure 1). We were unable to obtain data from the three additional hospitals in this area (also shown in figure 1). Asthma was defined as a diagnosis of ICD9 Codes 493, 493.01, 493.10, 493.90, and 493.91, and the gastroenteritis control was defined as ICD9 Code 558.90. During the study period there were 2,955 visits for asthma and 3,810 visits for gastroenteritis symptoms at the eight hospitals. Steps for quality assurance of recorded data involved constant review of log pages during data entry. After each page of the log was scanned and cases entered, the page was rescanned to check for possible missed diagnoses and errors in entered numbers. Errors were also detected through a system of counting entries in the data base and comparing these to multiples of the numbers of entries per page on the data printouts; several omissions were detected in this fashion. Data files created from hospital data printouts were checked in a similar manner. The information gained from computer files was checked at one hospital by pulling a sample of 100 medical records that were referenced by medical record number in the file. The medical record was compared to the computer report. The only discrepancies found were the reporting of two gastroenteritis cases. There was a complete match between the asthma cases in the data base report and those in the corresponding medical record file.

Air quality data were obtained from the Washington State Department of Ecology and the Puget Sound Air Pollution Control Agency. Sulfur dioxide (SO_2) values were available only from an industrial site. Daily light-scattering (b_{sp}) and PM_{10} values were available from a residential site in a wood-burning neighborhood (figure 1). Ozone values were obtained from a site approximately 20 km east of Seattle. The ozone was monitored for only 5 months (May through September).

Past studies have shown a high correlation between airborne particle concentrations measured across the airshed in the Seattle metropolitan area (17). For example, the weekly mean $PM_{2.5}$ concentrations at our monitoring site, at a site at Puyallup, approximately 45 km south of downtown Seattle, and at Marysville, approximately 60 km north of Seattle, are shown in figure 2. In addition, every sixth day PM_{10} data were available from the Harbor Island and South Park monitoring stations near central Seattle (see figure 1). For those days the correlation between these PM_{10} values and the measurements at our monitoring site were 0.72 and 0.78, respectively.

Recently, unpublished work in nine homes in Seattle, Washington without stoves and without smokers found a median indoor/outdoor ratio less than 1.0 for over 3,000 h of continuous nephelometer data, with elevated indoor levels in wood-burning neighborhoods (J. Anusewski, M.S.E. thesis, University of Washington, 1992).

Statistical Analysis

The fraction of the population suffering from serious asthma attacks on a given day is quite small. The counts of independent rare events randomly occurring in time generally follow the Poisson distribution. Poisson regression analysis assumes that conditional on the explanatory variables, the counts of events follow Poisson distribution, and this was used in our main analysis. In contrast, ordinary least-squares regression assumes that, conditional on the explanatory factors, the outcome is normally distributed. This is clearly not true in our data, in which the mean count per day in each hospital ranged from 0.3 to 2.4, with even lower counts if the data were broken down by subject age.

Serial correlation in imperfectly controlled for or omitted explanatory factors, such as weather or epidemics, may result in serial correlation in the counts of asthma emergency visits, even after conditioning on the explanatory variables. Uncontrolled differences in the underlying risk of different subpopulations can lead to a greater variability in the data than in a classic Poisson process. Ignoring either of these factors can lead to understating the standard errors of the regression coefficients and consequently to biased hypothesis tests. To address these issues we used

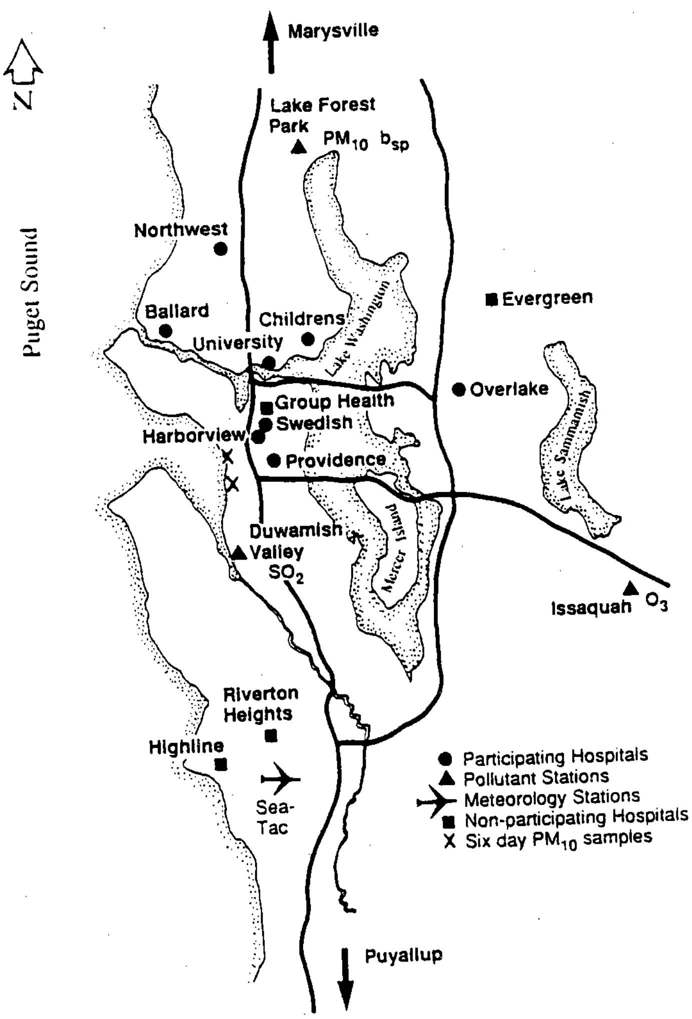

Figure 1. Map of the study area showing the location of hospitals and atmospheric monitoring stations.

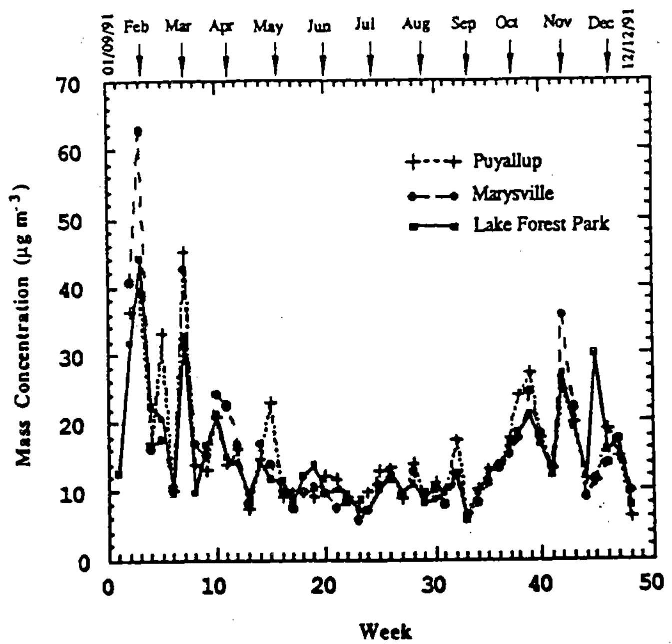

Figure 2. Weekly mass concentrations of $PM_{2.5}$ for three sampling sites during 1991. These sites are plotted on the map in figure 1. Crosses = Puyallup; circles = Marysville; squares = Lake Forest Park.

the general estimating equations of Liang and Zeger (18). As in the classic Poisson model, they assume

$$\log E(Y_{ijk}) = X_{ijk}\beta$$

where $E(Y_{ijk})$ denotes the expected number of emergency room visits for asthma in Hospital i for age Strata j on Day k, X_{ijk} is the matrix of covariates on Day k for age Strata j and Hospital i, and β is the vector of estimated regression coefficients. The covariance was assumed to have the autoregressive structure often found in long time series. The Liang and Zeger approach incorporates the covariance structure into the estimation of the regression coefficients as well as their variances, giving more efficient estimates of the parameters. The extra-Poisson variability was estimated using the technique of McCullagh and Nelder (19) and also incorporated into estimating the standard errors of the regression coefficients. This approach has been used successfully in the past to model daily counts of mortality (12, 13), counts of respiratory symptoms in preschool children (20), and counts of pediatric visits for croup (21). Separate counts were kept for each hospital because of the potential heterogeneity in the populations served by each hospital. Counts were also stratified into four age groups (≤5, 5 to 20, 21 to 65, and >65).

Asthma attacks may be triggered directly by weather conditions (such as cold, dry air), or weather may be associated with infectious disease that subsequently triggers attacks (22). In either case, the dependence on weather is likely to be highly non-linear. To control for this, temperature was divided into 6 ranges, and indicator variables were used for each range. Previous studies (6, 11) found that the minimum daily temperature was a better predictor of asthma symptoms and hospital admissions than the mean or maximum daily temperature. We followed this strategy. The ranges of minimum temperature chosen were $T \leq -3°$ C, $-3°$ C $< T \leq 2°$ C, $2°$ C $< T \leq 7°$ C, $7°$ C $< T \leq 12°$ C, $12°$ C $< T \leq 16°$ C, and $T > 16°$ C. As a sensitivity test, ranges of average daily temperature were used instead. Previous studies of respiratory symptoms also suggested the previous day's temperature was most predictive (7). We used categories of the previous day's temperature in this analysis. Again, we tested the sensitivity of air pollution associations to changes in this approach.

Seasonal variation in other risk factors, such as pollen, may not be adequately captured by the temperature variables. Therefore, indicator variables for season were also included. Day of the week indicator variables also were used to capture such effects as the possibly greater use of hospital emergency rooms on the weekend, when fewer physicians' offices are open (9). In addition, there has been a time trend in reported asthma morbidity and mortality in the United States in recent years (23). We therefore included a term for a continuous time trend in our regression model.

Neither the lag with which particles influence asthma symptoms nor the appropriate averaging time have been established. The results of Pope and coworkers suggest that several previous days may contribute to asthma symptoms (6). In contrast, Bates and colleagues (9) report a 24-h lag. Hence we considered several previous days' pollution concentrations, as well as the average of several days, in our analysis.

A control diagnosis of emergency room visits for gastroenteritis was used. The same regression model was fit to both asthma and gastroenteritis visits.

RESULTS

The distribution of asthma visits, gastroenteritis visits, temperature, humidity, PM_{10}, and SO_2 in Seattle during the study period is shown in table 1. PM_{10} concentrations were quite low, with a maximum 24-h concentration of 103 µg/m³ and a mean of 29.6 µg/m³. Total asthma emergency visits for all ages by month, with the September peak evident, is plotted in figure 3. A peak in March is also apparent. PM_{10} concentrations were near their annual mean in September and highest in February, when asthma visits were very low. The September peak was absent in the population over 65, for whom 25 emergency visits were seen during the two September periods, compared to an expected value of 22 cases based on the average number of cases per month in this age group.

TABLE 1

DISTRIBUTION OF VARIABLES USED IN ANALYSIS

Variable	Mean	Minimum	Maximum	SD
Asthma*	7.1	0	18	3.2
Control*	9	1	21	3.5
PM_{10}, µg/m³	29.6	6	103	18
SO_2, ppb	6.5	0	29	5
Minimum temperature °C	7.9	−7	19	4.7
Humidity, %	74	33	100	13.8

* Sum for all hospitals on each day, age less than 65 yr.

TABLE 2

ASTHMA EMERGENCY VISITS BY QUARTILE OF PM_{10}*

PM_{10} Concentration (µg/m³)	Range (µg/m³)	Asthma Emergency Visits Day⁻¹	Confidence Interval
13	6–17	6.24	5.34–7.8
20.3	17–24	6.59	5.71–7.46
29.6	24–36	7.61	6.71–8.50
55.3	36–103	8.00	—

* Adjusted for effect of hospital and day of week.
Age ≤ 65 yr only.

For each day the deviations from the mean visits for each hospital for that day of the week were summed and compared with PM_{10} concentrations. A strong trend was evident by quartile of PM_{10} concentration. This is shown in table 2, where the grand means are added back, to give the mean number of emergency room visits for asthma in each quartile of PM_{10} concentration. A clear dose-related increase is seen.

In initial Poisson regression analyses by age strata, similar regression coefficients for prior days PM_{10} (µg/m³) (β = 0.00299, 0.00232, and 0.00402, respectively) were found for the first three

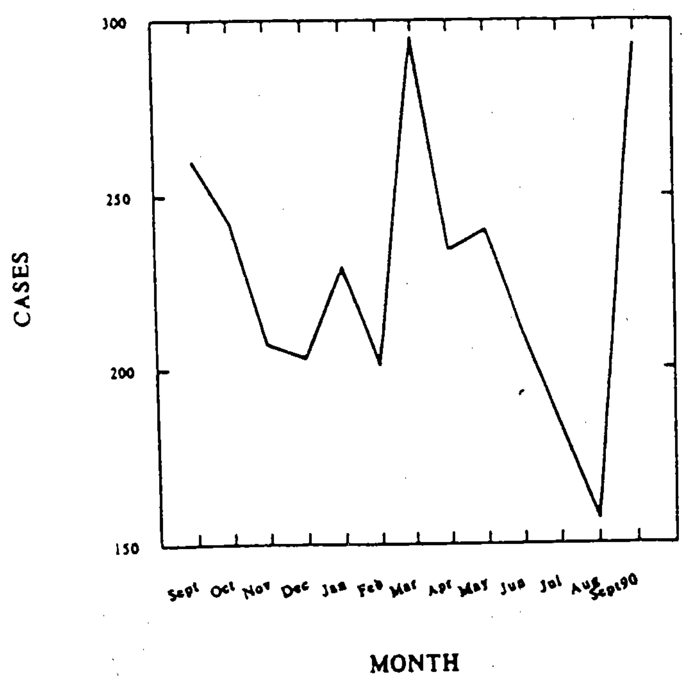

Figure 3. Monthly counts of asthma emergency visits for all ages at the eight study hospitals in Seattle. Note the peaks in March and September.

TABLE 3

ASTHMA EMERGENCY VISITS BY OTHER SELECTED FACTORS*

Hospital	Total Visits	Day of the Week	Total Visits	Age Category	Total Visits
1	102	Sunday	513	≤ 5	714
2	963	Monday	394	6–20	676
3	472	Tuesday	388	21–65	1,419
4	234	Wednesday	374		
5	357	Thursday	331		
6	285	Friday	346		
7	228	Saturday	463		
8	168				

* Age ≤ 65 yr only.

age groups. In contrast, no noticeable association was found between PM_{10} and asthma emergency visits for the elderly ($p = -0.00271 \pm 0.00548$). Subsequent analyses were restricted to emergency visits by patients under age 65, and all age strata were combined for those analyses. The counts of asthma emergency visits by age, hospital, and day of week are shown in table 3. Asthma emergency visits by season are shown in table 4.

In our basic model controlling for temperature categories (on the previous day), seasons, day of the week, hospital, September time trends, and age strata, PM_{10} on the previous day was a significant predictor of asthma emergency room visits ($\beta = 0.00333 \pm 0.00126$). PM_{10} values 2, 3, and 4 days before the visit were also significant predictors of asthma visits. The mean of PM_{10} on the previous 4 days had slightly better explanatory power ($\beta = 0.00367 \pm 0.00126$, $p < 0.005$) (relative risk = 1.12, 95% CI = 1.04 to 1.20). The relative risk is for a 30 $\mu g/m^3$ increase in PM_{10}. Additional lags did not add further information, so the average PM_{10} concentration for the 4 prior days was used in subsequent analyses. The odds ratio and 95% confidence intervals for a 30-$\mu g/m^3$ increase in PM_{10} (4-day average) for our model and for several sensitivity analyses are shown in table 5. The first examines the impact of using temperature categories on the same day rather than the previous day, the second the impact of controlling for cold, dry days, the third the impact of using categories of mean daily temperature instead of minimum daily temperature, the fourth the use of 48-h temperature categories, and the fifth the use of a continuous term for relative humidity. The relative risk for PM_{10} shows little sensitivity to the model specification. In addition, an interaction term to test for a different slope of the PM_{10}-asthma visit relationship during the warm months of the year (April through October) was highly insignificant. Pollen levels are highest in March in Seattle. Excluding March from our data had little impact on the PM_{10} regression (relative risk = 1.10, 95% confidence interval, CI, = 1.02 to 1.20).

To determine whether the relationship exhibited a dose-dependent increase, the continuous PM_{10} variable was replaced with indicators for quartiles of PM_{10} and the model reestimated. The relative risk of asthma emergency room visits by quartile of PM_{10}, with the risk in the lowest quartile taken as 1.0, is shown

TABLE 4

ASTHMA EMERGENCY VISITS BY SEASON*

Winter	587
Spring	734
Summer	519
Fall	969

* Age ≤ 65 yr only.

TABLE 5

RELATIVE RISK (95% CI) OF ASTHMA EMERGENCY VISITS FOR A 10-$\mu g/m^3$ INCREASE IN PM_{10} FOR DIFFERENT MODEL SPECIFICATIONS

Model	Relative Risk	95% CI
Base*	1.037	1.064–1.012
Same day temperature†	1.037	1.064–1.012
Cold, dry days‡	1.037	1.064–1.012
Mean daily temperature§	1.033	1.059–1.009
2-Day average temperature‖	1.037	1.063–1.012
Relative humidity¶	1.037	1.064–1.012

* Controlling for six categories of yesterday's minimum temperature, seasons, hospital, day of week, September, age group, serial correlation, and overdispersion.
† Using six categories of current day's temperature instead of previous day's temperature.
‡ Adding indicator variable for cold, dry days.
§ Using six categories of yesterday's mean temperature.
‖ Using the six categories of the mean of today and yesterday's temperature.
¶ Using a continuous term for relative humidity.

in figure 4. A dose-dependent increase is evident at concentrations well below the current air quality standards.

Light scattering (km^{-1}) in the residential neighborhood was also significantly associated with hospital emergency room visits for asthma ($\beta = 0.0145 \pm 0.0045$). For a change in light scattering comparable to the change in PM_{10} relative risk (7 km^{-1}), an essentially identical risk was seen using this different measure of particulate matter concentration (relative risk = 1.11, 95% CI = 1.04 to 1.18). When SO_2 was examined, no significant associations with asthma emergency visits were found (relative risk = 0.99, 95% CI = 0.94 to 1.05). Ozone was also insignificant as a predictor of asthma attendance (relative risk = 0.97, 95% CI = 0.89 to 1.05). The relative risk is for a 15 ppb change in average ozone concentration.

In contrast to the results for asthma, gastroenteritis visits were not significantly associated with PM_{10} pollution, and the sign of

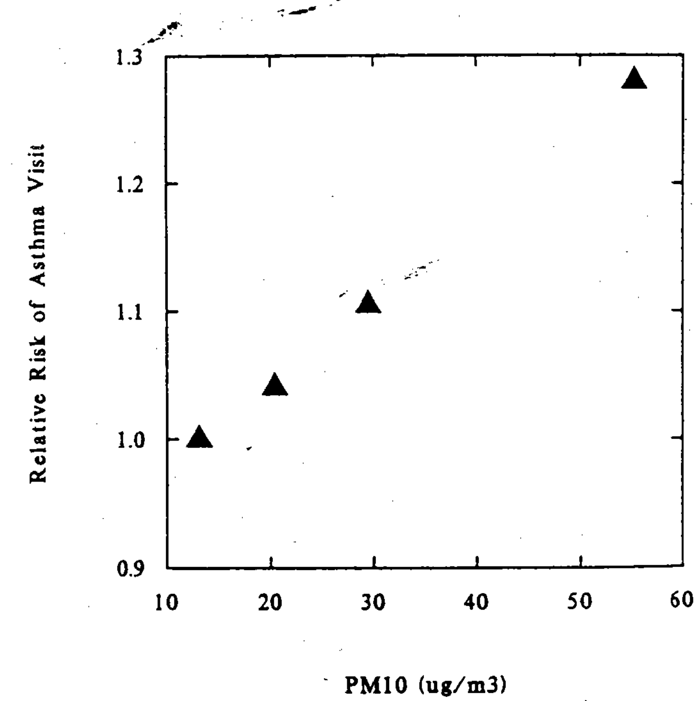

Figure 4. Relative risk of asthma visits by quartile of PM_{10} concentration, plotted against the mean PM_{10} concentration in the quartile. The relative risks are adjusted for temperature, seasons, day of week, hospital, time trends, age, and September peak.

the insignificant association was negative (relative risk = 0.96, 95% CI = 0.89 to 1.03).

DISCUSSION

A highly significant ($p < 0.005$) relationship between asthma admissions and PM_{10} concentrations was observed in this study. The association showed clear evidence of a dose-dependent increase and no evidence of a threshold. At the mean concentration (30 $\mu g/m^3$) of inhalable particles observed in the Seattle area during the study period, PM_{10} exposure appears to have been responsible for approximately 12% of the asthma emergency visits $[100(e^{0.00387 \times 30} - 1)]$. If this association is causal, it represents a nontrivial concern. Moreover, this association occurred in a community where 24-h PM_{10} concentrations never exceeded 70% of the current ambient air quality standard.

A 4-day average PM_{10} concentration had slightly greater predictive power than the prior days' PM_{10} in this study. Although the within-study evidence for a longer than 24-h average is not strong, the pattern is consistent with other recent studies associating longer term average particle concentration with increased need for asthma medication, decreased peak expiratory flow values, and increased symptom reporting and hospitalization (6, 10, 11).

Asthma emergency visits showed the same peak in September that was observed in Vancouver by Bates and colleagues (9). The PM_{10} association is consistent with the studies of Bates and coworkers (8, 9) and of Pope (10, 11) in that asthma visits were higher during periods of high PM_{10} concentrations. Similar findings have been reported at higher concentrations of total particulate matter (24, 25). Consistent with the results of Goldstein and Weinstein (26), no association was observed with SO_2. However, our SO_2 monitor was close to an industrial facility and not representative of the general population exposure. Other studies have reported significant relationships between asthma end points and SO_2 (27, 28). An SO_2 association also was reported in Vancouver (9). In the Utah studies, no appreciable concentrations of SO_2 were present.

Changes in diagnostic practices or coding seem an unlikely confounder in this study since the observed correlations occurred in a study whose duration was only 13 months. There is no reason to believe that day-to-day variations in diagnostic practices should vary with air pollution. Similarly, although unequal access to medical care might confound a cross-sectional analysis of air pollution and asthma emergency attendance, there is also no reason to believe that access to medical care fluctuates on a day-to-day basis in a manner correlated with air pollution.

The use of outdoor monitoring data to represent personal exposure introduces error into the exposure assessment and is a limitation of this study. A study comparing indoor and outdoor fine particulate matter concentrations in wood-burning residences reported an average indoor/outdoor ratio of 0.5 (29). Quackenboss and colleagues reported an indoor/outdoor ratio of 0.63 for PM_{10} in homes of nonsmokers in Tucson, Arizona (30), and Dockery and Spengler reported an indoor/outdoor ratio of 0.55 for total suspended particulates (TSP) in Steubenville, Ohio (31). Outdoor PM_{10} measurements appear to be a noisy but reasonable proxy for indoor exposure. In our study, 39% of the asthma visits occurred in people aged 20 or under, a population that spends more time outdoors than the average adult.

The observed association is supported by the associations between PM_{10} and peak flow decrements, symptoms, and increased need of medication that were reported recently (6). Peak flow decrements also were associated with indoor TSP concentrations in a study by Lebowitz and coworkers (32). Whittemore and Korn (3) reported positive associations of symptoms in a diary study of asthmatic subjects with total suspended particulate matter and ozone. $FEV_{0.75}$ and FVC declines have been noted in episode studies of schoolchildren (33, 34), although the concentrations of airborne particles seen in these episodes were considerably higher than those in this study.

In addition to the symptoms reported in these studies, chronic exposure to PM_{15} has been associated with acute bronchitis rates in the Six City Study (5). Several papers reported an association between PM_{10} and respiratory symptoms in diary studies of preschool children (19) and schoolchildren (7), and particulate matter exposure has also been associated with an increased risk of croup (26). Symptoms in adults have also been noted (35).

Although not identical in all details, the recent studies of hospital visits and admissions show a broad consistency, implicating airborne particles as a risk factor for asthma attacks. This is supported by panel data associating particulate matter exposure with increased response in asthmatic subjects and by the diary data in the general population. Other recent studies suggested that low concentrations of airborne particles increase the risk of acute mortality in sensitive subpopulations (12–14). In the absence of a plausible alternative explanation for these findings, airborne particles at concentrations previously considered safe must be considered a potential risk factor for asthmatic subjects.

The mechanism whereby particles may be triggering or exacerbating asthma attacks remains unclear. In the Seattle area the primary source of fine particulate matter in residential neighborhoods during the winter heating season is from wood burning. We have shown a significant association between measures of this particulate matter and declining lung function in elementary schoolchildren who have asthma (36). Our studies have shown that PM_{10} greater than 50 $\mu g/m^3$ is found primarily in the winter months, and thus the relationship shown between asthma visits and PM_{10} may in large part reflect the toxicity of wood smoke. However, the relationship in figure 4 continues to much lower PM_{10} concentrations, suggesting that wood smoke is not the only contributing factor. The interaction term testing for a different PM_{10} slope in warm weather, when wood smoke is a lesser factor in PM_{10}, was not significant.

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