Air Pollution–Associated Changes in Lung Function among Asthmatic Children in Detroit

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In a longitudinal cohort study of primary-school–age children with asthma in Detroit, Michigan, we examined relationships between lung function and ambient levels of particulate matter ≤ 10 μm and ≤ 2.5 μm in diameter (PM_{10} and $PM_{2.5}$) and ozone at varying lag intervals using generalized estimating equations. Models considered effect modification by maintenance corticosteroid (CS) use and by the presence of an upper respiratory infection (URI) as recorded in a daily diary among 86 children who participated in six 2-week seasonal assessments from winter 2001 through spring 2002. Participants were predominantly African American from families with low income, and > 75% were categorized as having persistent asthma. In both single-pollutant and two-pollutant models, many regressions demonstrated associations between higher exposure to ambient pollutants and poorer lung function (increased diurnal variability and decreased lowest daily values for forced expiratory volume in 1 sec) among children using CSs but not among those not using CSs, and among children reporting URI symptoms but not among those who did not report URIs. Our findings suggest that levels of air pollutants in Detroit, which are above the current National Ambient Air Quality Standards, adversely affect lung function of susceptible asthmatic children.
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As the prevalence of asthma, particularly among urban residents, has escalated over the past three decades (Aligne et al. 2000; Mannino et al. 1998, 2002), ambient air pollutants, especially ozone and particulate matter (PM), have come under scrutiny as stimuli of asthma exacerbations. O_3 is a potent lung irritant causing inflammatory changes in the lung and decreases in lung function (Buchdahl et al. 2000; McConnell et al. 2002; Mortimer et al. 2000, 2002). PM with an aerodynamic diameter of ≤ 10 μm (PM_{10}) and ≤ 2.5 μm ($PM_{2.5}$) has been linked to increases in respiratory symptoms, emergency department visits for asthma, and decreases in lung function (Delfino et al. 2002; McConnell et al. 2003; Norris et al. 1999; van der Zee et al. 1999; Yu et al. 2000).

Children with asthma are particularly at risk for adverse health effects of air pollutants including PM and O_3 (Boezen et al. 1999; Delfino et al. 2002; McConnell et al. 1999; Norris et al. 1999; Ostro et al. 2001). New lines of inquiry suggest that there may be particularly sensitive subpopulations even within this group. Because air pollutants are thought to stimulate a generalized inflammatory reaction in the asthmatic airway, several investigators have examined whether use of maintenance anti-inflammatory medication protects against the adverse effects of air pollutants, with mixed results: Some have reported protective effects (Delfino et al. 2002; Mortimer et al. 2000; Peters et al. 1997), whereas others instead have found that only those children using maintenance medications show associations between pollutant exposure and respiratory symptoms (Gent et al. 2003). Children experiencing a respiratory infection—another potent stimulus of airway inflammation—may also have increased susceptibility to the effects of air pollution (Chauhan et al. 2003; Delfino et al. 2002).

Based on the evidence for adverse health effects, U.S. National Ambient Air Quality Standards (NAAQS) were recently revised to lower the allowable ambient exposure to O_3 using a daily 8-hr maximum reference and to introduce a daily and annual standard for $PM_{2.5}$ [U.S. Environmental Protection Agency (EPA) 1997]. Although there have been improvements in some indicators of air pollution, many urban areas have not attained the new O_3 and $PM_{2.5}$ standards (U.S. EPA 2002). It is important to examine whether current ambient levels of pollutants at or near current standards are negatively affecting the health of sensitive subpopulations.

Detroit, Michigan, offers an ideal setting for elucidating urban environmental influences on childhood asthma. Detroit reflects many demographic trends seen in urban areas around the country. A high proportion of city residents have low income and are African American or Latino. Asthma prevalence among children is high in Detroit, with 14.3% reporting active physician-diagnosed asthma and an additional 14.3% with undiagnosed asthma (Joseph et al. 1996). Asthma hospitalization rates for children in Detroit are more than three times the statewide average (Michigan Department of Community Health 2002). In addition, Detroit and surrounding Wayne County have a long history of elevated air pollution and are currently in nonattainment of the newer $PM_{2.5}$ and O_3 standards. Detroit is the site of the busiest U.S.–Canadian border crossing for truck traffic (3,486,110 trucks/year). Typical daily traffic volumes for major highways in Detroit range from 47,000 to 153,000 vehicles (Michigan Department of Transportation 2001). Nearby point sources for pollutants include coal-fired utilities, municipal waste incineration, sewage sludge incineration, refineries, iron/steel manufacturing, coke ovens, and chemical plants (Keeler et al. 2002).

We hypothesized that ambient levels of PM and O_3 in Detroit communities would be associated with fluctuations in lung function among asthmatic children. We expected that more severe asthma, as indicated by concurrent

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use of maintenance corticosteroids (CSs), would confer additional susceptibility to the effects of air pollution. Additionally, we expected that co-inflammatory changes associated with a contemporaneous respiratory infection would increase the adverse effects of higher pollutant levels on measures of lung function. We were most interested in effects seen in the first few days after exposure that we felt were most likely to reflect inflammatory, as opposed to acute bronchospastic, asthmatic changes. Because the inflammatory changes represented by children using inhaled CSs and those with respiratory infection are likely to be different, we did not necessarily expect that the pollution effect lag structures would be the same for both types of children.

Materials and Methods

Community Action Against Asthma Partnership

There is a strong history of community-based participatory research (CBPR) partnerships in Detroit aimed at addressing asthma and other health-related issues (Israel et al. 2003). The study reported here is from Community Action Against Asthma (CAAA), a project of the CBPR partnership Michigan Center for the Environment and Children's Health. The CAAA partnership involves a steering committee composed of representatives of community-based organizations, health service agencies, an academic institution, and a community member at large that guided all phases of the research (see Acknowledgements for list of partners). The steering committee's role included the conceptualization of the research questions and methods, particularly related to interactions with the community, schools, and study participants; the design of data collection instruments and processes; the hiring of staff; and the interpretation and dissemination of research results (Edgren et al. 2005; Parker et al. 2003). CAAA involved a longitudinal epidemiologic cohort study of the effects of PM and O_3 on the respiratory health of children with asthma (present results) and a randomized controlled trial of an intervention involving home visits by community outreach workers to assist families in reducing exposure to indoor asthma triggers (Parker et al. 2003). These studies were conducted in two communities within Detroit (eastside and southwest) that demographically have a high proportion of low-income residents from African-American and Latino ethnic groups.

Exposure Assessment

Ambient monitoring sites were established on the rooftop of a representative school in both southwest and eastside Detroit to assess community-level exposures to PM and O_3. Two-week seasonal measurement campaigns were conducted for 11 seasons commencing in the fall (October) of 1999 and ending in the spring (May) of 2002.

Monitor placement. Many previous studies to assess health effects of air pollutants have used exposure data from the nearest available monitor (often existing state or federally mandated monitoring sites). These often urban-scale monitoring sites, as defined by the U.S. EPA (1997), are designed to represent exposure to large populations, in a geographic area up to 100 km in diameter. Our study sought to quantify community-level exposure within two Detroit communities, with the possibility that exposures between the two communities may be different (Keeler et al. 2002). Although the centroid of southwest Detroit study participants was 15 km from the centroid of eastside Detroit study participants, we determined on examination of the preexisting air monitoring sites in Detroit that additional community-level sites would need to be established for the sole purpose of this study to obtain more accurate measures of exposure. Each community monitoring site was established near the centroid of the study participants. Of the 86 children included in the data analyses for this report (see "Pulmonary function measures," below), 82 were located within 5 km of their respective community monitoring location, resulting in great improvement in exposure estimation when compared with the preexisting monitoring sites in Detroit or with the geographic representativeness of exposure estimates for many previous studies. The remaining four children were in the eastside Detroit community, 6–7.5 km from the community monitoring site.

U.S. EPA monitoring guidelines for PM and O_3 recommend sampler inlets be placed between 3 and 15 m above ground level because of surface reactivity and aerosol resuspension concerns near ground level (U.S. EPA 1998). Because of the landscape of the built environment in urban areas, it has been suggested that rooftop locations (up to four stories in height) serve as representative locations for pollutant exposure monitoring (Chow et al. 2002). Using these guidelines, we selected the community-level monitoring locations on elementary school rooftops, with sampler inlets 5–6 m above ground level as previously described (Keeler et al. 2002).

Field measurements. We performed 24-hr measurements of $PM_{2.5}$ and PM_{10} at each community sampling location using Teflon-coated aluminum cyclone inlets and filter-pack assemblies (University Research Glassware, Carrboro, NC) with 2-μm–pore 47-mm Teflon (polytetrafluoroethylene) membrane filters (Pall Life Sciences, Ann Arbor, MI). Samples were collected at a flow rate of 16.7 L/min from 0800 hr to 0800 hr, and the total volume of air sampled was measured with calibrated dry test meters (Schlumberger, Owenton, KY).

Ambient measurements of O_3 and meteorologic variables were also made at each community sampling location. O_3 was monitored continuously and logged as 30-min average values (Dasibi Environmental, Glendale, CA). Standard meteorologic variables including temperature, atmospheric pressure, relative humidity, wind speed, and wind direction (R.M. Young Co., Traverse City, MI) were also recorded in 30-min intervals at each of the community measurement sites (Keeler et al. 2002).

Laboratory analyses. All sample handling, processing, and analysis took place in a class 100 clean laboratory (University of Michigan Air Quality Laboratory, Ann Arbor, MI) uniquely suited for ultratrace element analysis with an emphasis on environmental determinations. All gravimetric determinations of Teflon filters for PM were made using a microbalance (Mettler MT-5; Mettler Toledo, Columbus, OH) in a temperature/humidity-controlled environment. Standard protocols included the use of field blanks, filter-lot blanks, laboratory blanks, replicate analyses, and externally certified standard weights for all gravimetric analyses for quality assurance and quality control purposes. The detection limit for mass determination, calculated as three times the standard deviation of seven replicate filter measures, was 5.1 μg. This corresponds to a detection limit of 0.2 $\mu g/m^3$ for a 24-hr sample collected at 16.7 L/min.

For PM, daily $PM_{2.5}$ and PM_{10} measurements were the exposure variables used in the health analysis. For O_3, the daily mean O_3 concentration and the rolling 8-hr averages were calculated. With consideration for the new U.S. EPA standard (U.S. EPA 1997), the maximum 8-hr average in a 24-hr period was called the O_3 8-hr peak and analyzed as a separate exposure variable.

Recruitment and Enrollment

An asthma screening questionnaire was mailed and/or hand delivered to parents of 9,627 children, 7–11 years of age, who attended one of 44 elementary schools in the eastside and southwest areas of Detroit (Lewis et al. 2004). Items on the questionnaire included parent report of their child's frequency of respiratory symptoms, presence of physician diagnosis of asthma, and frequency of doctor-prescribed asthma medication use. Among the 3,067 returned questionnaires, 708 were eligible for the study, based on the inclusion criteria that responses on the screening questionnaire be consistent with current persistent asthma and that the address be within the geographic boundaries of the study. We successfully contacted 510 of those eligible and invited them

to enroll. Of these, 328 children were enrolled. Thirty children were lost to follow-up between obtaining informed consent and commencing the study; therefore, the 298 children who began the study serve as the study cohort. There were no significant differences in demographic or asthma characteristics between the 328 children that enrolled in the study and the 179 who were contacted but chose not to enroll, or between the 298 children that began the study and the 30 who were lost to follow-up before the study began (Lewis et al. 2004). There were also no demographic differences between the 3,067 who returned screening questionnaires and the 86 children for whom lung function data are presented here.

Outcome Assessment

Pulmonary function measures. Each child was asked to complete three consecutive expiratory maneuvers in the morning and again in the evening on 14 consecutive days during each of the 11 seasonal measurement periods using a hand-held digital lung function monitoring device (AirWatch; iMetrikus Inc., Carlsbad, CA). The Airwatch devices are calibrated at the factory and are stated by the manufacturer to retain calibration for life. We did not attempt to independently calibrate the devices.

Peak flow (PF) and forced expiratory volume in 1 sec (FEV_1) were measured. Although it would have been desirable to examine additional measures of airway obstruction, such as mid-volume flows [forced expiratory flow between 25 and 75% of vital capacity ($FEF_{25–75}$)], these were not available from simple hand-held devices at the time of the study. During the first five seasons, all expiratory maneuvers were carried out at home. Preliminary review of the data raised concerns about quality of these expiratory maneuvers. Therefore, for the final six seasons we switched to using the newly available AirWatch 2 model, which included error messages both for quality and length of expiratory maneuver. In addition, all weekday morning blows during the final six seasons were performed at school under observation and coaching by research staff. To maximize the efficiency of limited staff, this required restricting participation to those 86 children who attended a school with at least two other study participants. Other than being on average 6 months younger, these 86 children did not differ significantly in demographic characteristics or in intervention group assignment from those who did not continue with pulmonary function measures in the last six seasons. These protocol changes produced substantial improvement in the quality of the expiratory maneuvers. Results presented here are based on these final six seasons of data [winter 2001 (February 10–23), spring 2001 (May 5–18), summer 2001 (July 14–27), fall 2001 (September 22–October 5), winter 2002 (January 18–31), and spring 2002 (May 18–31)].

Lung function parameters of interest were diurnal variability in these measures, as well as the lowest value of the day. We defined variability as the difference between morning and evening value divided by the larger of the two values for that day. Variability increases during asthma exacerbation and was expected *a priori* to be higher in response to high pollution exposure. Lowest daily value, measured as percent predicted for sex, age, height, and ethnicity (Hankinson et al. 1999), was defined as the lower of the morning and evening values for that day. High pollution exposure was hypothesized to be associated with reduction in lowest daily value. Data were analyzed for days when a valid measurement was obtained in both morning and evening. A valid measure was defined as one obtained on an error-free expiratory maneuver. We excluded extreme measures, which we felt were more likely to be attributable to undetected errors in technique than to be truly representative of the child's respiratory health. For FEV_1, we defined extreme as being > 140% or < 30% predicted.

Medication and symptom diary. As part of the 2-week seasonal measurements, the child's primary caregiver completed a medication and symptom diary at the end of each day. Children were considered to have an upper respiratory tract infection (URI) on any day for which the caregiver checked "yes" for "Does your child have a cold, the flu, or other respiratory infection today?" Caregivers also wrote in the number of times each of the asthma medications were administered that day. Children were defined as being on a CS if, and only if, *a*) at least 7 of the 14 diary days were completed and *b*) the parent reported use of an inhaled or oral steroid for ≥ 50% of the days for which the diary was completed. The assessment of whether or not a child was on a CS was made for each season independently.

Each participating caregiver was interviewed face to face annually to obtain information about family demographics, the child's health status, and the perceived exposure of the child to tobacco smoke.

Analysis Methods

We examined descriptive statistics and bivariate analyses of exposures with health outcomes and then examined multivariable regression models that included interaction terms between exposure measures and CS use or, alternatively, presence of a URI. We used generalized estimating equations (GEE) (exchangeable covariance structure), a multivariate analog of linear regression to account for the within-participant correlation of the repeated measures. GEE was chosen over generalized linear models because of the non-normally distributed exposure data.

With respect to timing of exposures, we examined outcomes occurring 1 and 2 days after the day that exposure was assessed (lag 1 and lag 2). In addition we considered outcomes associated with the average daily exposure 3–5 days before the outcome (lag 3–5).

Covariates in the final models included sex, home location, annual family income, presence of one or more smokers in household, race, season (entered as dummy variables), and parameters to account for intervention group effect. Home location (eastside vs. southwest) was determined by ZIP code of residence. Caregivers were asked to identify their child's race, and responses were categorized as African American or not African American. Annual family income was asked as a multiple choice question with 11 response categories ranging from "< $5,000" to "≥ $80,000." For regression analysis, these were condensed to four categories: < $10,000, $10,000–19,999,

Table 1. Characteristics of children participating from winter 2001 through spring 2002 as reported on baseline caregiver interview ($n = 86$).

Characteristic	Value
Child age at start of winter 2001[a]	9.13 ± 1.44
Percent female	43.0
Child ethnicity (%)	
African American	77.9
Latino	15.1
Other	7.0
Child location of residence (%)	
Eastside	70.1
Southwest	29.9
Caregiver education (%)[b]	
1–8 grade	8.1
9–11 grade	33.7
High school graduate/GED	27.9
Any college	30.2
Household annual income (%)	
< $10,000	44.7
$10,000–20,000	32.9
$20,000–40,000	17.6
≥ $40,000	4.7
Caregiver smokes cigarettes (self-report) (%)	31.4
Any household member smokes cigarettes (%)	51.2
Child's asthma severity (%)	
Moderate–severe persistent	50.0
Mild persistent	25.6
Mild intermittent	24.4
Asthma medication use by asthma severity	
Persistent (mild severe) [$n = 65$ (%)][b]	
CS	15.4
Nonsteroid controller[c]	23.1
Short-acting bronchodilator[d]	30.8
None	30.8
Intermittent [$n = 21$ (%)]	
CS	4.8
Nonsteroid controller	4.8
Short-acting bronchodilator	14.3
None	76.2

[a]Mean ± SD. [b]Percentages may not add to 100% because of rounding. [c]Use of a leukotriene modifier, long-acting bronchodilator, cromolyn, or theophylline, but no use of a CS. [d]Use of a short-acting bronchodilator but no use of any controller medication.

$20,000–39,000, and ≥ $40,000. Children were considered to be exposed to tobacco smoke if caregivers reported one or more cigarette smokers living in the home. To adjust for an influence of being simultaneously enrolled in the companion home intervention study, two indicator variables were included: whether a child had been randomized to the intervention or to the control groups, and whether the exposure was occurring before or after the intervention was complete. An interaction term between intervention group and time was also included.

In separate models, interactions of each exposure variable with CS use or with presence of URI were also included. This allowed the pollution effects and the lag structure to differ with the different types of effect modification being examined. We did not adjust for relative humidity and temperature because of the high degree of collinearity with exposure measurements within several seasons. Adjusting for season accounts for most of the variability in temperature and humidity between seasons, as well as other unmeasured season-specific covariates (e.g., incidence of respiratory infections in the community).

We analyzed single-pollutant models examining the effects of PM and O_3 independently, as well as two-pollutant models simultaneously including a measure of PM and of O_3. To be able to directly compare the effect sizes across pollutants, exposures were standardized to the interquartile range for each specific pollutant. The number of observations on which models were based varies depending on the pattern of missing data by pollutant, lag, and season.

Results

Demographic and Asthma Characteristics of Cohort

Characteristics of the 86 children participating in the last six seasons of data collection, and thus contributing to the analyses presented here, are shown in Table 1. Most participants were African American, were from the eastside, and had household annual income < $20,000. Approximately one-half of the caregivers reported at least one tobacco smoker in the household. At baseline, half of the children had symptoms consistent with moderate-to-severe persistent asthma. Among the 65 children with persistent asthma, fewer than one-half were reported to be taking a controller medication (steroid or nonsteroidal), and 30% were using no medication at all. CS use reported on daily diaries ranged from 13 to 26% of all participants, depending on the season. Frequency of respiratory infection ranged from a low of 7% of reported person-days (in spring 2001 and spring 2002) to a high of 24% of person-days in winter 2001. CS use and respiratory infection were uncorrelated: Of the > 1,900 person-days of observations entering the regressions, only 3% were contributed by children reporting both CS use and presence of respiratory infection, 11% were contributed by children reporting CS use but not respiratory infection, and 19% by children reporting respiratory infection but not CS use.

Description of Ambient Exposure Measurements

Means across the six seasons of ambient exposure measures [winter (February) 2001 through spring (May) 2002] by location are shown in Table 2. The mean concentrations of $PM_{2.5}$ were 15.7 and 17.5 μg/m^3 measured at the eastside and southwest sites, respectively (Table 2). In addition to seasonal variability in PM [lowest seasonal means occurred in fall (September) 2001: $PM_{2.5}$ = 10.6 μg/m^3, PM_{10} = 20.5 μg/m^3; highest seasonal means occurred in spring (May) 2001: $PM_{2.5}$ = 23.3 μg/m^3, PM_{10} = 28.4 μg/m^3], there was considerable day-to-day variability in PM measurements (lowest daily mean $PM_{2.5}$ = 1.0 μg/m^3, PM_{10} = 2.9 μg/m^3; highest daily mean $PM_{2.5}$ = 56.1 μg/m^3, PM_{10} = 70.9 μg/m^3). The observed levels of pollutants were similar to values measured at these sites during the first five seasons of the study, fall 1999 through fall 2000 (Keeler et al. 2002), and the Detroit area has since been designated in nonattainment for the annual NAAQS for $PM_{2.5}$ of 15 μg/m^3. The increased levels of both PM_{10} and $PM_{2.5}$ at the southwest site are likely due to a combination of the local proximity of heavy industrial sources (including coal-fired power plants, refineries, and iron/steel mills) and differences related to traffic density (e.g., diesel emissions).

As with PM, there was both seasonal variability and day-to-day variability in O_3 levels (lowest daily mean = 5.6 ppb, lowest 8 hr-peak = 14.8 ppb; highest daily mean = 66.3 ppb, highest 8-hr peak = 92.0 ppb). Non-negligible levels of O_3 were measured during the winter 2002 (eastside: daily mean = 22.2, 8-hr peak = 24.1; southwest: daily mean = 21.2, 8-hr peak = 24.2). The interquartile ranges were 12.5 μg/m^3, 19.1 μg/m^3, 14.5 ppb, and 16.0 ppb for $PM_{2.5}$, PM_{10}, daily O_3, and 8-hr peak O_3, respectively. Correlations between PM measures and O_3 measures were mostly in the 0.5–0.6 range. The intra-PM and intra-O_3 correlations were around 0.9 (Table 3).

Description of Lung Function

There were 12,962 error-free observations available for analysis out of a possible 14,448 (twice-daily measures for 14 days per six seasons for each of the 86 children). We restricted our analysis to the 10,784 FEV_1 observations between 30 and 140% predicted, which represents approximately 83% of the error-free data. Population mean lung function values for FEV_1 diurnal variability and lowest daily FEV_1 are shown by use of CS medications and by report of the presence of respiratory infection in Table 4. These values suggest that, on average, our population experienced a mild to moderate degree of airway obstruction. The lack of differences between those reporting and those not reporting respiratory infection suggests that aggravation of underlying asthma was not routinely being confused with respiratory infection by the respondents.

Association of Exposure and Lung Function

Single-pollutant models. Regression models expressing the association between ambient pollutant exposure and lung function for children on CSs are shown in Table 5. Results for children not on CSs are not presented, because no statistically significant relationships were identified at the p = 0.05 level. Associations for children reporting presence of URI symptoms are shown in Table 5. Only one statistically significant relationship was observed for children who did not report respiratory infection symptoms (described in "Additional analyses," below).

All associations with p-values < 0.2 were in the expected direction (increased pollutant associated with increased FEV_1 diurnal variability and decreased lowest daily value), indicating consistency across the models examined. For children on maintenance CSs, PM_{10} and

Table 2. Ambient pollutant and meteorologic measurements (mean ± SD) in two Detroit communities averaged across six seasons (winter 2001 through spring 2002).

Measurement	Eastside	Southwest	Interquartile range
$PM_{2.5}$ daily mean (μg/m^3)	15.7 ± 10.6	17.5 ± 12.2	12.5
PM_{10} daily mean (μg/m^3)	23.0 ± 13.5	28.2 ± 16.1	19.1
O_3 daily mean[a] (ppb)	27.6 ± 12.5	26.5 ± 9.8	14.5
O_3 peak 8-hr mean[a] (ppb)	40.4 ± 18.2	41.4 ± 18.6	16.0
Temperature (°C)	11.5 ± 9.8	11.7 ± 9.8	
Relative humidity (%)	72.2 ± 14.1	73.1 ± 14.7	

[a]O_3 was not measured during winter 2001.

Table 3. Pearson correlation matrix of pollutant measures made in two locations (eastside and southwest) during six seasons (winter 2001 through spring 2002).

	Daily mean		O_3
Pollutant	PM_{10}	O_3	8-hr peak
$PM_{2.5}$ daily mean	0.93	0.57	0.53
PM_{10} daily mean		0.59	0.57
O_3 daily mean			0.87

8-hr peak O_3 were both associated with poorer lung function 2 days after exposure. For children reporting symptoms of respiratory infection, both $PM_{2.5}$ and PM_{10} were associated with poorer lung function 3–5 days after exposure. O_3, particularly the 8-hr peak concentration, was associated with poorer lung function, predominantly at lag 1 and lag 2. In general, the estimated effect sizes were modest and were in similar ranges for PM and for O_3.

Two-pollutant models. In models including either of the PM measurements simultaneously with daily mean O_3, all associations with *p*-values < 0.1 were in the expected direction (Tables 6 and 7). The pattern of these associations differed from that in the single-exposure models, most likely owing to differences in missing data patterns across these analyses. The two-pollutant models suggest that PM and O_3 independently affect lung function, even after adjustment was made for the effect of the other pollutant. Among children taking CSs (Table 6), the combination of $PM_{2.5}$ and daily O_3 was more likely to have a significant effect in the longer lags, whereas the effects of PM_{10} and daily O_3 were seen in both shorter and longer lags. A similar pattern was also seen among children reporting respiratory infection on the day of lung function assessment (Table 7). Some of the largest and most significant effect estimates were seen for the models including PM_{10} and O_3 among those children with respiratory infections.

Additional analyses. Regressions including either of the PM measures simultaneously with 8-hr peak O_3 also showed associations with lung function in the expected direction, although these were statistically significant slightly less often than the presented PM/daily O_3 models.

We examined identical models using PF as an alternative health outcome. Data cleaning for PF was the same as for FEV_1, except that, based on the distribution of the data, a slightly narrower range of values were considered valid (values between 30 and 120% predicted). As with FEV_1 models, PF models showed multiple statistically significant associations between pollutants and respiratory outcomes, with all but one of these associations seen among children who either used CSs or who reported URIs. In general, the pattern of significant associations was similar in the PF and the FEV_1 models. There were several instances where an exposure would be significantly associated with worsening lung function in the FEV_1 model and in the PF model would have a point estimate in the expected direction of worse lung function, but where the *p*-value was > 0.05, implying that FEV_1 was a more sensitive indicator than PF for pollution effects on lung function.

The vast majority of analyses for children not on CSs or not reporting a URI did not show significant associations (data not shown). Of the 144 models examined (associations between $PM_{2.5}$, PM_{10}, daily O_3, and 8-hr peak O_3 exposures singly or jointly with FEV_1 or PF diurnal variability or lowest daily value), only four models showed significant associations between pollutants and lung function in the groups not on CSs or not reporting URIs. These exceptions are described here. Among children without URIs, *a*) the single-pollutant model examining the association between PM_{10} and diurnal variability in PF at lag 1 showed an odds ratio (OR) of 1.72 [95% confidence interval (CI), 0.38 to 3.06; $p = 0.012$], whereas among children with URIs, OR = 1.83 (95% CI, –4.26 to 7.91; $p = 0.56$); and *b*) the two-pollutant model of PM_{10} and daily O_3 exposure on diurnal variation of FEV_1 at lag 1 showed an OR for O_3 exposure of 3.27 (95% CI, 0.30 to 6.23; $p = 0.03$; OR for PM_{10} was not significant), contrasted with children with URIs (OR for O_3 exposure = 9.53; 95% CI, 5.82 to 13.47; $p < 0.001$; OR for PM_{10} was not significant). For children not on CSs, *a*) the two-pollutant model evaluating the joint effects of $PM_{2.5}$ and daily O_3 exposure on diurnal variation of FEV_1 at lag 3–5 days showed an OR for $PM_{2.5}$ exposure of 2.21 (95% CI, 0.26 to 4.16; $p = 0.03$; OR for O_3 exposure was not significant), contrasted with children on CSs (OR for $PM_{2.5}$ exposure = 2.70; 95% CI, 1.0 to 4.40; $p = 0.002$; OR for O_3 exposure was not significant); and *b*) the

Table 4. Distribution of valid FEV_1 diurnal variability[a] and lowest daily FEV_1[a] values (mean ± SD) over the six seasonal assessment periods by at-risk status determined by seasonal diary (winter 2001 through spring 2002).

Subgroup of children	Person-days (*n*)	Variability FEV_1	Lowest daily FEV_1
On CSs[a]	393	15.8 ± 14.2	78.1 ± 17.5
Not on CSs	1,545	15.0 ± 11.6	71.7 ± 18.9
Reporting URI[a]	231	14.9 ± 12.3	74.0 ± 19.0
Not reporting URI	1,481	15.7 ± 12.3	71.5 ± 19.4

[a]See "Materials and Methods" for definitions.

Table 5. Associations of ambient pollutant concentrations with lung function of children with asthma: single-pollutant models.[a]

	Daily mean											
	$PM_{2.5}$			PM_{10}			O_3			O_3 daily 8-hr peak		
Lung function[b]	Coefficient[c]	95% CI	*p*-Value	Coefficient	95% CI	*p*-Value	Coefficient	95% CI	*p*-Value	Coefficient	95% CI	*p*-Value
Among children reporting use of maintenance CSs[d]												
Diurnal variability FEV_1												
Lag 1[e]	1.61	–0.50 to 3.72	0.14	1.53	–0.85 to 3.90	0.21	–0.41	–3.02 to 2.19	0.76	1.75	–0.20 to 3.70	0.08
Lag 2[e]	2.96	–1.74 to 7.66	0.22	5.32	0.32 to 10.33	0.04	–0.73	–3.21 to 1.75	0.56	3.19	0.29 to 6.08	0.03
Lag 3–5[e]	1.37	–1.49 to 4.22	0.35	1.46	–2.21 to 5.13	0.43	–1.86	–4.86 to 1.14	0.22	–0.03	–0.28 to 0.22	0.82
Lowest daily value FEV_1												
Lag 1[e]	–2.23	–6.99 to 2.53	0.36	–0.28	–2.34 to 1.77	0.79	–0.28	–4.94 to 4.39	0.91	–1.0	–5.68 to 3.68	0.68
Lag 2[e]	–0.21	–4.09 to 3.68	0.92	–2.21	–3.97 to –0.46	0.01	0.21	–3.06 to 3.48	0.90	–3.95	–6.78 to –1.12	0.006
Lag 3–5[e]	–0.76	–5.00 to 3.49	0.73	–2.58	–7.65 to 2.49	0.32	–1.05	–7.68 to 5.58	0.76	0.07	–0.28 to 0.41	0.70
Among children reporting presence of URI on day of lung function assessment												
Diurnal variability FEV_1												
Lag 1[e]	2.00	–2.64 to 6.64	0.40	3.51	–4.52 to 11.55	0.39	4.08	–1.78 to 9.94	0.17	5.79	1.74 to 9.85	0.005
Lag 2[e]	0.35	–5.90 to 6.60	0.91	1.12	–4.62 to 6.86	0.70	7.62	–0.49 to 15.73	0.07	4.74	0.46 to 9.02	0.03
Lag 3–5[e]	2.51	0.06 to 4.95	0.05	3.90	0.34 to 7.47	0.03	1.47	–7.73 to 10.67	0.75	0.27	0.01 to 0.53	0.04
Lowest daily value FEV_1												
Lag 1[e]	–1.21	–5.62 to 3.21	0.59	–2.72	–9.47 to 4.03	0.43	–2.65	–6.16 to 0.87	0.14	–3.00	–5.16 to –0.84	0.007
Lag 2[e]	–0.10	–4.36 to 4.16	0.96	–0.24	–5.10 to 4.63	0.92	–4.36	–8.26 to –0.47	0.03	–2.64	–5.45 to 0.18	0.07
Lag 3–5[e]	–2.88	–5.46 to –0.30	0.03	–4.48	–8.36 to –0.60	0.02	–1.01	–3.98 to 1.96	0.50	–0.03	–0.18 to 0.12	0.70

[a]Each coefficient is an estimate of percent change in lung function shown and is derived from a separate linear regression model using GEE. Covariates in each model: sex, home location, annual family income, presence of one or more smokers in household, race, season, randomization assignment for the intervention, and interaction between time and this randomization assignment. [b]Assessment of a child's lung function based on error-free expiratory maneuvers. [c]The regression coefficient is the estimated change in lung function associated with an increase of one interquartile range in the ambient pollutant concentration. [d]Regressions pertain to those children reporting use of inhaled and/or oral CSs at least 50% of days in a given season on diary. [e]Number of days between measurement of ambient pollutant concentration and lung function; lag 3–5 is based on the mean of pollutant concentrations on those days.

two-pollutant model of PM_{10} and daily O_3 on diurnal variation of FEV_1 at lag 3–5 days showed an OR for PM_{10} exposure of 2.92 (95% CI, 0.74 to 5.11; $p = 0.009$; OR for O_3 exposure not significant), contrasted with children using CSs (OR for PM_{10} exposure 3.30; 95% CI, 0.58 to 6.02; $p = 0.02$; OR for O_3 exposure not significant).

Discussion

$PM_{2.5}$ and 8-hr O_3 concentrations in Detroit measured in this study are close to or exceed the updated NAAQS standards, whereas levels of PM_{10} are well within current standards. Our findings in single- and two-pollutant regression models strongly suggest that these levels of air pollutants were associated with adverse effects on pulmonary function among at-risk children with asthma. Among the subgroup of asthmatic children using maintenance CSs, single-pollutant models suggest lag 2 effects for PM_{10} and 8-hr peak O_3. The two-pollutant models revealed effects more broadly across various lags for children on steroids. For children reporting respiratory infection, the single-pollutant models showed PM effects in later lags and a striking O_3 effect, particularly when examining the 8-hr peak concentration. In several of these two-pollutant models, PM and O_3 measures simultaneously showed statistically significant associations with poorer lung function, strongly suggesting the presence of independent effects. Moreover, the fact that the same single- and two-pollutant models for children not on CSs and, separately, children without a current URI showed essentially no significant associations between any pollutant measures and any lung function measures greatly decreases the likelihood that some kind of unrecognized systematic bias is responsible for the positive findings among those on CSs or with URIs. On the whole, the observed effects, although mostly modest in absolute terms, appear quite statistically robust.

Strengths of our study include multiple assessments of air pollution and lung function across seasons; the use of FEV_1 as an outcome measure; an ability to examine two susceptible subgroups—children on maintenance CSs and children reporting respiratory infections; an ability to examine simultaneous effects of O_3 and suspended particles; and a CBPR approach that contributed to high retention of participants across seasons.

Several limitations of this study need to be considered. The data presented here are based on 86 children from an original group of 510 eligible children with persistent asthma who were successfully contacted, raising the potential for selection biases affecting exposure–health outcome associations. It appears unlikely that such biases are substantively operative given that *a*) demographic and disease status of the 86 children for whom data are analyzed here were very similar to those of the other 212 children who began the study; *b*) the basis on which the 86 were chosen (i.e., having at least one other participating child present in the same school) is very unlikely to be associated with the magnitude of the child's health response to air pollutants; and *c*) in that, in this longitudinal design, each child essentially serves as his or her own control, different distributions of unmeasured covariates among the 86 compared with the other children are substantially less likely to affect exposure–health outcome associations.

Repeated measurements of lung function in the community setting are notoriously difficult to obtain accurately. This was corroborated by our own experience with the first

Table 6. Associations of ambient pollutant concentrations with lung function among children with asthma reporting use of maintenance CSs: two-pollutant models.[a,b]

	$PM_{2.5}$ daily mean			O_3 daily mean		
Lung function[c]	Coefficient[d]	95% CI	*p*-Value	Coefficient	95% CI	*p*-Value
Effect of concurrent exposure to both $PM_{2.5}$ and O_3						
Diurnal variability FEV_1						
Lag 1[e]	0.99	–5.64 to 7.62	0.77	1.27	–3.58 to 6.11	0.61
Lag 2[e]	4.62	–4.31 to 13.54	0.31	3.51	–3.79 to 10.81	0.35
Lag 3–5[e]	2.70	1.0 to 4.40	0.002	3.76	0.27 to 7.26	0.04
Lowest daily value FEV_1						
Lag 1[e]	3.36	–3.92 to 10.63	0.37	–2.53	–9.78 to 4.71	0.49
Lag 2[e]	0.88	–8.69 to 10.46	0.86	–0.13	–8.09 to 7.83	0.98
Lag 3–5[e]	–2.78	–4.87 to –0.70	0.009	–2.81	–9.02 to 3.41	0.38
Effect of concurrent exposure to PM_{10} and O_3						
Diurnal variability FEV_1						
Lag 1[e]	2.94	–1.07 to 6.96	0.15	5.32	1.82 to 8.82	0.003
Lag 2[e]	13.73	8.23 to 19.23	< 0.001	5.55	1.93 to 9.17	0.003
Lag 3–5[e]	3.30	0.58 to 6.02	0.02	–1.63	–6.97 to 3.72	0.55
Lowest daily value FEV_1						
Lag 1[e]	–6.25	–11.15 to –1.36	0.01	–2.33	–4.85 to 0.02	0.07
Lag 2[e]	–5.97	–11.06 to –0.87	0.02	–9.92	–13.28 to –6.56	< 0.001
Lag 3–5[e]	1.98	–0.38 to 4.33	0.10	–4.56	–7.92 to –1.20	0.008

[a]Each coefficient is an estimate of percent change in lung function shown and is derived from a separate linear regression model using GEE. Covariates in each model: sex, home location, annual family income, presence of one or more smokers in household, race, season, randomization assignment for the intervention, and interaction between time and this randomization assignment. [b]Regressions pertain to those children reporting use of inhaled and/or oral CSs at least 50% of days in a given season on diary. [c]Assessment of a child's lung function based on error-free expiratory maneuvers. [d]The regression coefficient is the estimated change in lung function associated with an increase of one interquartile range in the ambient pollutant concentration. [e]Number of days between measurement of ambient pollutant concentration and lung function. Lag 3–5 is based on the mean of pollutant concentrations on those days.

Table 7. Associations of ambient pollutant concentrations with lung function among children with asthma reporting symptoms of URI: two-pollutant models.[a,b]

	$PM_{2.5}$ daily mean			O_3 daily mean		
Lung function[c]	Coefficient[d]	95% CI	*p*-Value	Coefficient	95% CI	*p*-Value
Effect of concurrent exposure to both $PM_{2.5}$ and O_3						
Diurnal variability FEV_1						
Lag 1[e]	3.99	–2.76 to 10.74	0.25	4.69	–0.72 to 10.09	0.09
Lag 2[e]	4.10	–1.41 to 9.60	0.15	6.51	–1.96 to 14.98	0.13
Lag 3–5[e]	3.81	–1.83 to 9.45	0.19	3.52	–1.27 to 8.30	0.15
Lowest daily value FEV_1						
Lag 1[e]	–0.74	–4.14 to 2.65	0.67	–2.82	–6.34 to 0.70	0.12
Lag 2[e]	–1.67	–5.09 to 1.75	0.34	–3.99	–7.54 to –0.44	0.03
Lag 3–5[e]	–2.78	–4.79 to –0.77	0.007	–2.16	–14.59 to 10.28	0.73
Effect of concurrent exposure to PM_{10} and O_3						
Diurnal variability FEV_1						
Lag 1[e]	3.21	–1.28 to 7.71	0.16	9.53	5.58 to 13.47	< 0.001
Lag 2[e]	5.40	–0.82 to 11.62	0.09	7.66	–0.50 to 15.83	0.07
Lag 3–5[e]	6.27	0.07 to 12.47	0.05	2.53	–8.40 to 13.45	0.65
Lowest daily value FEV_1						
Lag 1[e]	–13.11	–21.59 to –4.62	0.003	–4.41	–7.81 to –1.00	0.01
Lag 2[e]	–3.32	–6.83 to 0.18	0.06	–5.22	–8.29 to –2.16	0.001
Lag 3–5[e]	–3.17	–5.82 to –0.51	0.02	1.97	–2.56 to 6.51	0.39

[a]Each coefficient is an estimate of percent change in lung function shown, and is derived from a separate linear regression model using GEE. Covariates in each model: sex , home location, annual family income, presence of one or more smokers in household, race, season, randomization assignment for the intervention, and interaction between time and this randomization assignment. [b]Regressions pertain to those children reporting URI on the day of lung function assessment. [c]Assessment of a child's lung function based on error-free expiratory maneuvers. [d]The regression coefficient is the estimated change in lung function associated with an increase of one interquartile range in the ambient pollutant concentration. [e]Number of days between measurement of ambient pollutant concentration and lung function. Lag 3–5 is based on the mean of pollutant concentrations on those days.

Airwatch model and protocol, and prompted our switch to the updated Airwatch 2 model and change in protocol to allow supervision and coaching of a large portion of the lung function data collection. These changes substantially improved the reproducibility of PF and FEV_1 measurements based on visual inspection of the data and supported by a reduction in the within-child intra-half-day coefficient of variation (0.202 vs. 0.102 for PF, and 0.238 vs. 0.114 for FEV_1). During the final data collection period (May 2002), we performed an exercise to validate the Airwatch data. We compared morning FEV_1 values obtained by an experienced respiratory therapist at the child's school using a standard spirometer (Renaissance II; Puritan Bennett, Pleasanton, CA) to those error-free FEV_1 values obtained the same morning with Airwatch while the child was being coached in the usual manner by study staff for a convenience sample of 37 children. After removal of two outliers with clearly invalid technique, the mean difference (spirometry value – Airwatch value) was –0.14 L. A *t*-test revealed that this value is not statistically different than zero. Lung function values obtained by spirometry were in general quite reproducible (mean difference between two best blows, 0.19 L). This reproducibility measure was unassociated with pollution levels of either PM or O_3, so there is no indication that ambient pollution levels differentially affected the quality of expiratory maneuvers.

To help guard against the potential for spurious associations due to inaccuracies in lung function measures, we opted to exclude very high (> 140% predicted) or very low (< 30% predicted) lung function values, which were expected to be most likely a result of suboptimal exhalation technique. If this data-cleaning step inadvertently excluded some valid data, the effect would be to blunt the true variability in lung function, most likely biasing findings toward the null hypothesis.

The data set used for regression models was limited by the decision to use only FEV_1 measures from the revised protocol in place during the last six seasons and from some limits on the exposure data collected (i.e., PM exposures were determined only on days on which lung function was measured, and O_3 measurements were made only during one winter). These restrictions should not introduce any systematic bias, and most of those models with modest effect estimates size of 2–3% reached statistical significance at the $p = 0.05$ level, indicating retention of reasonable power.

Another potential limitation was our reliance on caregiver report for information about asthma severity, medication use, and presence of URI symptoms. There was no independent method to verify these reports. We also did not attempt to learn what medications the child's physician had actually prescribed; rather, we focused on what the child was actually taking through daily diary reports. Although there may be some misclassification of steroid use, our ability to detect a difference in the effect of pollutants among those we classified as steroid users compared with nonusers reassures us that our methods and definitions were able to separate the children into clinically meaningful groups. It is also possible that unmeasured characteristics of the children or their home environment may have influenced their responsiveness to pollutants that were not included in our models. However, beyond the changes attributable to the household intervention (which were included in our models), these characteristics were unlikely to vary much within the same individual and therefore were unlikely to confound the observed relationships.

The pattern of association within each group was not always consistent across lags or between the single- and two-pollutant models, a common finding in the literature (Delfino et al. 2002; Gent et al. 2003; van der Zee et al. 1999). Factors that may contribute to this phenomenon here include the following: *a*) The set of observations on which regressions were based varied somewhat among models because each model used all available data for the contributing variables; *b*) some within-season correlations between PM and O_3 (particularly in the summer months) were higher than the general correlations, which may have influenced standard error calculations; and *c*) our data-cleaning steps may have been too conservative, potentially obscuring true relationships.

Because of practical field measurement conditions, we were limited to examination of PF and FEV_1. Although FEV_1 is a more sensitive indicator of lower airway function than is PF, measures of small airway function, such as $FEF_{25–75}$, could have been even more sensitive and might have been able to detect more consistent relationships. We examined two different parameters of the lung function measures (diurnal variability and lowest daily value) to capture slightly different potential influences on airways. Diurnal variability in PF has been shown to correlate with symptoms (Gern et al. 1994) and responsiveness to methacholine (Gibson et al. 1995; Valletta et al. 1995), and to be more sensitive to changes in the environment than the mean absolute value of PF (Valletta et al. 1995). We extrapolated that a similar phenomenon might be likely with FEV_1. Diurnal variability and lowest daily value were expected to track together, but not necessarily to be concordant (Brand et al. 1997; Valletta et al. 1995), which was what we observed. We feel that the weight of the evidence—specifically, the presence of many statistically significant associations of pollution and lung function among children taking CSs regularly or children reporting respiratory infection versus none or few significant associations among children lacking these characteristics—combined with the generally consistent pattern of effect estimates in the expected direction across models, supports the existence of a true underlying relationship.

The relationship of routine asthma medication use to observed health effects of air pollution is complex, because it sometimes appears to be a marker for disease severity and at other times appears to protect against the adverse effects of pollution. An assessment of the effect of sulfur dioxide on mild asthmatic patients in the Czech Republic in 1991–1992 showed an inverse association between air pollutant levels and PF for children on medication (either theophylline or beta-agonists; no children were on CSs) but not for children not on medication (Peters et al. 1997). Another study (Gent et al. 2003) found consistent effects of O_3 and PM on respiratory symptoms among those children using maintenance medication for asthma but not among medication nonusers. These authors concluded that asthma medication serves as a proxy for disease severity in their analyses. In studies that have compared groups of asthmatic children with similar frequencies of symptoms at baseline, positive associations between exposure to O_3, PM_{10}, and nitrogen dioxide and symptoms were present only among those not taking anti-inflammatory medications (CSs or cromolyn) (Delfino et al. 1998, 2002). A mixed picture was seen by Mortimer et al. (2000): Among children who were full-term or normal birth weight, children on cromolyn were more symptomatic in response to O_3 exposure than were those who were on no medication or were on beta-agonists, methylxanthines, or steroids; but among preterm or low-birth-weight children, those who did not use any medications were more symptomatic than those on any type of medication. In our cohort, CS use appears to act as a proxy for disease severity. It appears possible that there is subclinical airway inflammation or preexisting airway remodeling that is "unmasked" by exposure to higher air pollutant levels, resulting in greater pollution-related effects on lung function among children on CSs.

Our investigation is consistent with the few other studies that have examined the relationship between pollution exposure and asthma exacerbation associated with viral illness. Tarlo et al. (2001) reported that asthma exacerbations with diary-reported colds were associated with higher levels of sulfur dioxide and nitrogen oxides compared with exacerbations without colds. Chauhan et al. (2003) found that participants exposed to high levels of NO_2 in the week before the onset of polymerase-chain-reaction confirmed virally induced exacerbation had worse symptom scores and lower PF than did participants exposed to low levels of NO_2 before their virally induced exacerbations.

Potential mechanisms by which pollutants may increase susceptibility to viral infection include disruption of mucociliary clearance (Ehrlich 1980; Schlesinger and Driscoll 1987), impairment of cellular immunity (Zwick et al. 1991), or release of inflammatory mediators (Rusznak et al. 1996).

In summary, in our population of predominantly African-American and Latino children living in the economically stressed city of Detroit, children with asthma who were CS dependent or who had URIs were adversely affected by current levels of ambient air pollution. Our results emphasize the continued need for enforcement of existing standards as well as the importance of considering susceptible subgroups within the population when formulating new standards. CBPR partnerships can play a critical role in this policy process.

Correction

The "Demographic and Asthma Characteristics of Cohort" section of "Results" in the manuscript originally published online was incorrect in describing less than two-thirds and 15% of the cohort; it has been corrected here to fewer than one-half and 30%.

References

Aligne CA, Auinger P, Byrd RS, Weitzman M. 2000. Risk factors for pediatric asthma—Contributions of poverty, race, and urban residence. Am J Respir Crit Care Med 162(3 pt 1):873–877.

Boezen HM, van der Zee SC, Postma DS, Vonk JM, Gerritsen J, Hoek G, et al. 1999. Effects of ambient air pollution on upper and lower respiratory symptoms and peak expiratory flow in children. Lancet 353(9156):874–878.

Brand PL, Duiverman EJ, Postma DS, Waalkens HJ, Kerrebijn KF, van Essen-Zandvliet EE. 1997. Peak flow variation in childhood asthma: relationship to symptoms, atopy, airways obstruction and hyperresponsiveness—Dutch CNSLD Study Group. Eur Respir J 10:1241–1247.

Buchdahl R, Willems CD, Vander M, Babiker A. 2000. Associations between ambient ozone, hydrocarbons, and childhood wheezy episodes: a prospective observational study in south east London. Occup Environ Med 57(2):86–93.

Chauhan AJ, Inskip HM, Linaker CH, Smith S, Schreiber J, Johnston SL, et al. 2003. Personal exposure to nitrogen dioxide (NO_2) and the severity of virus-induced asthma in children. Lancet 361(9373):1939–1944.

Chow JC, Engelbrecht JP, Watson JG, Wilson WE, Frank NH, Zhu T. 2002. Designing monitoring networks to represent outdoor human exposure. Chemosphere 49:961–978.

Delfino RJ, Zeiger RS, Seltzer JM, Street DH. 1998. Symptoms in pediatric asthmatics and air pollution: differences in effects by symptom severity, anti-inflammatory medication use and particulate averaging time. Environ Health Perspect 106:751–761.

Delfino RJ, Zeiger RS, Seltzer JM, Street DH, McLaren CE. 2002. Association of asthma symptoms with peak particulate air pollution and effect modification by anti-inflammatory medication use. Environ Health Perspect 110:A607–A617.

Edgren KK, Parker EA, Israel BA, Lewis TC, Salinas M, Robins TG, et al. 2005. Conducting a health education intervention and an epidemiological research project involving community members and community partner organizations: the Community Action Against Asthma Project. Health Promot Pract 6(3):263–269.

Ehrlich R. 1980. Interaction between environmental pollutants and respiratory infections. Environ Health Perspect 35:89–100.

Gent JF, Triche EW, Holford TR, Belanger K, Bracken MB, Beckett WS, et al. 2003. Association of low-level ozone and fine particles with respiratory symptoms in children with asthma. JAMA 290(14):1859–1867.

Gern JE, Eggleston PA, Schuberth KC, Eney ND, Goldstein EO, Weiss ME, et al. 1994. Peak flow variation in childhood asthma: a three-year analysis. J Allergy Clin Immunol 93(4):706–716.

Gibson PG, Mattoli S, Sears MR, Dolovich J, Hargreave FE. 1995. Increased peak flow variability in children with asymptomatic hyperresponsiveness. Eur Respir J 8(10):1731–1735.

Hankinson JL, Odencrantz JR, Fedan KB. 1999. Spirometric reference values from a sample of the general U.S. population. Am J Respir Crit Care Med 159(1):179–187.

Israel BA, Schulz AJ, Parker EA, Becker AB, Allen AJ, Guzman JR. 2003. Critical issues in developing and following community-based participatory research principles. In: Community-Based Participatory Research for Health (Minkler M, Wallerstein N, eds). San Francisco, CA:Jossey-Bass, 56–73.

Joseph CLM, Foxman B, Leickly F, Peterson E, Ownby D. 1996. Prevalence of possible undiagnosed asthma and associated morbidity among urban schoolchildren. J Pediatr 129(5):735–742.

Keeler GJ, Dvonch T, Yip F, Parker EA, Israel BA, Marsik FJ, et al. 2002. Assessment of personal and community-level exposures to particulate matter among children with asthma in Detroit, Michigan, as part of Community Action Against Asthma (CAAA). Environ Health Perspect 110(suppl 2):173–181.

Lewis TC, Robins TG, Joseph CLM, Parker EA, Israel BA, Rowe Z, et al. 2004. Identification of gaps in the diagnosis and treatment of childhood asthma using a community-based participatory research approach. J Urban Health 81(3):472–488.

Mannino D, Homa DM, Akinbami LJ, Moorman JE, Gwynn C, Redd SC. 2002. Surveillance for asthma—United States, 1980–1999. MMWR Surveill Summ 51(1):1–13.

Mannino DM, Homa DM, Pertowski CA, Ashizawa A, Nixon LL, Johnson CA, et al. 1998. Surveillance for asthma—United States, 1960–1995. Morb Mortal Wkly Rep 47(1):1–27.

McConnell R, Berhane K, Gilliland F, London SJ, Islam T, Gauderman WJ, et al. 2002. Asthma in exercising children exposed to ozone: a cohort study. Lancet 359(9304):386–391.

McConnell R, Berhane KT, Gilliland F, London SJ, Vora H, Avol EL, et al. 1999. Air pollution and bronchitic symptoms in Southern California children with asthma. Environ Health Perspect 107:757–760.

McConnell R, Berhane K, Gilliland F, Molitor J, Thomas D, Lurmann F, et al. 2003. Prospective study of air pollution and bronchitic symptoms in children with asthma. Am J Respir Crit Care Med 168(7):790–797.

Michigan Department of Community Health. 2002. Preventable Hospitalizations and Rates per 10,000 Population for Patients under 18 Years of Age by Selected Leading Diagnoses, 1996–2000. Lansing, MI:Division for Vital Records and Statistics, Michigan Department of Community Health.

Michigan Department of Transportation. 2001. 2001 Average Daily Traffic (ADT) Map. Lansing, MI:Michigan Department of Transportation. Available at: http://www.michigan.gov/mdot/0,1607,7-151-9622_11033_11149---,00.html [accessed 20 April 2005].

Mortimer KM, Neas LM, Dockery DW, Redline S, Tager IB. 2002. The effect of air pollution on inner-city children with asthma. Eur Respir J 19(4):699–705.

Mortimer KM, Tager IB, Dockery DW, Neas LM, Redline S. 2000. The effect of ozone on inner-city children with asthma: identification of susceptible subgroups. Am J Respir Crit Care Med 162(5):1838–1845.

Norris G, Young Pong SN, Koenig JQ, Larson TV, Sheppard L, Stout JW. 1999. An association between fine particles and asthma emergency department visits for children in Seattle. Environ Health Perspect 107:489–493.

Ostro B, Lipsett M, Mann J, Brazton-Owens H, White M. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Epidemiology 12:200–208.

Parker EA, Israel BA, Brakefield-Caldwell W, Keeler GJ, Lewis TC, Ramirez E, et al. 2003. Community Action Against Asthma: examining the partnership process of a community-based participatory research project. J Gen Intern Med 18:558–567.

Peters A, Dockery DW, Heinrich J, Wichmann HE. 1997. Medication use modifies the health effects of particulate sulfate air pollution in children with asthma. Environ Health Perspect 105:430–435.

Rusznak C, Devalia JL, Sapsford RJ, Davies RJ. 1996. Ozone-induced mediator release from human bronchial epithelial cells in vitro and the influence of nedocromil sodium. Eur Respir J 9(11):2298–2305.

Schlesinger RB, Driscoll KE. 1987. Mucociliary clearance from the lungs of rabbits following single and intermittent exposures to ozone. J Toxicol Environ Health 20(1–2):125–134.

Tarlo SM, Broder I, Corey P, Chan-Yeung M, Ferguson A, Becker A, et al. 2001. The role of symptomatic colds in asthma exacerbations: influence of outdoor allergens and air pollutants. J Allergy Clin Immunol 108:52–58.

U.S. EPA (Environmental Protection Agency). 1997. Primary and Secondary Ambient Air Quality Standards. 40 CFR Part 50. Washington, DC:U.S. Government Printing Office.

U.S. EPA. 1998. Guideline on Ozone Monitoring Site Selection. EPA 454/R-98-002. Research Triangle Park, NC:U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

U.S. EPA. 2002. Latest Findings on National Air Quality: 2001 Statistical Trends. EPA 454/K-02-001. Research Triangle Park, NC:U.S. Environmental Protection Agency, Office of Air Quality Planning and Statistics.

Valletta EA, Comis A, Del Col G, Spezia E, Boner AL. 1995. Peak expiratory flow variation and bronchial hyperresponsiveness in asthmatic children during periods of antigen avoidance and reexposure. Allergy 50:366–369.

van der Zee S, Hoek G, Boezen HM, Schouten JP, van Wijnen JH, Brunekreef B. 1999. Acute effects of urban air pollution on respiratory health of children with and without chronic respiratory symptoms. Occup Environ Med 56(12):802–812.

Yu O, Sheppard L, Lumley T, Koenig JQ, Shapiro GG. 2000. Effects of ambient air pollution on symptoms of asthma in Seattle-area children enrolled in the CAMP study. Environ Health Perspect 108:1209–1214.

Zwick H, Popp W, Wagner C, Reiser K, Schmoger J, Bock A, et al. 1991. Effects of ozone on the respiratory health, allergic sensitization, and cellular immune system in children. Am Rev Respir Dis 144(5):1075–1079.