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Association of FEV_1 in Asthmatic Children with Personal and Microenvironmental Exposure to Airborne Particulate Matter

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Exposure to particulate matter (PM) air pollution has been shown to exacerbate children's asthma, but the exposure sources and temporal characteristics are still under study. Children's exposure to PM is likely to involve both combustion-related ambient PM and PM related to a child's activity in various indoor and outdoor microenvironments. Among 19 children with asthma, 9–17 years of age, we examined the relationship of temporal changes in percent predicted forced expiratory volume in 1 sec (FEV_1) to personal continuous PM exposure and to 24-hr average gravimetric PM mass measured at home and central sites. Subjects were followed for 2 weeks during either the fall of 1999 or the spring of 2000, in a southern California region affected by transported air pollution. FEV_1 was measured by subjects in the morning, afternoon, and evening. Exposure measurements included continuous PM using a passive nephelometer carried by subjects; indoor, outdoor home, and central-site 24-hr gravimetric $PM_{2.5}$ (PM of aerodynamic diameter < 2.5 μm) and PM_{10}; and central-site hourly PM_{10}, nitrogen dioxide, and ozone. Data were analyzed with linear mixed models controlling for within-subject autocorrelation, FEV_1 maneuver time, and exposure period. We found inverse associations of FEV_1 with increasing PM exposure during the 24 hr before the FEV_1 maneuver and with increasing multiday PM averages. Deficits in percent predicted FEV_1 (95% confidence interval) for given PM interquartile ranges measured during the preceding 24-hr were as follows: 128 μg/m^3 1-hr maximum personal PM, –6.0% (–10.5 to –1.4); 30 μg/m^3 24-hr average personal PM, –5.9% (–10.8 to –1.0); 6.7 μg/m^3 indoor home $PM_{2.5}$, –1.6% (–2.8 to –0.4); 16 μg/m^3 indoor home PM_{10}, –2.1% (–3.7 to –0.4); 7.1 μg/m^3 outdoor home $PM_{2.5}$, –1.1% (–2.4 to 0.1); and 7.5 μg/m^3 central-site $PM_{2.5}$, –0.7% (–1.9 to 0.4). Stronger associations were found for multiday moving averages of PM for both personal and stationary-site PM. Stronger associations with personal PM were found in boys allergic to indoor allergens. FEV_1 was weakly associated with NO_2 but not with O_3. Results suggest mixed respiratory effects of PM in asthmatic children from both ambient background exposures and personal exposures in various microenvironments. *Key words:* **asthma, epidemiology, forced expiratory volume, longitudinal data analysis, nitrogen dioxide, ozone, panel study, particulate air pollution.** *Environ Health Perspect* **112:932–941 (2004). doi:10.1289/ehp.6815 available via** *http://dx.doi.org/* **[Online 4 March 2004]**

Most panel studies of the daily relationship between acute asthma in children and exposure to particulate matter (PM) air pollution have relied on ambient data collected at central regional sites. All subjects are usually assigned the same daily exposures in these studies. Exposure misclassification from using central regional PM data is expected to diminish the accuracy of exposure–response estimates, possibly leading to null findings. Despite this expectation, with few exceptions (Roemer et al. 1999, 2000), recent panel studies of asthmatic children are largely consistent in showing positive associations between acute increases in asthma morbidity and ambient PM (Delfino et al. 1998, 2002, 2003; Gielen et al. 1997; Just et al. 2002; Koenig et al. 2003; Mortimer et al. 2000, 2002; Ostro et al. 2001; Pekkanen et al. 1997; Peters et al. 1997a, 1997b; Romieu et al. 1996; Segala et al. 1998; Slaughter et al. 2003; Thurston et al. 1997; Timonen and Pekkanen 1997; Vedal et al. 1998; Yu et al. 2000).

To improve the accuracy of the estimated associations, measurements of personal exposure to PM and adjustments to ambient exposure using time–activity data have been proposed (National Research Council 1998). In the case of children, high levels of physical activity are expected to generate higher levels of particle exposure in a variety of microenvironments. Other activities may bring the child close to an undiluted PM source such as a school bus. These phenomena have been referred to as the "personal dust cloud," which was originally described by Ozkaynak et al. (1996) to account for the difference between total personal exposure as measured by a personal monitor and the estimated time-weighted exposure in indoor and outdoor microenvironments. Studies performed later further clarified the major sources and components of the personal dust cloud (e.g., Liu et al. 2003; McBride et al. 1999) and have shown that the personal dust cloud is a combined result of particles generated from personal activities (e.g., cooking or dusting) and exposures to local sources (e.g., next to traffic exhaust on the street) that are not captured by the stationary indoor and outdoor monitors (Liu et al. 2003). Children's personal cloud PM is significantly higher than adults', resulting in a low prediction power with the traditional microenvironmental model that incorporates time–place–activity data and area monitor measurements (Liu et al. 2003). In addition, short-term exposures lasting minutes to hours may be relevant to respiratory responses and may not be fully captured by time-integrated PM measurements, as is done with 24-hr gravimetric filters.

In this study we evaluated the relationship of repeated measurements of forced expiratory volume in 1 sec (FEV_1) in asthmatic children to fine particle exposures using measurements of hourly personal PM and stationary-site 24-hr average PM of aerodynamic diameter < 2.5 μm ($PM_{2.5}$; indoor and outdoor home, and central regional). Stationary-site 24-hr average PM_{10} (PM of aerodynamic diameter < 10 μm) is also evaluated. To assess the relative importance of peaks and averaging times, we examined relationships of FEV_1 to hourly maxima and 24-hr mean personal $PM_{2.5}$ exposures for the period preceding the expiratory maneuver, including current and past days.

Materials and Methods

Design. This is a panel study, which involves repeated measurements of outcomes and exposures in individuals. Asthmatic children were

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monitored for personal PM exposures and health outcomes for 2 weeks (three subjects at a time), during September–October 1999 or April–June 2000 in Alpine, California. There were two 14-day runs in 1999 and five runs in 2000. Measurements of PM were also made at indoor and outdoor home sites of each subject in addition to central regional outdoor measurements. We conducted daily home visits for data collection and instrument preparation and calibration. Subjects also electronically recorded health outcome data daily for approximately 8 weeks. The 2-week personal exposure study was nested in the 8 weeks and is the focus of this article.

Population. The study was conducted in Alpine, a southern California community located inland from San Diego. The community receives long-range transported air pollutants from Los Angeles and San Diego, and it has experienced high ozone episodes. Wind direction is predominantly from the urban coastal regions to Alpine. People live near or above the air inversion layer base (~1,200 ft). Eligibility for participation in the study included physician-diagnosed asthma with at least a 1-year history; a historical confirmation of asthma exacerbations on at least one separate occasion each week during March–October that required the use of an as-needed, oral or inhaled, bronchodilator; a home address in Alpine; no active smoking or passive exposure to tobacco smoke at home; and age 9–19 years. Subjects were recruited with the assistance of the Alpine school district nurse. The institutional review boards of the University of California, Irvine, and San Diego State University approved the study protocol. Informed written consent was obtained from all subjects and from one of their legal guardians.

Twenty-four children were recruited. Three dropped out, and another was not compliant with self-administered spirometry. Another subject did not participate in the personal exposure assessment. Nineteen subjects completed the 2-week exposure assessment and were compliant with spirometry (Table 1). One subject participated in two 14-day runs. The other 18 subjects each participated in one 14-day run, except one who started 4 days late. Only five used anti-inflammatory medications (four on inhaled corticosteroids, one on the antileukotriene zafirlukast). Over all the FEV_1 measurements in the study, 16 subjects had < 80% predicted FEV_1, three had 84–87%, and one had 92% using normal lung function equations from the Third National Health and Nutrition Examination Survey (NHANES III; Hankinson et al. 1999).

Health outcomes and daily follow-up procedures. The health outcome described in this article is FEV_1, which represents the degree of airway obstruction as represented by the volume of air that can be forcibly exhaled in the first second of an expiratory maneuver starting from a maximal inhalation (forced vital capacity). Airway obstruction is a key phenotype of asthma. FEV_1 is lower than expected when flow rate decreases due to airway obstruction. Analyses here focus on the percentage of predicted normal FEV_1 (Hankinson et al. 1999) for a given height, age, sex, and race/ethnicity. This standardizes measurements between subjects and gives clinically meaningful overall estimates of association for the study population.

We used the Vitalograph 2110 handheld electronic expiratory flow meter (Vitalograph, Inc., Lenexa, KS) for subjects to self-administer measurements of FEV_1. It measures flow by sensing pressure across a resistive mesh. Before beginning the 2-week exposure assessments, calibration of Vitalographs was checked with a 3-L syringe, and all subjects used the expiratory flow meter for at least 1 week to assure that maneuvers were performed properly. Subjects were trained by staff to perform expiratory maneuvers and were given a subject manual reviewing instructions. Nose clips were not used. The Vitalograph alarm prompts the subject at home to begin the maneuver (or the subject can self-initiate) and to repeat maneuvers when shown an icon of a face blowing air during each maneuver session. The unit stops prompting if two peak expiratory flow (PEF) readings are within 10%, up to a maximum of five maneuvers. The percent reliability between the highest and second highest PEF is logged in memory; the highest flow is logged as "good" for time to peak flow between 40 msec and 290 msec, and "bad" otherwise to identify maneuvers performed with either the spitting technique or insufficient initial effort. The FEV_1 stored in memory is the highest volume achieved. All maneuvers were to be performed

Table 1. Subject characteristics and health outcomes during 2-week exposure assessment periods, August–October 1999 and April–June 2000: Alpine, California, Asthma Panel Study.

ID	Age (years)	Sex	Height (inches)	No. of 2-hr periods with bothersome or worse asthma symptoms (% total)	Daily prescribed asthma medications taken	Mean daily as-needed inhaler use ± SD	Mean morning FEV_1 (L/sec ± SD)	Mean afternoon FEV_1 (L/sec ± SD)[a]	Mean evening FEV_1 (L/sec ± SD)	Overall percent predicted FEV_1[b]
1	10	Male	57	0	None	0.29 ± 0.73	1.89 ± 0.07	1.93 ± 0.13	1.86 ± 0.16	84.1
1[c]	11		59	0	None	0.0	2.16 ± 0.10	2.11 ± 0.14	2.11 ± 0.07	84.7
2	12	Male	61	0	None	0.0	1.78 ± 0.10	1.56 ± 0.27	1.64 ± 0.13	56.1
3	13	Male	70	0	None	0.0	3.40 ± 0.12	3.45 ± 0.10	3.40 ± 0.17	86.9
4	11	Female	57	0	None	2.17 ± 2.33	1.51 ± 0.07	1.37 ± 0.11	1.43 ± 0.07	64.5
5	12	Male	62	1 (1.2)	Triamcinolone	3.00 ± 1.30	2.63 ± 0.11	2.75 ± 0.15	2.66 ± 0.14	92.3
6	10	Female	60	4 (14.3)	None	0.86 ± 2.27	1.78 ± 0.29	1.89 ± 0.18	1.69 ± 0.24	73.8
7	11	Female	58	0	None	0.29 ± 0.73	1.26 ± 0.11	1.34 ± 0.06	1.31 ± 0.15	55.4
8	11	Female	62	4 (4.9)	None	0.43 ± 0.85	2.04 ± 0.20	2.04 ± 0.18	2.09 ± 0.15	76.0
9	14	Male	64	0	None	0.0	1.99 ± 0.11	2.03 ± 0.08	2.02 ± 0.11	61.4
10	9	Male	59	0	None	1.00 ± 1.73	1.80 ± 0.08	1.84 ± 0.17	1.80 ± 0.11	75.1
11	9	Male	57	0	Budesonide, Salmeterol	0.0	1.51 ± 0.19	1.51 ± 0.27	1.55 ± 0.15	69.3
12	12	Male	62	24 (25.0)	None	2.07 ± 4.05	1.46 ± 0.30	1.63 ± 0.29	1.63 ± 0.32	54.3
13	9	Male	52	0	Budesonide, Salmeterol	0.0	1.45 ± 0.10	—	1.19 ± 0.27	77.7
14	13	Male	62	0	None	0.0	1.72 ± 0.12	1.90 ± 0.21	1.66 ± 0.14	59.4
15	11	Male	54	0	None	0.0	1.44 ± 0.13	1.62 ± 0.04	1.38 ± 0.16	71.5
16	15	Male	64	0	Fluticasone	0.0	2.39 ± 0.25	2.35 ± 0.24	2.29 ± 0.27	71.5
17	14	Male	65	0	Zafirlukast	0.46 ± 0.88	1.80 ± 0.15	1.89 ± 0.14	1.82 ± 0.17	54.1
18	17	Female	67	0	None	0.0	2.81 ± 0.14	2.71 ± 0.18	2.70 ± 0.16	76.9
19	11	Male	61	0	None	0.0	1.70 ± 0.19	1.98 ± 0.19	1.88 ± 0.08	69.8

ID, identification number.
[a]Subjects 11 and 13 were noncompliant with afternoon lung function maneuvers (ID11 performed four afternoon maneuvers, and ID13 performed none). [b]NHANES III (Hankinson et al., 1999). [c]Subject 1 participated in two 2-week exposure assessments in fall 1999 and spring 2000.

before β-agonist inhaler use. The morning maneuver was to be performed after being awake and alert soon after arising; the afternoon maneuver was to be performed around 1700–1800 hr, and the evening was to be performed around 2100 hr or near bedtime.

The expected number of FEV_1 measurements was 840. The observed number was 710 maneuvers, but some subjects did more than one session during one of the three daily periods (37 measurements). In these cases, the highest FEV_1 from the different sessions was chosen, leaving 673 maneuver sessions. Therefore, 167 (20% of expected) were missing because of noncompliance during the expected daily maneuver period. Although PEF was retained, an additional 67 FEV_1 measurements were missing because of inadequate expiratory maneuvers where forced expiratory time was < 1 sec. In addition, eight FEV_1 measurements were excluded because time to peak flow was not between 40 msec and 290 msec, and 50 others were excluded where the difference between the highest and second highest PEF was > 10%, which is evidence of low reliability. There were 548 FEV_1 maneuvers remaining for analysis.

Diary data on symptoms, as-needed inhaler use (short acting β_2-agonists), preventive medication use, respiratory infections, and time–activity were entered by subjects into small personal digital assistants (PDAs) every 2 waking hours. Subjects were prompted with 14 one-minute alarms and program lockout at the end of 15 min to ensure short-term recall at the appropriate times. Subjects gave touchpad responses to user-friendly interfaces: informational screens and ordinal and categorical list screens. We expect that this PDA diary enhanced data validity over paper diaries. Staff visited the subject's home daily to examine the quality of outcome data after they were downloaded from each electronic device to a laptop. Subjects were compliant with diary completion for 84.3% of data relevant to FEV_1 observations.

Analyses of time–activity diary data from the PDA and factors predicting personal PM exposures will be presented elsewhere. Although asthma symptom data and as-needed inhaler use were collected, the frequency of responses during the 2-week exposure assessment periods was low (only four subjects had any symptoms that were at least bothersome, and only nine subjects used as-needed inhalers; Table 1). Therefore, analyses of symptoms and inhaler use in relation to exposures are not presented in this article. Inhaler use in the 2–3 hr before FEV_1 measurements and respiratory infections were tested as covariates in regression models.

Environmental variables. To measure personal PM exposures, we used the Personal dataRAM (pDR; MIE Thermo Electron Corp. Inc., Franklin, MA), which is a nephelometer that measures light scatter (source wavelength, 880 nm) from PM that relates to mass concentration. The pDR is relatively small (15.2 × 9.1 × 6.4 cm) and lightweight (0.5 kg) and was easily carried by subjects at waist level using a fanny pack, shoulder harness, or vest. It was operated in passive sampling mode with the air exchange region open to air and without a size selective inlet. The pDR responds mainly to PM in the 0.1–10-μm range, with the highest response in the fine PM range. The measurements approximate $PM_{2.5}$ with an R^2 between 0.77 and 0.84 when compared with collocated stationary Harvard impactor (HI) measurements and an R^2 of 0.44–0.60 when compared with collocated Harvard personal environmental monitor measurements (Howard-Reed et al. 2000; Liu et al. 2003). The pDR reads in units of $\mu g/m^3$ as calibrated by the manufacturer using fine International Organization for Standardization test dust (specific gravity, 2.6 g/cm^3; index of refraction, 1.5; mass median diameter, 2–3 μm). Readings in micrograms per cubic meter can be converted to light scattering [$\mu g/m^3 = 1.027 \times b_{sp}$ (light scattering coefficient in 1×10^{-3}/m)].

The pDRs were set to report concentration averaged over 1-min intervals. Data were downloaded daily and a new 24-hr logging period was set. All pDRs had attached small relative humidity (RH), temperature, motion, and light intensity loggers recording at 1-min intervals (Onset Computer Corp, Pocasset, MA). Motion sensors (Onset's motor on/off), intended to monitor compliance with wearing the pDR, had limited memory and often did not cover the 24-hr periods of monitoring. Subjects were not informed of the purpose of the data loggers. All electronic exposure data were time synchronized and data processed to quarter-hour means to match PDA diary data. Electronic exposure data were downloaded to laptops every 24 hr during home visits by staff.

A more detailed description of our quality assurance procedure for the pDR data is given elsewhere (Wu et al. 2004). Briefly, we applied a correction equation that models the effect of RH on b_{sp} to adjust for the influence of RH > 60% on the pDR data (Richards et al. 1999). Personal RH rarely exceeded 70% (1.3%). Observations with personal RH > 95%, where the equation is not reliable, were deleted, but were few in number (0.18%). In the fall of 1999, the pDRs were zeroed daily with a zeroing bag (Z-Pouch; MIE Thermo Electron Corp. Inc.) attached to a small HEPA filter as supplied by the manufacturer. In the spring of 2000, pDRs were zeroed with particle-free air through an active sampling system attached to a HEPA filter before each 2-week run. Negative and positive drift was still detected, and, where possible, correction factors were applied using early morning data from collocated indoor pDRs, which did not drift, as we had previously reported (Quintana et al. 2000). In 0.5% of the personal pDR data, we also identified instances when subjects had not worn the pDR and left it in another microenvironment using subject reports and/or data from RH, temperature, motion, and light intensity loggers attached to the pDR, which suggested prolonged stationary positioning. These data were dropped from the analysis of personal PM exposures.

Indoor and outdoor home sites were monitored for $PM_{2.5}$ and PM_{10} gravimetric concentrations with HIs operated at 10 L/min (Air Diagnostics and Engineering, Inc., Naples, ME). The major living area of the house was the indoor sampling site. Outdoor impactor samplers were placed under a rain cover immediately outside the house. Samplers were placed at 1 m off the ground, at least 1 m from walls, and away from pollutant sources, including heavy foot traffic. The HI $PM_{2.5}$ and PM_{10} samples were collected onto Teflon filters (37 mm, 2.0 μm Teflon membrane; Gelman Labs, Ann Arbor, MI) for 24 hr from around 1700–2000 hr to 1700–2000 hr the next day, and weighed on a Cahn microbalance (model 30; Cahn Instruments, Madison, WI). Filters were conditioned at 23 ± 3°C and 33 ± 5% RH for at least 24 hr in an environmental chamber, and a Cahn polonium-210 source was used to eliminate interference by electrostatic charges on the filter. Forty-nine filters (3.8%) were removed from analysis because of ending pump flow rates that were < 9 or > 11 L/min, or errors including pump failure, damaged or dropped filters, and incorrect log sheet data. Mass measurements (in micrometers per cubic meter) were corrected by site of collection with one indoor alternated with one outdoor field blank per day.

The gaseous pollutants O_3 and nitrogen dioxide were measured at a stationary outdoor monitoring station located centrally in Alpine and operated by the San Diego Air Pollution Control District. Hourly data were available for O_3 measured with ultraviolet photometry, NO_2 measured with chemiluminescence, temperature, and RH. Central-site PM_{10} concentrations were also measured with a tapered-element oscillating microbalance (TEOM; Rupprecht and Patashnick Co., Inc., Albany, NY). The TEOM is an inertial instrument that measures particle mass in real time on an exchangeable filter cartridge by monitoring frequency changes of a tapered element. The TEOM sampler inlet was operated at 16.7 L/min, and the inlet air stream was heated to a constant 50°C to keep water in the vapor phase. Hourly TEOM PM_{10} data were used for comparison with the personal continuous PM exposure data (described above).

Statistical analysis. The pDR PM data were log normally distributed and were therefore log transformed before analysis. We wanted to

compare strengths of association for different pollutant metrics regardless of the monitor type (personal vs. fixed site), units of measurement, or concentration range of normally distributed regressors. Ideally, associations for different exposure variables should be compared for their relative impact during the same period and for the same subjects. Therefore, we expressed results as the change in percent predicted FEV_1 for an interquartile range (IQR) increase in the air pollutant, an approach to standardizing associations that is discussed elsewhere (Lipfert and Wyzga 1999). This is particularly important for comparisons of personal versus stationary-site PM measurements. Sampling is done by technologically different methods that are not entirely comparable in terms of particles measured, their size distribution, or toxicity.

Data were analyzed by a general linear mixed model (with both fixed and random effects). This type of model is particularly suitable for serially correlated data in individuals (Diggle et al. 2002). We used the restricted maximum likelihood method as implemented by the MIXED procedure in SAS, version 8.2 (Littell et al. 1996). Random intercepts were estimated for each individual. The model covariance structure was determined by the Akaike's information criterion and Bayesian information criterion (Littell et al. 1996). The best covariance structure was autoregressive of order 1 [AR(1)], which allows for within-subject autocorrelated error terms.

Pollutant regression models were tested for confounding by day of week, personal temperature and RH, time of FEV_1 maneuver (morning, afternoon, or evening), season (fall 1999 or spring 2000), 2-week period of exposure assessment (seven three-subject runs), as-needed medication use (inhaler puffs in the 2–3-hr period preceding the FEV_1 maneuver, or 24-hr cumulative use), and presence versus absence of upper or lower respiratory infections. Confounding was considered a ≥ 10% change in the regression parameter estimate for the air pollutant. We also tested for interaction of air pollutants with respiratory infections, with anti-inflammatory medication use (a binary variable indicating self-reported daily use vs. no use), with sex, and with allergy to indoor allergens.

We hypothesized that lung function would be inversely associated with particulate air pollution exposure. To test this, we examined the relationship of FEV_1 to air pollutant concentrations measured in the 24-hr preceding the maneuver (exposure lag 0) and for cumulative exposures up to 4 days before the day of the FEV_1 maneuver (2–5-day exposure averages). All three maneuvers were entered in the regression models except for models involving current-day (lag 0) 24-hr mean gravimetric measurements of $PM_{2.5}$ and PM_{10}, (which were completed by the afternoon or evening FEV_1 maneuver), and current-day 12-hr daytime pDR PM and TEOM PM_{10}. Only the afternoon and evening maneuvers were regressed on these lag 0 PM variables because the morning maneuvers were done within or before that day's sampling period. For personal pDR PM, the real-time nature of the measurements allowed the assessment of exposures in the period immediately before each of the FEV_1 maneuvers. This approach makes it possible to assess acute exposure–response relationships, hypothetically including early phase bronchospasm.

Data for exposure variables had to include ≥ 75% of the relevant exposure period (e.g., 18 hr out of a 24-hr averaging period). Exposure averaging times for personal PM included maximum 1-hr, 4-hr, and 8-hr during the preceding 24 hr; 2-hr average the preceding 2 hr; 24-hr average the preceding 24 hr; 12-hr average daytime (0800–2000 hr); and 12-hr average nighttime (2000–0800 hr). Lag days were set to the prior 24-hr periods (e.g., lag 1 would be the average pDR PM 24–48 hr before the FEV_1 maneuver). We tested models for multiday moving averages including lags 0, 1, 2, 3, or 4 days. The longer the PM lag, the fewer the FEV_1 observations available for analysis, and the more likely the FEV_1 data in the multiday average model differ from the full set of FEV_1 data used in models with lag 0 (current day) PM data. In other words, only the last 10 of 14 days of monitoring had FEV_1 data to regress against a 5-day moving average of PM.

Similar averaging times were used for central-site TEOM PM_{10}, which included 1-hr and 8-hr maximums and 24-hr averages. To correlate personal with stationary-site gravimetric measurements at the home and central sites, the personal data were also averaged for the 24-hr sampling period of the HIs. For central-site NO_2 and O_3, both 1-hr and 8-hr maximum concentrations in the preceding 24 hr plus multiday averages were examined.

Results

Descriptive statistics. Subject characteristics are shown in Table 1. One subject was Hispanic and the remaining subjects were white non-Hispanic, reflecting the overall composition of the community. Among asthmatic populations, lower lung function values are expected in the morning, with the maximum around noon (American Thoracic Society 1991). We saw lower values in the morning compared with afternoon for 12 of 19 subjects.

Table 2 shows univariate data for the exposures. Data for personal pDR PM show more than twice the average concentration during the daytime than during nighttime. In comparison, ambient daytime TEOM PM_{10} mass was around 50% higher than nighttime TEOM PM_{10}. The pDR PM variables show increased particle concentration as the averaging time decreases. Peak concentrations were much higher than seen for the ambient hourly TEOM PM_{10}, suggesting that personal activity led to higher exposures related to the so-called personal cloud (Liu et al. 2002). The highest 1-hr maximum TEOM PM_{10} was 95 $\mu g/m^3$, whereas the overall geometric mean of the 1-hr maximum pDR PM measurements (approximating $PM_{2.5}$) was 117 $\mu g/m^3$. Gravimetric mass measurements of 24-hr average $PM_{2.5}$ at all stationary sites were around one-third the 24-hr average pDR PM mass. Home indoor:outdoor PM ratios by person-day of paired nonmissing observations were 1.2 for $PM_{2.5}$ and 1.3 for PM_{10}. Neither $PM_{2.5}$ nor PM_{10} 24-hr average concentrations ever came close to the U.S. National Ambient Air Quality Standards (65 $\mu g/m^3$ for $PM_{2.5}$ and 150 $\mu g/m^3$ for PM_{10}; U.S. EPA 1990).

Table 3 shows Spearman rank correlations between selected exposures. Ambient O_3 showed only small to moderate correlations with stationary-site PM and virtually no correlation with personal PM. Ambient NO_2 was moderately correlated with outdoor home and central-site HI $PM_{2.5}$ and PM_{10}, and with indoor $PM_{2.5}$, but weakly correlated with personal pDR PM. Correlations between personal pDR PM and stationary-site PM were generally small. Correlations for the 1-hr maximum pDR PM (not shown) with stationary-site PM were similar to the 8-hr maximum pDR PM, but slightly weaker. Peak personal PM exposures and peak TEOM PM_{10} both occurred during the daytime but were only weakly correlated. TEOM PM_{10} was only moderately correlated with collocated central-site gravimetric PM_{10}, possibly because of loss of semivolatile components across the TEOM's 50°C heating element (Allen et al. 1997) and/or loss of other particle components on the filter with time. Correlations of indoor with outdoor $PM_{2.5}$ were moderately strong.

Regression analysis. Model fit was improved using an indicator variable for the 2-week period of exposure assessment, and this fit was better than an indicator variable for subject. In addition to being a surrogate for groups of subjects and their responses, exposure period also likely represents different outdoor sources, meteorologic conditions, home ventilation conditions, and thus infiltration efficiency (Allen et al. 2003). Although exposure period nominally predicted FEV_1 ($p < 0.1$), controlling for period resulted in tighter confidence intervals (CIs) and larger negative slope coefficients for PM, indicating stronger adverse effects of PM on lung function. Maneuver time (morning, afternoon, or evening FEV_1) was alone associated with FEV_1 ($p < 0.005$), and when added to models with the PM variables, it improved fit through its influence on

the intercept but did not confound pollutants. Including maneuver time as a heterogeneity factor for the AR(1) covariance matrix did not improve models further. Other covariates did not confound associations of air pollutants with FEV_1 and were not themselves associated with FEV_1, including mean personal temperature the preceding 2 hr ($p = 0.85$), 12 hr ($p = 0.62$), and 24 hr ($p = 0.96$) before the FEV_1; maximum 1-hr personal temperature the preceding 24 hr before the FEV_1 ($p = 0.24$); minimum 1-hr personal RH ($p = 0.53$) and maximum 1-hr personal RH the preceding 24 hr before the FEV_1 ($p = 0.94$); season (fall 1999, spring 2000, $p = 0.29$); as-needed inhaler use in the previous 2–3 hr ($p = 0.37$); cumulative as-needed inhaler use during that day ($p = 0.36$); respiratory infection ($p = 0.55$); and day of week ($p = 0.63$). The lack of association for respiratory infection and as-needed inhaler use was likely caused by the infrequency of respiratory infections (6% of observations) and lack of inhaler use in more than half the subjects and infrequency of inhaler use in most of the rest (Table 1). Therefore, all models include random subject-specific intercepts and control for 2-week period of exposure assessment, maneuver time, and autocorrelation in the covariance structure.

We found that personal pDR PM exposure was inversely associated with percent predicted FEV_1, and most pDR exposure variables showed upper 95% confidence limits that did not cross the null value of 0% (Figure 1). Values for 4-hr and 8-hr maximum pDR PM the preceding 24 hr showed similar magnitudes of association, so we present results only for the 8-hr maximum. For all averaging times (1-hr maximum, 8-hr maximum, 24-hr average, 12-hr daytime, and 12-hr nighttime), the most robust associations were for lag 0 and 2-, 4-, or 5-day averages, with associations ranging between –4 and –22% predicted FEV_1 per IQR increase in personal PM. Generally, associations with FEV_1 were stronger when more lags were added. The strongest association was for 5-day moving average 12-hr daytime personal PM (–22%; 95% CI, –34 to –11). Associations for 12-hr daytime were stronger than 12-hr nighttime average personal PM. Percent predicted FEV_1 was not associated with 2-hr average pDR PM measured over the 2 hr preceding the FEV_1 maneuver ($p = 0.5$; data not shown).

We also found that $PM_{2.5}$ gravimetric mass measured at indoor and outdoor home sites and at the central site was inversely associated with percent predicted FEV_1 (Figure 2), although for some exposure variables the 95% CI included the null value of no effect. There were small differences in the magnitude of association by monitoring site for lag 0 $PM_{2.5}$ gravimetric mass (indoor > outdoor > central site), but for multiple-day averages, associations were similar by site. PM_{10} gravimetric mass was also inversely associated with percent predicted FEV_1 (Figure 3), although again, for some

Table 2. Daily air pollution and weather measurements during a personal particle exposure assessment study, September–October 1999, and April–June 2000: Alpine, California, Asthma Panel Study.

Exposure and averaging time	No.[a]	Arithmetic mean ± SD	Geometric mean	IQR	Minimum/ Maximum	90th percentile
pDR PM (μg/m^3)						
Mean personal PM last 2 hr	452	34.4 ± 33.7	23.4	36.0	0.0/305.3	67.6
12-hr Daytime mean personal PM	178	55.7 ± 31.6	47.9	40.0	5.7/181.9	100.8
12-hr Nighttime mean personal PM	200	22.3 ± 13.6	19.2	18.4	2.7/65.6	40.2
1-hr Maximum personal PM last 24 hr	419	151.0 ± 120.3	117.3	128.0	9.1/996.8	292.4
4-hr Maximum personal PM last 24 hr	419	87.5 ± 55.3	72.8	63.8	7.1/344.1	168.2
8-hr Maximum personal PM last 24 hr	419	67.6 ± 39.0	57.5	53.7	5.3/225.9	121.9
Mean personal PM last 24 hr	419	37.9 ± 19.9	33.4	30.3	3.9/113.8	65.1
Home stationary-site PM (μg/m^3)						
24-hr Mean indoor gravimetric PM_{10}	216	30.3 ± 11.9	29.1	15.5	8.7/74.8	45.6
24-hr Mean indoor gravimetric $PM_{2.5}$	219	12.1 ± 5.4	12.0	6.7	2.8/35.3	20.2
24-hr Mean outdoor gravimetric PM_{10}	226	25.9 ± 10.4	24.8	14.9	6.6/68.4	38.6
24-hr Mean outdoor gravimetric $PM_{2.5}$	226	11.0 ± 5.4	10.7	7.1	1.8/31.0	18.4
Central outdoor stationary-site PM (μg/m^3)						
12-hr Daytime TEOM PM_{10}	232	35.1 ± 11.3	34.2	19.3	16.4/60.4	50.4
12-hr Nighttime TEOM PM_{10}	232	23.3 ± 8.4	22.8	13.5	9.0/45.1	33.5
1-hr Maximum TEOM PM_{10} last 24 hr	535	54.4 ± 13.8	53.7	17.7	24.4/95.4	71.0
4-hr Maximum TEOM PM_{10} last 24 hr	535	44.8 ± 12.4	44.1	16.1	20.8/77.6	62.4
8-hr Maximum TEOM PM_{10} last 24 hr	535	39.8 ± 11.2	39.2	16.6	16.8/70.7	53.9
Mean TEOM PM_{10} last 24 hr	535	29.7 ± 8.6	29.4	13.1	12.9/50.7	40.9
24-hr Mean gravimetric PM_{10}	236	23.6 ± 9.1	22.7	14.6	3.2/48.0	34.6
24-hr Mean gravimetric $PM_{2.5}$	232	10.3 ± 5.6	9.9	7.5	1.7/29.1	18.4
Central outdoor stationary-site pollutant gases and weather						
8-hr Maximum daily O_3 last 24 hr (ppb)	535	62.9 ± 15.1	62.1	22.0	25.0/105.9	83.9
8-hr Maximum daily NO_2 last 24 hr (ppb)	535	19.6 ± 7.0	19.3	10.5	5.3/38.4	28.9
1-hr Maximum temperature last 24 hr (°F)	543	79.1 ± 9.1	79.6	13.0	57.0/97.0	89.0
1-hr Minimum RH last 24 hr (%)	526	36.3 ± 19.7	31.3	34.0	5.0/92.0	60.0
Personal weather						
1-hr Maximum temperature last 24 hr (°F)	530	86.4 ± 5.6	87.2	6.9	73.1/103.5	93.8
1-hr Minimum RH last 24 hr (%)	530	30.8 ± 7.5	31.0	12.4	22.1/59.2	42.3

[a]The sample size refers to all unique data used in FEV_1 regression models. Where the data are continuously measured over the period before an FEV_1 maneuver (exposure "last 2" or "last 24 hr"), more than one measurement per person-day is possible (e.g., 1-hr maximum the preceding 24 hr before the morning, afternoon, and evening FEV_1). Data thus include up to 535 person-observation times with both FEV_1 and exposure. For measurements made during fixed time intervals, namely, gravimetric PM or 12-hr daytime or nighttime PM, the no. represents one unique observation per day, per site (up to 236 person-observation times).

Table 3. Exposure correlation matrix,[a] August–October 1999 and April–June 2000: Alpine, California, Asthma Panel Study.

Exposure	8-hr Max NO_2	8-hr Max personal PM	24-hr Mean personal PM	8-hr Max TEOM PM_{10}	24-hr Mean TEOM PM_{10}	24-hr Central HI PM_{10}	24-hr Central HI $PM_{2.5}$	24-hr Outdoor HI PM_{10}	24-hr Outdoor HI $PM_{2.5}$	24-hr Indoor HI PM_{10}	24-hr Indoor HI $PM_{2.5}$
8-hr Max O_3	–0.05	0.03	0.01	0.40	0.41	0.23	0.24	0.19	0.27	0.04	0.15
8-hr Max NO_2	1.00	0.26	0.27	0.57	0.58	0.73	0.73	0.56	0.66	0.24	0.50
8-hr Max personal PM		1.00	0.94	0.38	0.40	0.37	0.38	0.32	0.39	0.23	0.37
24-hr Mean personal PM			1.00	0.36	0.39	0.36	0.43	0.34	0.44	0.29	0.46
8-hr Max TEOM PM_{10}				1.00	0.92	0.78	0.71	0.72	0.75	0.36	0.58
24-hr Mean TEOM PM_{10}					1.00	0.86	0.78	0.79	0.78	0.36	0.59
24-hr Central HI PM_{10}						1.00	0.90	0.80	0.83	0.37	0.67
24-hr Central HI $PM_{2.5}$							1.00	0.72	0.89	0.40	0.73
24-hr Outdoor HI PM_{10}								1.00	0.86	0.44	0.66
24-hr Outdoor HI $PM_{2.5}$									1.00	0.45	0.79
24-hr Indoor HI PM_{10}										1.00	0.74

Definitions: Central, central regional U.S. EPA site; HI, Harvard impactor gravimetric mass on Teflon filters; Indoor, indoor home sites; Max, maximum; Outdoor, outdoor home sites.
[a]Spearman's rank correlations. Exposure measurements are observations from the period around 1800 hr to 1800 hr to match 24-hr sampling periods of the gravimetric samplers (HIs).

exposure variables the 95% CI included the null value of no effect. Indoor PM_{10} was more strongly associated with FEV_1 than was outdoor home or central-site PM_{10}. Associations shown for monitoring sites were notably smaller compared with personal PM (note graph scale difference in Figure 1).

Central-site TEOM PM_{10} was inversely related to percent predicted FEV_1 at magnitudes similar to that of collocated central-site gravimetric PM_{10}, but most 95% CIs included the null value of no effect (Figure 4). There were no differences between hourly maxima and 24-hr averages.

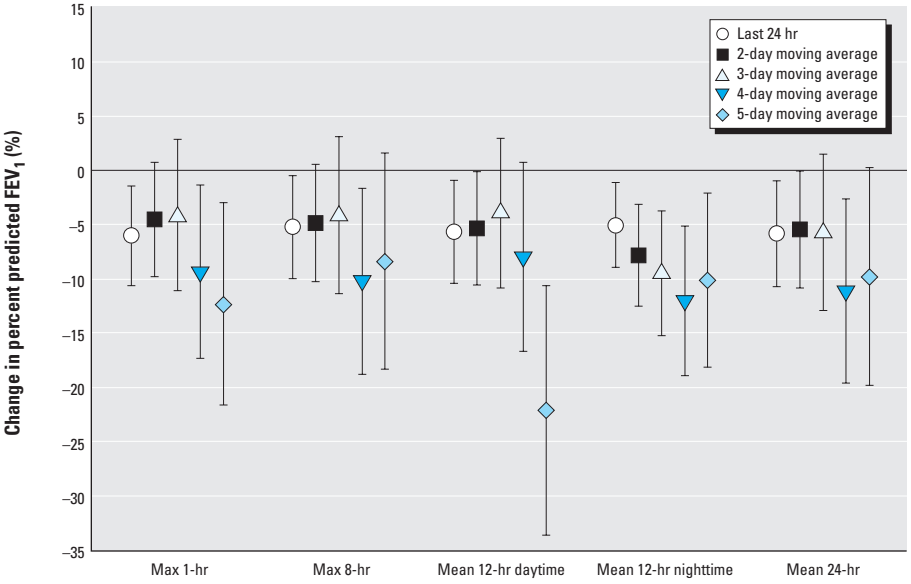

Figure 1. Results of mixed models for the relationship between percent predicted FEV_1 and personal exposure to particulate air pollution measured by a passive nephelometer: Alpine, California, Asthma Panel Study. Last 24 hr refers to exposures occurring in the 24-hr period preceding the FEV_1 maneuver. Multiple-day averages include the current day plus days preceding the FEV_1 maneuver up through lag 4 for the 5-day moving average. Results are expressed for an interquartile increase in pollutant concentrations (Table 2); error bars indicate 95% CIs.

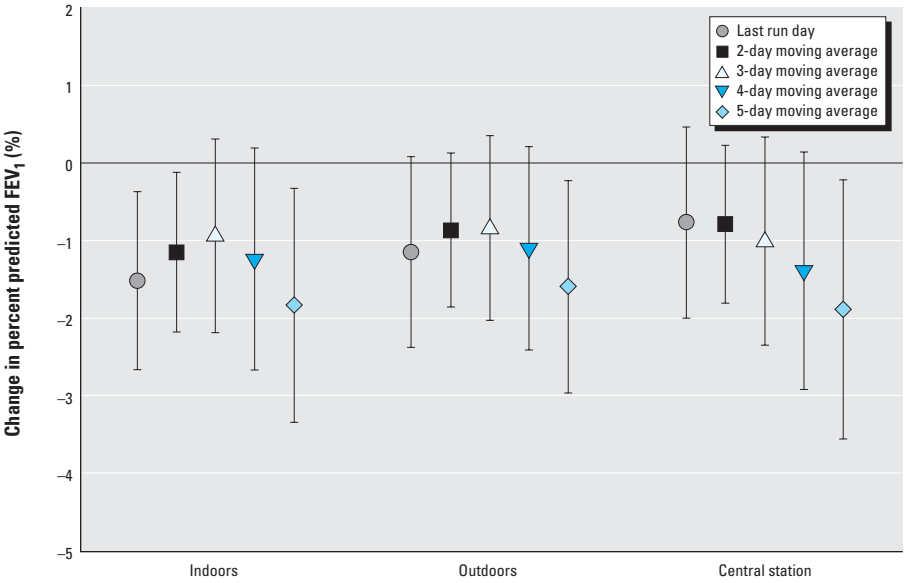

Figure 2. Results of mixed models for the relationship between percent predicted FEV_1 and $PM_{2.5}$ gravimetric mass measured at indoor and outdoor home sites and at the central regional station: Alpine, California, Asthma Panel Study. Last run day refers to HI filter samples collected before the FEV_1 maneuver and occurring in a 24-hr sampling period from around 1700–2000 hr the previous day to 1700–2000 hr the current day. Multiple-day averages include the current day plus days preceding the FEV_1 maneuver up through lag 4 for the 5-day moving average. Results are expressed for an interquartile increase in pollutant concentrations (Table 2); error bars indicate 95% CIs.

Central-site 5-day average 8-hr maximum NO_2 was inversely associated with percent-predicted FEV_1 (per IQR increase in NO_2, –1.16%; 95% CI, –2.4 to 0.1), and associations were similar for the 3- and 4-day average and for 1-hr maximum NO_2. Central-site O_3 was not associated with percent predicted FEV_1 for any averaging times ($p \geq 0.4$). Between-pollutant confounding was tested with two-pollutant regression models including an individual PM variable with central-site NO_2. Interaction was tested first but was nonsignificant. We found that associations for personal PM were minimally affected by NO_2, in that the above-reported associations with FEV_1 remained unchanged (for mean 24-hr) or more inversely associated (20–27% change for mean 12-hr daytime). However, NO_2 was confounded by personal PM with parameter estimates falling near zero.

Product term models for the interaction of pDR PM mass with a binary indicator for whether a subject was taking anti-inflammatory medications (five subjects) versus not taking them (14 subjects) showed no significant interaction ($p = 0.9$ for 8-hr maximum pDR PM, $p = 0.8$ for 24-hr average pDR PM). A similar product term for respiratory infection was also nonsignificant ($p = 0.5$ for 8-hr maximum pDR PM, $p = 0.6$ for 24-hr average pDR PM). Product term models for the interaction of pDR PM mass with a binary indicator for sex were usually significant, particularly for 2–4-day moving averages. The 14 boys showed more inverse associations than did the five girls, who showed responses not different from zero. For instance, we found an increase of –16% predicted FEV_1 (95% CI, –26 to –6) per IQR in 4-day average personal PM for boys, but only –1% predicted FEV_1 (95% CI, –16 to 14) for girls. Consistent interactions were found for stationary-site PM.

To indirectly test this assumption, we performed an analysis of effect modification by the presence versus absence of allergy to common indoor allergens. Allergy was based on positive allergen reactivity as assessed using skin prick tests for cat (*Felis domesticus* 1) and house dust mites (HDM; *Dermatophagoides farinae* and *D. pteronyssinus*) and defined as a skin wheal 3 mm greater than the saline negative control or having a diameter ≥ 50% of a histamine dihydrochloride–positive control. None of the girls was allergic to these allergens; therefore, the analysis was conducted only on boys because we found significant differences in associations between boys and girls as reported above. Two boys were not tested, leaving six having positive HDM/cat allergies (Table 1: ID 1, 5, 11–14) and six having negative HDM/cat allergies (Table 1: ID 2, 3, 9, 10, 15, 16). Three were allergic to HDM alone, two to cat alone, and one to both. Figure 5 shows results of product term models

for personal PM and atopy to HDM/cat, and Figure 6 shows results of product term models for stationary-site gravimetric PM and atopy to HDM/cat. We found that allergic subjects had stronger responses to personal PM (product term p-value < 0.07 for 2- and 3-day averages). However, responses were generally similar for stationary-site PM. Some associations with gravimetric $PM_{2.5}$ and PM_{10} were slightly and nonsignificantly stronger among nonallergic subjects, except 5-day average indoor PM_{10}, which was significantly stronger among allergic subjects.

Discussion

Findings. A key finding of this study is that percent predicted FEV_1 was inversely associated with personal exposure to fine particles (pDR PM; Figure 1). This is among the first reports of the relationships of personal PM exposure and FEV_1 in schoolchildren with asthma. The magnitudes of associations were in some cases clinically relevant at –6% predicted FEV_1 or worse. For instance, airway reversibility (one hallmark of asthma) can be identified in clinical evaluations of asthma using spirometry when there is an observed increase of ≥ 12% in FEV_1 from pre- to postbronchodilator administration. Given our overall average FEV_1 of 2.00 L/sec, and an overall percent predicted FEV_1 of 70%, a 12% increase from an FEV_1 of 2.00 L/sec would represent an 8.4% increase in percent predicted FEV_1. The largest association we observed was –22% predicted FEV_1 for 5-day moving average daytime personal PM.

We also found inverse associations of FEV_1 with stationary-site indoor, outdoor and central-site gravimetric $PM_{2.5}$ and PM_{10}, and with hourly TEOM PM_{10} (Figures 2–4). Personal PM was more strongly associated with FEV_1 than was stationary-site PM. Exposure misclassification from using stationary PM data may have diminished the accuracy of exposure–response estimates compared with personal exposures, thus potentially weakening associations with stationary PM. Personal exposures may have been not only quantitatively different (Table 2) but also qualitatively different. Recent studies have shown that personal PM includes not only infiltrated PM from vegetative burning, mobile sources, or secondary sulfate sources but also several classes of crustal materials that are related to personal activities (Hopke et al. 2003; Larson et al., in press; Yakovleva et al. 1999). It is likely that exposures to causally relevant airborne particles occurred at times not represented by the stationary-site monitors. These exposures may be encountered only in certain environments (e.g., at a bus stop) or only during certain activities (e.g., cleaning the house or classroom activities). Nevertheless, the consistency in associations with FEV_1 for personal PM compared with ambient PM suggests that some part of the association for personal PM exposure was attributable to ambient PM. The stronger associations for personal PM, especially the daytime average, imply that indoor activities, personal cloud, as well as daytime outdoor point sources contributed more to decrements in FEV_1 than did the average background PM (largely transported PM).

Associations of FEV_1 with lag 0 indoor (p < 0.01) and outdoor home $PM_{2.5}$ (p < 0.07) were more significant and stronger than for central-site $PM_{2.5}$ (p < 0.22; Figure 2). Similarly, associations for lag 0 indoor (p < 0.02) and outdoor home PM_{10} (p < 0.21)

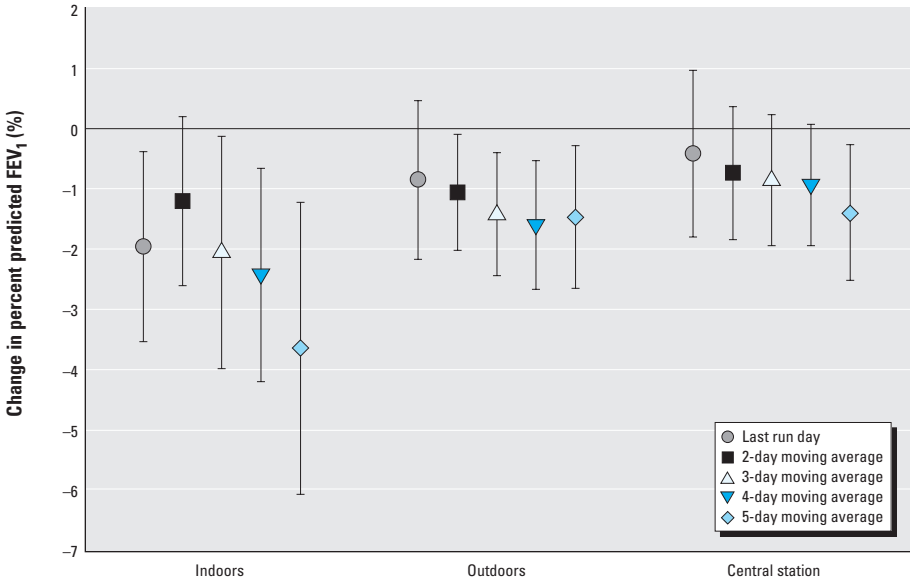

Figure 3. Results of mixed models for the relationship between percent predicted FEV_1 and PM_{10} gravimetric mass measured at indoor and outdoor home sites and at the central regional station: Alpine, California, Asthma Panel Study. Last run day refers to HI filter samples collected before the FEV_1 maneuver and occurring in a 24-hr sampling period from around 1700–2000 hr the preceding day to 1700–2000 hr the current day. Multiple-day averages include the current day plus days preceding the FEV_1 maneuver up through lag 4 for the 5-day moving average. Results are expressed for an interquartile increase in pollutant concentrations (Table 2); error bars indicate 95% CIs.

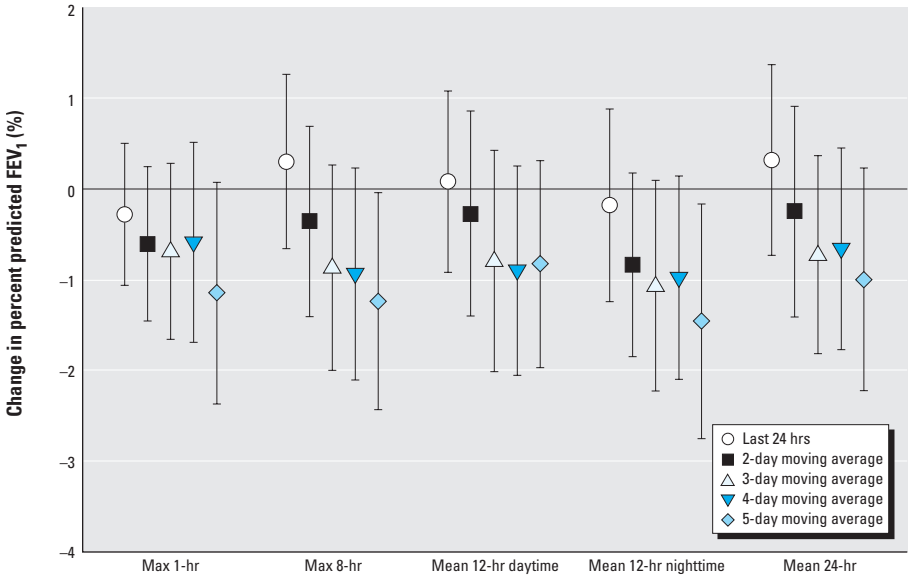

Figure 4. Results of mixed models for the relationship between percent predicted FEV_1 and hourly PM_{10} mass measured by a TEOM at the central regional station: Alpine, California, Asthma Panel Study. Last 24 hr refers to exposures occurring in the 24-hr period preceding the FEV_1 maneuver. Multiple-day averages include the current day plus days preceding the FEV_1 maneuver up through lag 4 for the 5-day moving average. Results are expressed for an interquartile increase in pollutant concentrations (Table 2); error bars indicate 95% CIs.

were more significant and stronger than for central-site PM_{10} ($p < 0.55$; Figure 3). We speculate that this is because the home measurements better represented personal exposures. Correlations between home and central-site PM were moderate to strong (Table 3). All of this suggests that central-site PM measurements could be sufficiently representative of ambient exposures for larger sample sizes in panel studies that are reliant on central-site data.

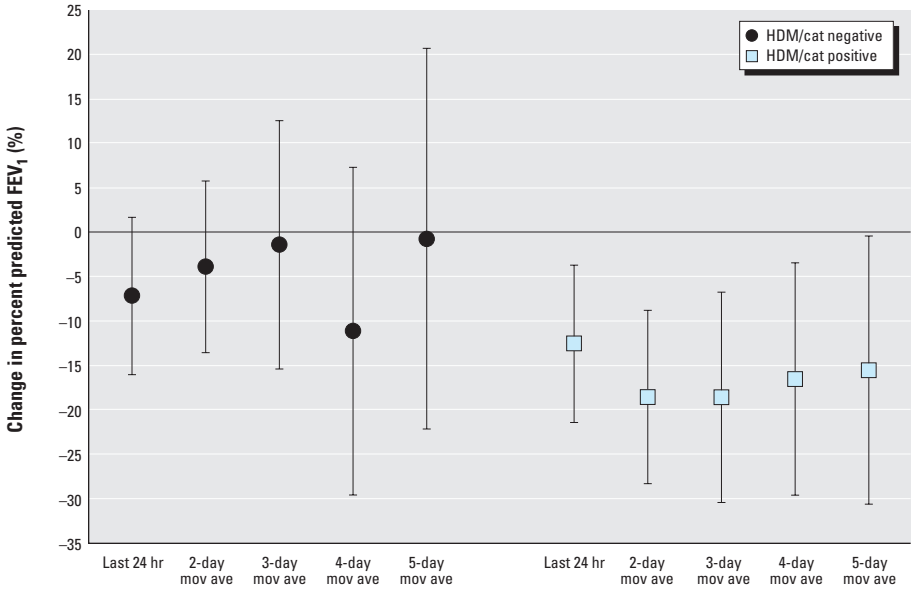

Figure 5. Results of mixed models for the relationship between percent predicted FEV_1 and personal exposure to particulate air pollution: effect modification by allergy to indoor allergens in boys. Mov ave, moving average. Six boys are allergic to HDM and/or cats (HDM/cat positive), and six are not (HDM/cat negative). Last 24 hr refers to exposures occurring in the 24-hr period preceding the FEV_1 maneuver. Multiple-day averages include the current day plus days preceding the FEV_1 maneuver up through lag 4 for the 5-day moving average. Results are expressed for an interquartile increase in pollutant concentrations (Table 2); error bars indicate 95% CIs.

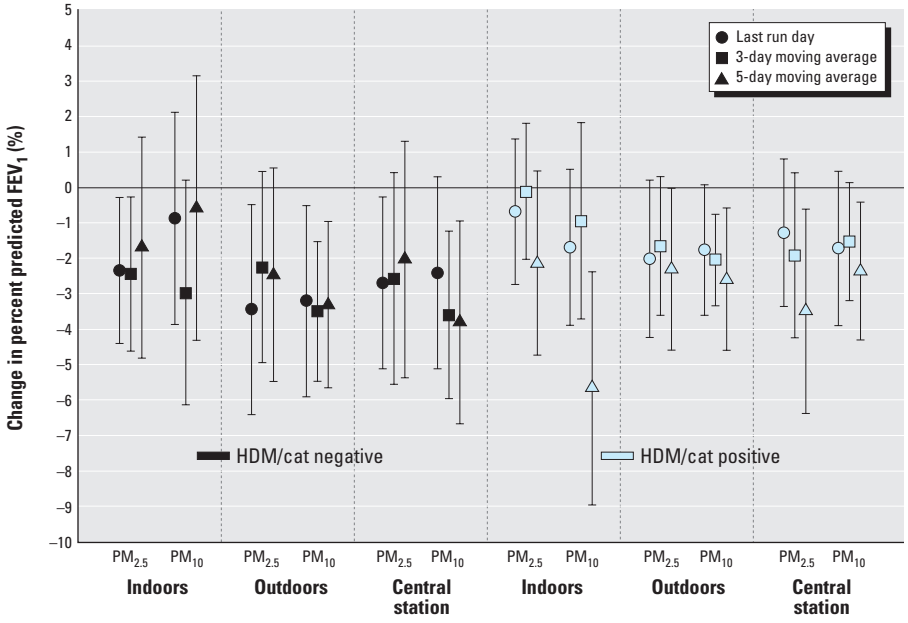

Figure 6. Results of mixed models for the relationship of percent predicted FEV_1 to $PM_{2.5}$ and PM_{10} gravimetric mass measured at indoor and outdoor home sites and at the central regional station: effect modification by allergy to indoor allergens in boys. Six boys are allergic to HDM and/or cats (HDM/cat positive), and six are not (HDM/cat negative). Last run day refers to HI filter samples collected before the FEV_1 maneuver and occurring in a 24-hr sampling period from around 1700–2000 hr on the previous day to 1700–2000 hr the current day. Multiple-day averages include the current day plus days preceding the FEV_1 maneuver up through lag 4 for the 5-day moving average. Results are expressed for an interquartile increase in pollutant concentrations (Table 2); error bars indicate 95% CIs.

Results for personal PM versus stationary-site PM monitors can be compared with those of only one recent study, by Koenig et al. (2003), who reported results of another panel study in 19 Seattle schoolchildren with asthma using up to 10 consecutive daily measurements of exhaled nitric oxide (eNO), which is a marker of airway inflammation. They found a positive association between eNO and lag 0 24-hr TEOM measurements of $PM_{2.5}$ at central outdoor sites that was similar in magnitude to associations of eNO with lag 0 24-hr gravimetric indoor home, outdoor home, and personal measurements of $PM_{2.5}$. Associations were significantly stronger for 10 subjects not using inhaled corticosteroids, consistent with our previous findings for asthma symptoms in children (Delfino et al. 1998, 2002). We may have observed no effect modification by anti-inflammatory medications because only five subjects were on them.

We found that there were significantly stronger associations of FEV_1 with PM in boys than in girls; but again inferences are somewhat limited because we compared responses in five girls with those in 14 boys. It is conceivable that boys may have been more exposed to outdoor PM and to personal cloud PM from increased physical activity. Time–activity diaries showed that boys spent more time outdoors on average (3 hr 17 min/day vs. 2 hr 32 min/day in girls), and boys were engaged in moderate to strenuous physical activity more often (37 min/day vs. 23 min/day in girls). No consistent sex differences in the relationship of PEF and ambient particulate or gaseous air pollutants were found in a large European panel study (Roemer et al. 1999), but another large U.S. panel study found stronger inverse associations between PEF and ambient O_3 in boys than in girls (Mortimer et al. 2000). Mixed sex differences in associations were found for one time series study of asthma hospitalization in relation to ambient NO_2 and sulfur dioxide in Vancouver, Canada (Lin et al. 2004). Stronger cross-sectional associations between lung function and ambient air pollution were found for girls in a general population cohort study in southern California, particularly among girls spending more time outdoors, and similar differences were seen for asthmatic subjects (Peters et al. 1999).

Evidence for PM associated with specific personal activities was shown in our previous study using time-stamped voice recorders and pDRs worn by 10 adult subjects over 1 week (Quintana et al. 2001). In that study, we found that compared with periods with no reported pollution events, pDR PM exposures were significantly higher while the subject was near pets, construction activities, cooking, barbecues, or environmental tobacco smoke or when doing yard work. These daily exposure patterns showing large excursions in PM were

consistently found both within subjects and for specific daily activities such as those described above. Modest differences in PM concentrations were seen for routine daily changes in indoor and outdoor microenvironments, such as differences between home and work. Large excursions in PM driven by activities may be particularly important in active children. A recent study by Liu et al. (2003) in Seattle found that children with asthma had higher personal $PM_{2.5}$ exposures than did elderly adults, and microenvironmental models used to predict personal $PM_{2.5}$ were weakest for asthmatic children (R^2 = 0.09) compared with elderly adults (R^2 = 0.45–0.62).

We found no notable differences in associations with FEV_1 by averaging time (1-hr, 8-hr, or 24-hr average) for personal PM (Figure 1). However, the strongest association was for 5-day moving average 12-hr daytime personal PM, but other multiday personal PM averages were comparable between 12-hr nighttime and daytime periods. Contrary to previous findings (Delfino et al. 1998, 2002), there were minimal differences between averaging times for TEOM PM_{10} measured at the outdoor central site.

The present findings for some stationary-site PM variables are far from statistically significant, but most are in the direction expected (inverse). In general, all PM metrics were more robustly associated with FEV_1 when multiday moving averages were used. However, it is difficult to make a direct comparison between current day and cumulative lag exposures because the first days of an individual's FEV_1 data from the 14-day session could not be used in models involving the multiday moving averages. Other asthma panel studies have also found more robust associations of asthma morbidity with multiday moving averages of PM compared with single lag days (Delfino et al. 1998, 2002; Gielen et al. 1997; von Klot et al. 2002). This suggests either delayed or cumulative respiratory effects, and/or a smoothing of exposure misclassification for any single day lag.

Associations of FEV_1 with ambient NO_2 was isolated to 3–5-day average exposures but was confounded by personal PM, which was itself largely independent of NO_2. We previously reported associations between asthma symptoms and lag 0 NO_2 in another asthma panel study in Alpine, California (Delfino et al. 2002). Despite occasional high levels of central-site O_3 (8-hr maximum O_3 90th percentile, 83.9 ppb), O_3 was not associated with percent predicted FEV_1 in the present study. Time series studies investigating the relationship between gaseous ambient air pollutants and asthma hospital admissions or emergency department visits have been inconsistent (for a discussion, see Lin et al. 2004).

Associations for O_3 in the present study could be lacking because on hot days in this inland semi-arid desert region, when O_3 concentrations are highest, most subjects were indoors in air-conditioned buildings (r = 0.50 for 8-hr O_3 and 1-hr maximum outdoor temperature, vs. r = 0.10 for 8-hr O_3 and 1-hr maximum personal temperature). O_3 concentrations in southern California homes are considerably lower in air-conditioned buildings (Lee et al. 1999). We previously reported results of an O_3 exposure assessment study in Alpine that showed only small correlations between 12-hr daytime personal passive measurements of O_3 (median: spring 1994, 15.5 ppb; fall 1994, 12.7 ppb) and central-site O_3 (median: spring 1994, 54 ppb; fall 1994, 60 ppb). Although significant at $p <$ 0.001, using stationary-site O_3 as the sole predictor of personal O_3, the R^2 ranged from only 0.04 in the spring to 0.07 in the fall of 1994 (Liu et al. 1997). In comparison, for the present study, using central-site gravimetric $PM_{2.5}$ as the sole predictor of 24-hr average personal pDR PM (approximates $PM_{2.5}$), the R^2 is 0.18. More detailed exposure assessment analyses will be presented in a separate report.

Limitations. The relatively wider CIs for stationary monitor data compared with personal PM may occur because the personal sampling work was limited to three subjects at a time each followed over 2 weeks. This practical constraint is not an issue in other asthma panel studies that often rely exclusively on central-site PM data and are able to incorporate more person-days of outcome observation per subject. Given the limited duration of the individual time series, the likelihood is greater in personal exposure studies that exposure misclassification inherent in central-site data will inflate the error term for exposure–response relationships.

The pDR, like other nephelometers, is biased under high humidity conditions. We found this to be a minor and correctable problem in personal sampling data. The light scatter and mass relationship also depend on the diameter, refractive index, and density of particles (Thomas and Gebhart 1994), and particle size distribution in ambient air varies over space (Hering et al. 1997) and time (Morawska et al. 1999). Furthermore, although the pDR data may accurately record the timing of PM excursions, it does not inform us of the various sources and types of PM. Because of the differential light scattering responses to different PM components and lack of composition data, FEV_1 associations with maximum personal PM exposure should be interpreted with caution. Despite the drawbacks, we believe the pDR is the best available technology for real-time personal PM monitoring.

We made no measurements of aeroallergens. Our previous studies showed no confounding of air pollutant associations with asthma outcomes by outdoor fungal spores or pollen (Delfino et al. 1998, 2002). Nevertheless, it is conceivable that some of the relevant fine PM in the personal samples that led to FEV_1 deficits was allergenic. We know of no asthma panel study that has examined acute effects of aerometric measurements of indoor allergens such as dust mites and air pollutants simultaneously. Even though most high-molecular-weight allergens are likely carried by particles > 2.5 μm in diameter, a sizable fraction, including that of dust mite allergen, is carried by fine PM (Custovic et al. 1999). It is of interest in this regard that stronger and more robust associations were found for indoor PM_{10} than for outdoor PM_{10}, although CIs overlapped considerably (Figure 3), and we did not measure coarse particles directly (PM_{10} can be in large part $PM_{2.5}$). We speculate that this difference may have been a result of indoor activities that increased coarse particle fractions containing indoor allergens. This is supported by our finding of stronger associations between personal PM and FEV_1 among boys allergic to indoor allergens (Figure 5). For gravimetric stationary-site PM, some associations were nonsignificantly stronger among nonallergic subjects. However, 5-day average indoor PM_{10} was significantly stronger among allergic subjects (Figure 6).

Another asthma panel study found that asthmatic children who were both exposed (by dust assay or self-report) and sensitized to cat showed O_3 more strongly associated with morning PEF decreases and with asthma symptom increases, but this was not found for HDM (Mortimer et al. 2000). In the present study, only one of the subjects with cat allergies reported having cats in the home.

Conclusions

The inverse associations of FEV_1 with stationary-site and personal PM found in the present study may reflect mixed respiratory effects of personal cloud, microenvironmental, and ambient background exposures to airborne PM. Although ambient PM clearly affected FEV_1, additional high personal cloud exposures were likely captured by the pDR and may have involved exposures or sources not well represented by the stationary-site monitors at either home microenvironments or central outdoor sites. This is supported by several findings as follows: *a*) Personal exposures showed stronger associations than stationary measurements; *b*) over all subjects, indoor PM exposures showed stronger associations than outdoor and central-site measurements; and *c*) among boys, subjects allergic to indoor allergens showed stronger associations for personal PM but generally similar associations for most stationary PM measurements compared with nonallergic subjects. This suggests two possible sources of PM may be driving associations: combustion sources (ambient infiltrated

into homes or indoor sources) and personal and indoor activities that dominate during the daytime.

The present study, as with previous epidemiologic studies of particulate air pollution and asthma, is limited in the scope of inferences that can be made because particle exposures were represented only by total mass measurements. Further advancement in methods for assessing personal exposure to ambient PM is needed. This includes assessment of particle components that may influence airway inflammation or induce bronchoconstriction, and better assessment of particle sources, including allergenic or combustion sources that may be controlled or avoided. These exposure assessment methods should be developed for use in epidemiologic research.

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