Title
Personal and Ambient Air Pollution Exposures and Lung Function Decrement in Children with Asthma

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Acute adverse effects of air pollution on asthma outcomes in small cohorts of children have been reported in longitudinal studies using repeated daily measurements (panel studies). More recently, this includes positive associations between a biomarker of airway inflammation, exhaled nitric oxide, and both personal and outdoor ambient air pollutant exposures in children with asthma (Delfino et al. 2006; Koenig et al. 2005). Most panel studies of daily air pollution and acute changes in expiratory lung function reported before 2004 used measurements of peak expiratory flow (PEF). They generally showed consistent, albeit heterogeneous, inverse associations of PEF with ambient particulate matter (PM) < 2.5 μm in diameter (PM$_{2.5}$), with somewhat weaker associations for PM < 10 μm in diameter (PM$_{10}$) [reviewed by Ward and Ayers (2004)]. However, PEF is more effort dependent than another measure of lung function, forced expiratory volume in 1 sec (FEV$_1$). PEF is also a poor surrogate of the more clinically relevant FEV$_1$ (Giannini et al. 1997; Thiadens et al. 1999) because PEF measures only the first portion of expiration from larger proximal airways, whereas FEV$_1$ reflects resistance in both proximal and distal airways. Lower FEV$_1$ occurs when flow rate decreases because of airway obstruction, which is a key phenotype of asthma.

Most previous studies of the relationship between acute asthma in children and air pollution have relied on ambient central-site data (Sarnat and Holguin 2007; Trasande and Thurston 2005). Exposure error from using this data will likely diminish the accuracy of exposure–response estimates. High interpollutant correlations at ambient monitoring sites also make it difficult to identify independent associations from different regulated criteria air pollutants such as PM$_{2.5}$ and nitrogen dioxide. Furthermore, criteria pollutants may be serving as markers for components not routinely monitored, such as combustion-related organic compounds. These component mixtures may lead to airway inflammation and bronchoconstriction.
with personal PM$_{2.5}$ mass (Delfino et al. 2006). These findings suggested that in addition to products of fossil fuel combustion, other particle components in personal air samples were proinflammatory. Here we aim to expand on these previous findings in the same cohort of children by evaluating the relationship of FEV$_1$ to both personal and central-site NO$_2$, PM$_{2.5}$ mass, and EC–OC fractions of PM$_{2.5}$.

Materials and Methods

Design and population. We followed a panel of 63 schoolchildren with asthma for daily repeated measures of personal exposure to air pollution in two regions of the Los Angeles air basin in Southern California: Riverside and Whittier. These regions are characterized by high levels of air pollution predominantly from mobile sources of fossil fuel combustion. Geographic areas of recruitment were delimited to a 10-mile radius around a central air monitoring site in Riverside (population density, 3,538/mi$^2$), and a 5-mile radius around a central air monitoring site in Whittier (5,947/mi$^2$) (RAND California 2007). The institutional review board of the University of California, Irvine, approved the study protocol.

We obtained informed written consent from all subjects and one of their legal guardians. We recruited subjects by referral to the study office by local school district nurses. Eligibility criteria included ages 9–18 years and parent-reported physician-diagnosed asthma, with a history of episodic symptoms including wheezing, cough, or dyspnea. For the cohort, we targeted children with evidence of mild to moderate persistent asthma, including a) a history in the previous 12 months of asthma exacerbations requiring the use of prescribed bronchodilator(s) on ≥ 2 days per week, regardless of anti-inflammatory medication use; b) current use of oral or inhaled anti-inflammatory medications, regardless of symptom frequency; or c) < 80% predicted normal FEV$_1$ from office spirometry at the subject’s baseline visit to the General Clinical Research Center, University of California, Irvine. Subjects were ineligible if they smoked or if someone smoked in the subject’s home.

We followed subjects daily over a continuous 10-day period that involved wearing air samplers to measure personal exposure to air pollutants. There were sixteen 10-day periods of follow-up (a run) from July to December 2003 (Riverside) and 2004 (Whittier). Four subjects were followed daily at their home in each 10-day run (except one run with three subjects).

Lung function and diary data. We have presented spirometry methods and validation results for the present panel subjects in detail in our previous report (Thompson et al. 2006). Subjects self-administered spirometry at home using the hand-held ndd EasyOne Frontline Spirometer (ndd Technologies, Chelmsford, MA). Subjects were given detailed instructions and trained on its use in the home during a 5-day run-in period. Subjects were instructed to perform spirometry in the morning (up to 1100 hours), afternoon (1500–1800 hours), and evening (2000–2400 hours), referred to here as “session period.” Subjects were also instructed to complete a personal digital assistant (PDA) diary every 2 waking hours reporting asthma medication use. We mitigated missed PDA diary prompts with paper diaries and daily technician-administered questionnaires. Medications reported included daily preventive (controller) medications and as-needed (rescue) medications (inhaled β$_2$-agonist bronchodilators). Near bedtime, the PDA diary prompted recall of rescue and controller medication use throughout the day. In the morning, it prompted recall of rescue inhaler use during the night. We also measured rescue inhaler use with a pressure-actuated recording device (Doser; Meditrac Products, Hudson, MA) that logged puffs in 24-hr intervals from midnight to midnight.

During each session, the spirometer stopped after three good spirometry maneuvers were obtained, and it gave each subject up to six chances to meet acceptability and repeatability criteria. Intermittent instructions to subjects were displayed on the spirometer’s display based on the success or type of error of each attempt. Subjects were instructed to perform sessions before the use of inhaled β$_2$-agonist bronchodilator medications unless necessary, and to wait at least 4 hr after the use of them before performing a session. At the end of spirometry maneuvers, subjects answered a yes/no question on the spirometer screen: “Did you need to use your rescue medication in the last hour?”

Research technicians downloaded the spirometry data into laptops during daily home visits, and checked compliance and acceptability of maneuvers as generated by the ndd software (version 2.6). We retrained subjects as needed. Compliance was enhanced by monetary incentives, an on-screen point system, and audio alarms. We later evaluated each curve for acceptability and repeatability by selected criteria as previously described (Thompson et al. 2006). We then further evaluated these curves for visual acceptability. We found compliance was high (94%) and the number of sessions with acceptable and reproducible maneuvers by objective criteria as well as visually acceptable was moderately good (69%) (Thompson et al. 2006). To ensure a suitably complete time series of repeated measures, subjects included in the present analysis had to have at least a third of their 29 expected FEV$_1$ maneuvers over the 10 days that were valid as such. We excluded 10 subjects who did not meet this compliance threshold, leaving 53 subjects who had 1,249 observed of 1,537 expected spirometry sessions (81%) with acceptable and reproducible maneuvers (individual subject range, 41–100%, median 86%).

The highest FEV$_1$ (best effort) from the two acceptable and reproducible maneuvers was selected for analysis. We analyzed percent-predicted normal FEV$_1$ based on a subject’s height, age, sex, and race/ethnicity (Hankinson et al. 1999). This standardizes measurements between subjects, provides overall estimates of association for the study population, and is clinically meaningful.

Exposures. The personal air monitors were active air samplers worn in a backpack daily over the 10 consecutive days. Personal measurements included continuous nephelometer mass measurements of PM$_{2.5}$ (personal DataRAM model 1200; MIE Inc., Bedford, MA) and 24-hr EC and OC fractions of PM$_{2.5}$, collected on quartz filters (Whatman Inc., Florham Park, NJ) using an attached filter cassette. A 2.5-μm sharp-cut cyclone was attached upstream of the nephelometer, and PM$_{2.5}$ for EC and OC was collected downstream at a flow rate of 4 L/min. We measured NO$_2$ over 24-hr periods using a miniaturized diaphragm pump (VMP1625; Virtual Industry, Colorado Springs, CO) run at 0.1 L/min to sample air through triethanolamine-treated molecular sieve sorbent tubes (SKC West Inc., Fullerton, CA). We measured NO$_3$ based on National Institute for Occupational Safety and Health (1994) Method 6014. We collected personal temperature and relative humidity with attached loggers (Onset Computer Corp., Pocasset, MA). Elsewhere we provide data on the validation of both the personal PM$_{2.5}$ sampler (Chakrabarti et al. 2004) and our personal NO$_3$ active sampler (Staiger et al. 2005).

We measured a parallel set of exposures at our own outdoor central sites, one in Riverside and one in Whittier. PM$_{2.5}$ and PM$_{10}$ mass (Teflon filters), and PM$_{2.5}$ and OC (quartz filters) were collected there using standard procedures with Harvard Impactors (Air Diagnostics and Engineering, Inc., Naples, ME). Sampling start and stop times occurred during the early evening of each day near the same time as personal samplers. For both personal and central-site sample collection on quartz filters, particulate carbon was speciated into OC and EC using the thermal manganese dioxide oxidation technique (Fung et al. 2002). Central-site gases included hourly ozone and NO$_2$ measured by the South Coast Air Quality Management District. In Riverside, the district site was centrally located, and we sited Harvard Impactors there. In Whittier, we
constructed a central site at a subject home elevated on a hill. However, data for O3 and NO2 came from two district sites at opposite ends of the Whittier study region. We averaged hourly concentrations of these gases for the two stations.

**Analysis.** We tested the relationship between percent-predicted FEV1 and each air pollutant using linear mixed-effects models, with each subject serving as his or her own control (Verbeke and Molenberghs 2001). Because correlation among outcomes was present for the within-individual repeated measures, and possibly for the exposure run, we assumed a two-stage hierarchical model with random effects at the subject level, nested within a run. We fit an autoregressive-1 correlation structure given the observed variability from empirical variograms. Air pollutant exposures were mean-centered by subject to yield comparability between subjects and across runs (Sheppard et al. 2005).

We investigated impacts of personal hourly PM2.5 mass exposures preceding the FEV1 measurement including the average of the preceding 24 hr (lag 0), the average of the 25th through 48th hr (lag 1), and a cumulative 2-day moving average. We retained PM2.5 data if at least 75% of the hours were nonmissing. The same approach was used for central-site hourly NO2. Given our previous findings (Delfino et al. 1998, 2002), we also examined 1-hr and 8-hr maximum moving average in personal PM2.5 during the 24 hr preceding the FEV1 measurement. We examined 8-hr peak central-site O3 given its well-known diurnal trend. For the filter-based measurements (personal and central-site EC and OC, and central-site PM2.5 mass) and for personal NO2, we defined lag 0 to be the same day and lag 1 was the preceding day’s 24-hr measurement. We did not extend the number of lags beyond that last 2 days to maintain a reasonable within-subject sample size, because a subject’s data were limited to a single 10-day consecutive monitoring period.

We expressed results as percent change in predicted FEV1 per interquartile range (IQR) increase in each pollutant to standardize inter-pollutant comparisons.

We fit transitional models by adjusting for the previous FEV1 measurement to control for observed sinusoidal circadian rhythms. Transitional models condition the outcome in the current time on the previous outcome observation (e.g., afternoon FEV1 is regressed on the morning FEV1) (Diggle et al. 2002). We also tested for effect modification by session period (morning, afternoon, evening), and found several differences that we present below.

We decided _a priori_ to adjust for use of rescue inhalers, including use last night, which was associated with a decrease of 3.5 percent-predicted FEV1 in the afternoon and evening [95% confidence interval (CI), –6.5 to –0.4]. We also included cumulative daily use of rescue inhalers during the previous day using Doser data [PDA diary data for 119 person-days were used where Doser data were missing (9.5%)]. Cumulative inhaler use was positively associated with an increase of 1.1 percent-predicted FEV1 in the morning per two-puff dose (95% CI, –0.2 to 2.5). In addition, we excluded observations where subjects reported use of rescue inhalers in either the EDD spirometer diary or PDA diary report covering the last 2–4 hr (57 FEV1 observations, 4.6% of total). Such use was associated with an increase of 2.2 percent-predicted FEV1 (95% CI, 0.07 to 4.3). Models also adjusted for personal temperature and relative humidity (both positively associated with FEV1).

We tested potential confounding by self-reported respiratory infections (22 person-days, 4.4% of total, _p_ = 0.86 in relation to FEV1). We also tested confounding by the two regions of study, session period of day (morning, afternoon, or evening), and weekend. None of these variables influenced associations, with one exception discussed below for session period.

We conducted residual diagnostics to assess the presence of influential data points and subject clusters, as well as deviations from assumed functional form. One 10-year-old white female subject influenced personal PM2.5 models leading to a decrease in personal PM2.5 regression parameter estimates and increase in SE (Cook’s D, 0.38; restricted likelihood distance, 4.41). We present results with this subject and sensitivity analyses removing her data.

Given prior evidence (Becklake and Kauffman 1999; Delfino et al. 1998, 2002, 2006), we further tested models for effect modification by sex and by asthma controller medications using product terms with each air pollutant. We assumed product term interactions with a _p_-value < 0.1 suggested possible effect modification. We tested a binary (yes/no) indicator for use of anti-inflammatory medications, as well as indicators for inhaled corticosteroids with versus without leukotriene receptor antagonists. We also tested a binary indicator for prescribed daily use of short- or long-acting bronchodilators as controller medications. We anticipated both controller and rescue bronchodilators to have major impacts on temporal changes in FEV1.

We tested two-pollutant regression models to assess between-pollutant confounding after testing interaction between the pollutants in product term models. The aim here was to assess the extent to which associations with one pollutant was independent of another pollutant.

We retested selected regression models using generalized estimating equations with robust standard error estimates (Diggle et al. 2002) as a validity check to likelihood assumptions of the linear mixed-effects model. We found no qualitative differences in our study results.

Finally, we used a fifth-order polynomial distributed-lag mixed-effects model (Schwartz 2000) to investigate the relationship of FEV1 to lagged hourly personal PM2.5 exposures out

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**Table 1. Study group characteristics.**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years, mean [range])</td>
<td>13.8 (9–18)</td>
</tr>
<tr>
<td>Sex (no. [%])</td>
<td>Male 34 (64.1) Female 19 (35.9)</td>
</tr>
<tr>
<td>Race/ethnicity no. [%]</td>
<td>Hispanic 26 (49.1) White 12 (22.6) Black 13 (24.5) Asian 2 (3.8)</td>
</tr>
<tr>
<td>No. [%] with percent-predicted FEV1 &lt; 80%</td>
<td>18 (34.0)</td>
</tr>
</tbody>
</table>

*Includes 20 Hispanic subjects who gave no race and 6 who gave their race as white; two blacks and 2 Asians also gave their ethnicity as Hispanic. Predicted from the Third National Health and Nutrition Examination Survey (NHANES III) (Hankinson et al. 1999) from baseline spirometry.

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**Table 2. Differences in subject FEV1 by time of day and medication use.**

<table>
<thead>
<tr>
<th>Percent-predicted FEV1</th>
<th>Mean ± SD</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall (53 subjects)</td>
<td>86.8 ± 15.9</td>
<td>89.4</td>
<td>30–126</td>
</tr>
<tr>
<td>Morning</td>
<td>84.7 ± 17.0</td>
<td>88.0</td>
<td>33–116</td>
</tr>
<tr>
<td>Afternoon</td>
<td>88.6 ± 15.0</td>
<td>90.5</td>
<td>40–123</td>
</tr>
<tr>
<td>Evening</td>
<td>87.5 ± 15.7</td>
<td>89.2</td>
<td>30–126</td>
</tr>
</tbody>
</table>

Differences by medication use

| No controller medications (20 subjects) | 86.3 ± 15.5 | 89.1 | 41–119 |
| Inhaled corticosteroids (27 subjects) | 88.0 ± 14.4* | 89.0 | 44–126 |
| Antileukotrienes ± inhaled corticosteroids (13 subjects) | 85.2 ± 16.8* | 89.2 | 30–126 |
| Controller bronchodilators (16 subjects) | 86.1 ± 15.7 | 87.1 | 44–116 |

*Predicted from NHANES III (Hankinson et al. 1999) and based on data from the panel follow-up used in the present analysis. aOne subject was also using inhaled cromolyn. qFour subjects were using antileukotrienes only, and nine were using antileukotrienes plus inhaled corticosteroids. b Five subjects were using daily short-acting (β2-agonist) medications, two of whom were also using an anticholinergic medication (ipratropium bromide). 11 were using long-acting bronchodilator medications (sustained release theophylline and the long-acting β2-agonist, salmeterol xinafoate), and 14 were also using anti-inflammatory medications. Random-effects model _p_ < 0.05 for predicted FEV1 difference from subjects not on controller medications, adjusted for study region.
to 48 hr. We found negligible difference in the response curves when models that are more flexible were considered. We fit distributed lag models via a linear mixed-effects model assuming an autoregressive-1 correlation structure.

**Results**

**Descriptive data.** Descriptive statistics for the 53 subjects in the present analysis are presented in Table 1. On average, FEV1 was lowest in the morning and gradually increased to its highest in the afternoon, then decreased toward the evening (Table 2). We found percent-predicted FEV1 was significantly higher among 28 subjects taking inhaled corticosteroids, and significantly lower among 13 subjects taking antileukotrienes compared with 20 subjects not taking controller medications (Table 2). There was no significant difference in FEV1 for 16 subjects taking controller bronchodilators versus those not taking them.

We collected 519 person-days of valid observations for the personal NO2 air monitor. It malfunctioned for only 3 person-days. The PM2.5 nephelometer malfunctioned for two subjects during most of their 10-day run and periodically for other subjects, leaving 416 person-days of observation. Table 3 presents descriptive statistics for the exposure data. Concentrations of peak hourly personal PM2.5 were high, averaging 90 µg/m3 with a maximum reaching 603 µg/m3. The U.S. Environmental Protection Agency National Ambient Air Quality Standard (NAAQS) for 8-hr ambient O3 (80 ppb) was never exceeded. However, the NAAQS for 24-hr average ambient PM2.5 (35 µg/m3) was exceeded on 28 of 170 days and NAAQS for 24-hr average ambient PM10 (150 µg/m3) was exceeded on only 1 day at the central sites.

Figure 1 shows hourly average concentrations of personal PM2.5. Concentrations were lowest in the early morning, abruptly rising mid-morning with maximums around noon and sustained concentrations until late evening. The mid-morning peak occurred around 0800 hr during the school weekday but was delayed by several hours and was higher on weekends.

Table 4 shows the between-pollutant correlations. Small significant correlations of personal PM2.5 with personal EC, OC, and NO2 were found. Personal PM2.5 was moderately correlated with ambient PM2.5 (Spearman r = 0.60), and had small correlations with personal NO2 (r = 0.38) and ambient NO2 (r = 0.32). Personal NO2 showed low moderate correlation with ambient NO2 (Spearman r = 0.43). However, personal EC and OC were not correlated with ambient EC and OC but were weakly correlated with ambient NO2. Ambient exposures were moderately correlated with each other.

**Regression analysis.** Table 5 shows models for the relationship between percent-predicted FEV1 and air pollutants. We found significant inverse associations between FEV1 and 1-hr and 8-hr peak personal PM2.5 measured over the 24-hr periods preceding the lung function measurements (lag 0). The model for lag 0 24-hr average personal PM2.5 showed smaller associations for an interquartile increase in exposure, and was of borderline significance (p < 0.08). However, dropping the one influential subject discussed in “Methods” led to a stronger significant association with 24-hr personal PM2.5 (–0.69% predicted FEV1; 95% CI, –1.34 to –0.04%). Outdoor central-site 24-hr average PM2.5 (Table 5) and PM10 (not shown) were not associated with FEV1. Neither personal nor central-site EC or OC was associated with FEV1. Personal NO2 exposures were significantly inversely associated with FEV1, at lag 0 day and almost significant at lag 1 day (p = 0.06). This association was stronger with a 2-day moving average of lag 0 + 1 personal NO2 (not shown; –1.75%; 95% CI, –2.83 to –0.67%). Central-site NO2 was more weakly but significantly associated with FEV1 deficits at lag 0, but not at lag 1 day. Although regression coefficients were negative,
central-site $O_3$ was not significantly associated with FEV$_1$.

There was no difference in FEV$_1$ associations between sexes in models including a product term of sex by air pollutant. There were also no significant interactions between use of anti-inflammatory medications and air pollutants. However, we did find significantly weaker associations among 16 children taking daily bronchodilator controller medications compared with those not taking these medications. Table 6 shows models for the relationship between percent-predicted FEV$_1$ and lag 0 day air pollutants stratified by use of bronchodilator controller medications. Associations for personal NO$_2$ and PM$_{2.5}$ and ambient NO$_2$ largely reflect those found among all subjects (Table 5), but are stronger in the 37 subjects not taking controller bronchodilators, including 24-hr average personal PM$_{2.5}$. For an interquartile increase of 16.8 ppb 2-day average personal NO$_2$, (not shown) percent-predicted FEV$_1$ decreased by $-2.45\%$ (95% CI, $-3.57$ to $-1.33\%$) in subjects not taking controller bronchodilators, but there was no association in subjects taking controller bronchodilators ($p = 0.74$).

To assess the potential importance of indoor NO$_2$ sources, we retested NO$_2$ models by including the presence of gas stoves as a binary variable, and a trinomial variable to account for gas stoves with or without pilot lights. Concentrations of personal NO$_2$ were significantly higher for 22 subjects with gas stoves having pilot lights than for 12 subjects without gas stoves (mean $= 32.4$ ppb vs. 25.0 ppb, respectively), and higher than for 19 subjects with gas stoves but no pilot lights (mean $= 26.4$ ppb). However, gas stove covariates in the mixed models did not affect the magnitude or statistical significance of associations of FEV$_1$ with personal NO$_2$. In addition, stratified analyses by gas stoves did not reveal significant differences in associations between FEV$_1$ with NO$_2$ ($p > 0.6$). These findings held when stratified by bronchodilator group.

Figure 2 shows single-pollutant compared with two-pollutant models including subjects with both personal PM$_{2.5}$ and NO$_2$ data, and excluding the influential subject. Significant associations for 2-day average personal NO$_2$ and lag 0 1-hour maximum PM$_{2.5}$ remained when regressed together in the same model, with small decreases in estimates of association. A two-pollutant model with lag 0 24-hour averages of both personal NO$_2$ and PM$_{2.5}$ was consistent with these findings (not shown). Models testing product terms between personal NO$_2$ and PM$_{2.5}$ on FEV$_1$ showed no evidence of interaction.

We also tested two-pollutant models for 24-hour average personal NO$_2$ and ambient NO$_2$, and for 24-hour average personal PM$_{2.5}$ and ambient NO$_2$, excluding the influential subject. Figure 3 shows that personal NO$_2$ led to a halving of the estimated FEV$_1$ regression coefficient for ambient NO$_2$, whereas personal NO$_2$ is reduced by 20% in the two-pollutant model. Similarly, personal PM$_{2.5}$ led to a 43% reduction in the estimated regression coefficient for ambient NO$_2$ whereas the personal PM$_{2.5}$ coefficient is reduced by 18% in the

### Table 4. Exposure correlation matrix.

<table>
<thead>
<tr>
<th></th>
<th>Personal</th>
<th>Central site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM$_{2.5}$</td>
<td>EC</td>
</tr>
<tr>
<td>24-hr personal PM$_{2.5}$</td>
<td>1.00</td>
<td>0.22**</td>
</tr>
<tr>
<td>24-hr personal EC</td>
<td>1.00</td>
<td>0.44**</td>
</tr>
<tr>
<td>24-hr personal NO$_2$</td>
<td>1.00</td>
<td>0.21**</td>
</tr>
<tr>
<td>24-hr central PM$_{2.5}$</td>
<td>1.00</td>
<td>0.51**</td>
</tr>
<tr>
<td>24-hr central EC</td>
<td>1.00</td>
<td>0.84**</td>
</tr>
<tr>
<td>24-hr central OC</td>
<td>1.00</td>
<td>0.56**</td>
</tr>
<tr>
<td>24-hr central NO$_2$</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.05, and **p < 0.001, from Wald-based tests of Spearman correlation coefficients.

### Table 5. Mixed-model estimates of the association between percent-predicted FEV$_1$ and lag 0 air pollutant exposures and percent-predicted FEV$_1$ in 53 schoolchildren with asthma.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Personal Coefficient (95% CI)</th>
<th>p-Value</th>
<th>Central site Coefficient (95% CI)</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$</td>
<td>1-hr maximum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag 0</td>
<td>-0.989 (-1.538 to -0.399)</td>
<td>0.001</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 1</td>
<td>0.073 (-0.595 to 0.740)</td>
<td>0.831</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 2</td>
<td>-0.801 (-1.465 to -0.137)</td>
<td>0.018</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 3</td>
<td>0.107 (-0.584 to 0.798)</td>
<td>0.761</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>8-hr maximum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag 0</td>
<td>-0.592 (-1.251 to 0.068)</td>
<td>0.079</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 1</td>
<td>0.049 (-0.613 to 0.711)</td>
<td>0.885</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 2</td>
<td>-0.080 (-0.397 to 0.238)</td>
<td>0.623</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 3</td>
<td>0.067 (-0.467 to 0.602)</td>
<td>0.763</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>24-hr average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag 0</td>
<td>-0.278 (-1.222 to 0.666)</td>
<td>0.564</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 1</td>
<td>-0.386 (-1.548 to 0.812)</td>
<td>0.540</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 2</td>
<td>-1.217 (-1.958 to -0.476)</td>
<td>0.001</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Lag 3</td>
<td>-0.713 (-1.456 to 0.030)</td>
<td>0.060</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>D$_2$</td>
<td>8-hr maximum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag 0</td>
<td>NA</td>
<td>NA</td>
<td>-0.383 (-1.752 to 0.988)</td>
<td>0.583</td>
</tr>
<tr>
<td>Lag 1</td>
<td>NA</td>
<td>NA</td>
<td>-0.904 (-2.314 to 0.506)</td>
<td>0.209</td>
</tr>
</tbody>
</table>

NA, not available. Lag 0: most recent 24-hour average measurement preceding the FEV$_1$ measurement; lag 1: previous 24-hour average measurement preceding the FEV$_1$ measurement.

We also tested two-pollutant models for 24-hour average personal NO$_2$ and ambient NO$_2$, and for 24-hour average personal PM$_{2.5}$ and ambient NO$_2$, excluding the influential subject. Significant associations for 2-day average personal NO$_2$ and lag 0 1-hour maximum PM$_{2.5}$ remained when regressed together in the same model, with small decreases in estimates of association. A two-pollutant model with lag 0 24-hour averages of both personal NO$_2$ and PM$_{2.5}$ was consistent with these findings (not shown). Models testing product terms between personal NO$_2$ and PM$_{2.5}$ on FEV$_1$ showed no evidence of interaction.

We also tested two-pollutant models for 24-hour average personal NO$_2$ and ambient NO$_2$, and for 24-hour average personal PM$_{2.5}$ and ambient NO$_2$, excluding the influential subject. Figure 3 shows that personal NO$_2$ led to a halving of the estimated FEV$_1$ regression coefficient for ambient NO$_2$, whereas personal NO$_2$ is reduced by 20% in the two-pollutant model. Similarly, personal PM$_{2.5}$ led to a 43% reduction in the estimated regression coefficient for ambient NO$_2$ whereas the personal PM$_{2.5}$ coefficient is reduced by 18% in the...
two-pollutant model. Models with maximum personal PM$_{2.5}$ were consistent with these findings (not shown). An enhancement of FEV$_1$ deficits was observed with a product term of personal NO$_2$ with ambient NO$_2$ ($p < 0.06$).

Figure 4A shows a distributed lag model across 48 hr of personal PM$_{2.5}$ data including all 51 subjects with data. Inverse associations are shown between personal PM$_{2.5}$ at the 9th through 18th hr preceding FEV$_1$ measurements (FEV$_1$ association with 9th through 18th-hr average, $-0.73\%$; 95% CI, $-1.25$ to $-0.22\%$). After 24 hr, CIs cross zero and there is evidence of a repeating 24-hr pattern across the 2 days. An unexpected positive association is shown in the 5 hr preceding FEV$_1$ measurements (FEV$_1$ association with 0–through 5th-hr average, $0.34\%$; 95% CI, $-0.13$ to $0.81$). The 0–through 5th-hr average was confounded to $-0.19\%$ by adding an indicator for session period (morning, afternoon, or evening). This finding is attributable to morning FEV$_1$ when both lung function (Table 2) and personal PM$_{2.5}$ (Figure 1) were lowest, as expected. Thus, the positive association was temporarily confounded. In contrast, the session period indicator did not confound the inverse association for the average of the 9th–through 18th-hr PM$_{2.5}$ preceding FEV$_1$. Figure 4B adjusts for the average of the 9th–through 18th-hr indicator did not confound the inverse association. In contrast, the session period revealed a more consistent pattern for the morning FEV$_1$ ($-1.11\%$, $p < 0.08$) or evening FEV$_1$ ($-0.42\%$, $p < 0.29$). In subjects not using bronchodilators, the coefficient for personal PM$_{2.5}$ was significantly more negative for afternoon FEV$_1$ ($-1.47\%$, $p < 0.05$) and morning FEV$_1$ ($-1.53\%$, $p < 0.1$) than for evening FEV$_1$ ($1.46\%$, $p < 0.1$). The coefficient for personal PM$_{2.5}$ was also significantly different for morning and afternoon FEV$_1$ ($-1.16\%$, $p < 0.0005$) than other FEV$_1$ ($p = 0.5$).

**Discussion**

We found that increased personal exposures to NO$_2$ and PM$_{2.5}$ were associated with lung function deficits in schoolchildren with persistent asthma. To our knowledge, this is the first report of associations between personal exposure to daily NO$_2$ and FEV$_1$ decrements in children with asthma. The large magnitude of association was a 2.45% drop of percent-predicted FEV$_1$ for a small interquartile increase of 16.8 ppb 2-day average NO$_2$ in 37 subjects not taking controller bronchodilators. We found consistent but weaker associations for ambient NO$_2$ measured at central regional sites. However, we found no associations of FEV$_1$ with ambient PM, likely because of exposure error and the short sampling period of 10 days per subject.

In two-pollutant models for personal NO$_2$ and PM$_{2.5}$, we showed considerable independence of associations with FEV$_1$ suggesting that personal PM$_{2.5}$ mass represents different causal components than personal NO$_2$. This may have at least partly resulted from the different averaging times for each of the pollutants because NO$_2$ was sampled over fixed 24-hr intervals, whereas PM$_{2.5}$ was measured continuously and linked to thrice daily FEV$_1$ by real time. We previously reported consistent independent associations of exhaled NO (measured once daily) with personal PM$_{2.5}$ and NO$_2$ averaged across the same 24-hr intervals in 45 of the subjects in the present analysis (Delfino et al. 2006). In addition to products of fossil fuel combustion, personal PM$_{2.5}$ mass may also represent a variety of other exposures, including bioaerosols such as endotoxin that can exacerbate asthma. Our data also suggest that personal PM$_{2.5}$ reflects ambient PM$_{2.5}$ given the moderate correlation between them ($r = 0.60$).

Because of the presumed superiority of personal exposures in assessments of exposure–response relationships, we anticipated that associations for personal exposures would confound associations for ambient exposures. Furthermore, Sarnat et al. (2005) found that ambient NO$_2$ concentration was a good surrogate of personal PM$_{2.5}$ exposure. This suggests that epidemiologic findings for ambient NO$_2$ may be attributable to personal PM exposures. We confirmed and expanded these expectations by finding that both personal NO$_2$ and personal PM$_{2.5}$ confounded associations of FEV$_1$ with ambient NO$_2$. Because personal PM$_{2.5}$ and personal NO$_2$ had largely independent effects and both confounded ambient NO$_2$, they may represent both similar and different information about causal components. The interaction between personal and ambient exposure...
NO2 further support this. In a previous panel study of children with asthma in Southern California, we also found that FEV1 was inversely associated with ambient NO2, but this was completely confounded by personal PM (Delfino et al. 2004). These findings suggest that personal PM2.5 and NO2 represent some set of causal background air pollutants also represented by ambient NO2. What pollutant components and sources are driving associations, though?

Outdoor NO2 is strongly influenced by local traffic density (Jerrett et al. 2005). Although indoor sources such as gas stoves did not explain the association of FEV1 with personal NO2. In a large study of 482 homes in Los Angeles, outdoor home NO2 was well correlated with personal NO2 ($R^2 = 0.52$) because of indoor infiltration (Spengler et al. 1994). Traffic-related sources of NO2 contribute to high spatial variability of potentially important particulate and gaseous co-pollutants (Sioutas et al. 2005). There is considerable evidence that such variability is best captured by personal exposure measurements (Jerrett et al. 2005). This is important among children who may be exposed at home, at school, and at other locations including times in vehicles. The correlation between personal and ambient NO2 ($r = 0.43$) as well as the confounding of the ambient NO2 association by personal NO2 were consistent with the view that in addition to local traffic sources, some part of the association we found between personal NO2 and FEV1 was attributable to ambient background sources of NO2. The statistical interaction between personal NO2 with ambient NO2 may reflect this source difference.

Plausible mechanisms of NO2 toxicity have been well described (Persinger et al. 2002) and may contribute to part of our findings. However, in experimental exposure studies of adults with mild asthma, adverse pulmonary effects of NO2 have generally been demonstrated at levels of exposure a

Figure 4. Estimated lag effect of hourly personal PM2.5 on FEV1 in the full cohort of 51 subjects. (A) Not adjusted for maneuver; (B) adjusted for maneuver. Estimates are based on a 5th-degree linear mixed-effects polynomial distributed lag model with AR(1) correlation structure. Expected change in FEV1 for each hour corresponds to an IQR change (21.6 µg/m3) in 24-hr average PM2.5 and estimates are plotted by solid circles. Pointwise 95% CIs are plotted by error bars. All estimates are adjusted for the previous FEV1 measurement, personal temperature, personal relative humidity, cumulative inhaler use on the previous day, and inhaler use during the last night, and excluding observations where there was use of inhaled as-needed bronchodilators in the preceding 4 hr.

Figure 5. Estimated lag effect of hourly personal PM2.5 on FEV1 by session period in 37 subjects with no controller bronchodilator use. (A) morning; (B) afternoon; and (C) evening. Estimates are based on a 5th-degree linear mixed-effects polynomial distributed lag model with AR(1) correlation structure. Expected change in FEV1 for each hour corresponds to an IQR change (21.6 µg/m3) in 24-hr average PM2.5, and estimates are plotted by solid circles. Pointwise 95% CIs are plotted by error bars. All estimates are adjusted for the previous FEV1 measurement, personal temperature, personal relative humidity, cumulative inhaler use on the previous day, and inhaler use during the last night, and excluding observations where there was use of inhaled as-needed bronchodilators in the preceding 4 hr.
through oxidative stress responses induced by be causally related to asthmatic responses related air pollutants. These pollutants may likely to have served as a surrogate for traffic-related air pollutants. These pollutants may be causally related to asthmatic responses through oxidative stress responses induced by pollutants highly correlated with NO₂ (Li et al. 2003; Seaton and Dennekamp 2003).

Given this evidence and our findings for NO₂, it is paradoxical that we did not find FEV1 to be associated with particulate EC or OC in either personal or ambient samples, except in subjects not using bronchodilators, associations of personal OC with morning and afternoon FEV1 and personal EC with morning FEV1. The carbon fraction of PM is derived primarily from products of fossil fuel combustion, so EC and OC should be reasonably good surrogates for causative pollutant components derived from those sources. In our previous report using exhaled NO, we found associations with personal and ambient NO₂ were largely independent of associations with personal and ambient EC and OC fractions of PM₂.₅ in two-pollutant models, thus suggesting different causal pollutant components (Delfino et al. 2006). It is conceivable that volatile and semivolatile organic compounds are behind these findings given their traffic-related sources and role in particle formation (Biswas et al. 2007; Schauer and Cass 2000).

Our results for personal PM₂.₅ are consistent with recent studies showing inverse associations of personal and/or ambient PM mass with FEV1 among schoolchildren with asthma (Ackplakorn et al. 2003; Delfino et al. 2004; Lewis et al. 2005; Trenga et al. 2006). Magnitudes of association could not be compared, though, because of differences in both the expression of lung function effect estimates and PM measurement methods. Investigators of a recent Denver panel study failed to show associations of ambient PM₁₀ with personal FEV1 in schoolchildren with persistent asthma (Rabinovich et al. 2004), but later showed that urinary leukotriene E₄ and rescue inhaler use during school hours were positively associated with morning average and peak PM₂.₅ (Rabinovich et al. 2006).

Few studies of lung function in children with asthma have used personal particulate air pollution measurements, and fewer still have used real-time personal measurements that allow the assessment of effects of peak air pollution exposures (Delfino et al. 2004, 2006). We previously followed for 2 weeks per subject a panel of 19 children, 9–17 years of age, with persistent asthma in San Diego County (Delfino et al. 2004). We found that FEV1 significantly decreased similarly in relation to both 24-hr personal PM and 1-hr maximum personal PM, but FEV1 was not associated with outdoor ambient PM₂.₅. In the present study, we found that personal hourly peak was a stronger and more significant predictor of FEV1 compared with 24-hr average personal PM₂.₅.

The present associations of FEV1 with hourly PM₂.₅ in the distributed lag models suggest that inverse associations were primarily from exposure ≥ 8 hr before the lung function measurement. PM₂.₅ concentrations peaked in mid-morning and they were sustained for several hours into the afternoon and evening (Figure 1). Particles from morning rush hour traffic and in-vehicle exposures followed by secondary photochemical particle formation would have occurred throughout the late morning and afternoon, including time in school. Although this was possibly important in our findings, the resolution of the hourly PM₂.₅ data is limited primarily by the fact that we used fine particle mass rather than composition or other particle size fractions.

We previously conducted distributed lag analyses of hourly personal PM₂.₅ using the present panel and showed that exhaled NO (collected in the late afternoon to early evening) was positively associated with PM₂.₅ in the 5 hr before measurement (Delfino et al. 2006).

Conclusions. The associations we found between personal NO₂ and FEV1, deficits may be attributable to other more toxic pollutants from traffic-related sources. Largely independent associations between personal PM₂.₅ and FEV1 suggest a subset of causal components different from personal NO₂. We further conclude that associations of lung function with particulate air pollutants might be missed using ambient central-site data alone unless a large number of repeated observations per person are available. Our results may also not be generalizable to situations where central-site measurements are more representative of personal exposures in other geographic locations. Future work should focus on identifying causal pollutant components and their sources. This will require detailed assessments of exposure close to where children at risk live and attend school—such as not possible using available criteria air pollutant data.

References


