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Acute effects of outdoor air pollution on forced expiratory volume in 1 s: a panel study of schoolchildren with asthma

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ABSTRACT: Urban air pollution has been associated with morbidity but little information exists on how it affects diurnal variation of lung function in children with asthma. The purpose of this study was to investigate the acute effects of traffic-related pollution on lung function among children with asthma.

We recorded morning and evening forced expiratory volume in 1 s (FEV_1) for 28 consecutive days in 182 elementary schoolchildren with physician-diagnosed asthma, and monitored ambient hourly air pollution concentrations.

An interquartile range (IQR) increase (6.0 $\mu g \cdot m^{-3}$) in the previous 24-h (20:00 h to 20:00 h) mean concentration of fine particulate matter 2.5 μm in diameter ($PM_{2.5}$) was associated with a 0.54% (95% confidence interval (CI) 0.06–1.02) decrease in bedtime FEV_1 ($p=0.027$). This association persisted in two-pollutant models with ozone, nitrogen dioxide and sulphur dioxide. An IQR increase in mean daytime (08:00 h to 20:00 h) $PM_{2.5}$ of 6.5 $\mu g \cdot m^{-3}$ was associated with a 0.73% (95% CI 0.10–1.37) decrease in FEV_1 over the course of the day expressed as 100 × (FEV_1 bedtime - FEV_1 morning)/FEV_1 morning ($p=0.024$).

This study suggests that, in children with asthma, relatively low concentrations of urban air pollution worsen lung function over a short period of time, even within a day. Of the pollutants measured, $PM_{2.5}$ appears to be the most important.

KEYWORDS: Air pollution, children, environment, lung function

Acute and chronic exposure to urban air pollution in North America and Europe has been associated with increased respiratory symptoms, reduced lung function, increased number of hospitalisations and increased number of deaths from respiratory diseases [1–5]. Although many different study designs have been used, the majority of the evidence comes from comparisons of daily concentrations of air pollutants with daily mortality or hospital admission counts. There have also been several panel studies which have reported associations between daily symptoms and/or lung function and daily measures of various air pollutants [6–14]. The present study focuses on acute changes in lung function. We studied the effects of between-day changes in air pollution and tested a relatively unique hypothesis that acute change in lung function within a day, between morning and evening (diurnal change), was associated with fine particulate concentrations on the same day.

METHODS

Study population

The study was carried out in Windsor, ON, Canada, with an estimated population of 216,473 in 2006 [15]. A unique aspect of the city is the Ambassador Bridge, which carries several thousand trucks daily between Windsor and Detroit, MI, USA. We identified children with asthma from a questionnaire survey carried out in the previous year of ~16,000 elementary schoolchildren in Windsor. For the present study, we selected children whose parent or guardian had given a positive response to the question ''Has a physician ever told you this child had asthma?'', and who had agreed to be contacted about future research. We selected children who were between 9 and 14 yrs of age when the initial questionnaires were completed, who spoke either of Canada's official languages (English or French) and who lived in homes without cigarette smoke. A list of all eligible children satisfying these criteria was compiled. We telephoned their

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homes in random order and recruited the first 182 subjects who agreed to participate. The number of respiratory therapists available in Windsor to work on this study limited the number of subjects who could participate. The parent or guardian of each child gave written informed consent before the child participated in the study. The study protocol was approved by the Research Ethics Board of Health Canada.

Study design

A short-term longitudinal study design with repeated measures was used. Each child completed a daily symptom diary, and performed forced expiratory flows in the morning and at bedtime for 28 consecutive days. Owing to resource constraints, children were studied in one of two test periods: October 11 to November 7, 2005 or November 14 to December 11, 2005.

Air pollution measurements

City-wide air pollution hourly levels were estimated by averaging measures from two fixed-site monitors located in the western area of the city, upwind from the prevailing winds. These monitors, which are part of Environment Canada's National Air Pollution Monitoring System, provided ambient levels of hourly fine particulate matter with a mass median aerodynamic diameter <2.5 μm in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), ozone (O_3) and sulphur dioxide (SO_2). The majority of the population lived within 10 km downwind.

Forced expiratory volume in 1 s

Respiratory therapists instructed parents and children on the use of hand-held flow meters and daily symptom diaries. Forced expiratory volume in 1 s (FEV_1) was estimated using a PiKo-1 electronic peak expiratory flow/FEV_1 meter (Ferraris Medical, Louiseville, CO, USA). Three flows were to be recorded twice each day, first thing on arising in the morning and again at bedtime, before taking breathing medications. For analyses, we used the maximum evening and morning FEV_1 values expressed as a percentage of the predicted value based on the equations derived by HANKINSON *et al.* [16]. We also analysed the diurnal (within-day) variation in lung function, which was expressed as 100 × (FEV_1 bedtime - FEV_1 morning)/FEV_1 morning.

Statistical analyses

All statistical analyses were performed using the SAS software package version 9.1 (SAS Institute, Cary, NC, USA). Differences in the distribution of children's characteristics between the two study periods were evaluated using the Chi-squared test. Daily mean concentrations of the ambient pollutants as well as temperature and relative humidity were calculated, and Pearson correlation coefficients were estimated to better understand their inter-relationships.

To estimate the mean pollution values 12 and 24 h before the FEV_1 measurement, we assumed that, on average, morning FEV_1 was performed at approximately 08:00 h and bedtime testing at 20:00 h. To evaluate temporal associations between ambient levels of air pollution and FEV_1, we calculated the mean of the hourly air pollution measures for the following periods preceding the FEV_1 measure: <12 h, 12 to <24 h and 0 to 24 h. A similar approach was used to create temporal metrics for temperature and relative humidity.

The results obtained from linear mixed models were expressed as the percentage change in median FEV_1 corresponding to an increase in the interquartile range (IQR) in air pollutant levels. The use of the IQR serves to standardise each pollutant, facilitating comparisons between the magnitude of effect of different pollutants [17].

We used an autoregressive covariance structure (AR1), which allows for a greater within-subject autocorrelation for FEV_1 measures taken more closely in time. We assumed a random intercept and a fixed slope. There were no statistically significant differences in the fit of the models using fixed slopes compared with random slopes.

The same approach was used to control for confounding in the logistic and linear mixed model. We adjusted symptoms and FEV_1 for all variables that were associated at a level of significance of $p \leqslant 0.15$ with both ambient measures of air pollution and FEV_1 (table 1). This list of potential confounders included the daily mean temperature, relative humidity, day of the week, number of hours spent on outdoor activities (<2 or ⩾2 h), sex and study period. Two pollutant models were used to characterise which pollutant was more strongly associated with FEV_1 after adjusting for the effects of other correlated ambient measures.

RESULTS

Characteristics of the participants are shown in table 1. During the first period of enrolment, a smaller percentage of participants were female (30.5%) compared with the second period (44.8%; $p<0.05$). Overall, 58.8% of children's households were reported as having a household pet. To be included in the study, all subjects had a history of ''ever had asthma'', and most (95.1%) reported that they still had asthma. Of the participants, 96.7% reported at least one respiratory symptom during the 28-day study period, but 42.3% did not report taking any asthma medication during this same time. Children in the first study group reported a mean of 2.2 h outside daily compared with 1.6 hours in the second group ($p<0.0001$).

For each child, we calculated the morning and bedtime FEV_1 % predicted averaged over their 28 days of study (table 2). The median values for both these measures were similar to the mean values (<2%), which were consistent with a near normal distribution. The diurnal change in FEV_1 from morning to evening, expressed as 100 × (FEV_1 bedtime - FEV_1 morning)/FEV_1 morning was 2.3%, whereas the median (IQR) change was only 0.4 (0.4–7.6)%. We assessed the effect of time on lung function to determine whether there was evidence of a learning effect. The variables time (number of days each subject was studied), study period (October–November, November–December) and time × study period were not significantly associated with FEV_1 (all p-values greater than 0.2).

Concentrations of air pollutants and IQRs were well below the US Environment Protection Agency ambient air quality guidelines for $PM_{2.5}$ of 35 $\mu g \cdot m^{-3}$ for a 24-h average and 15 $\mu g \cdot m^{-3}$ for an annual average [18]. In the present study, the 24-h mean was 7.8 $\mu g \cdot m^{-3}$ and the IQR was 6.0 $\mu g \cdot m^{-3}$ (table 3). O_3 decreased, SO_2 increased and $PM_{2.5}$ remained stable over the study period (fig. 1).

SO_2, NO_2 and $PM_{2.5}$ were positively correlated with each other, whereas ozone was negatively correlated with these

TABLE 1 Selected characteristics of the 182 participating children, by study period in Windsor (ON, Canada) in 2005

Characteristics	Study period		Overall	p-value#
	October 11–November 7	November 14–December 11		
Age yrs				
9–10	16 (16.8)	8 (9.2)	24 (13.2)	0.39
11	20 (21.1)	26 (29.9)	46 (25.3)	
12	26 (27.4)	33 (37.9)	59 (32.4)	
13–14	33 (34.7)	20 (23)	53 (29.1)	
Female	29 (30.5)	39 (44.8)	68 (37.4)	0.05
Caucasian	83 (87.4)	77 (88.5)	160 (87.9)	0.79
Has household pets	53 (55.8)	54 (62.1)	107 (58.8)	0.66
Currently has asthma	90 (94.7)	83 (95.4)	173 (95.1)	0.84
Respiratory symptoms during the study period				
None	5 (5.3)	1 (1.1)	6 (3.3)	0.20
Breathing	62 (65.3)	64 (73.6)	126 (69.2)	0.44
Chest tightness	52 (54.7)	57 (65.5)	109 (59.9)	0.27
Cough	84 (88.4)	83 (95.4)	167 (91.8)	0.20
Wheeze	56 (58.9)	59 (67.8)	115 (63.2)	0.38
Medication use during the study period				
Inhaled corticosteroid	36 (37.9)	32 (36.8)	68 (37.4)	0.88
Short acting β_2-agonist	33 (34.7)	31 (35.6)	64 (35.2)	0.90
Other asthma medication	20 (21.1)	13 (14.9)	33 (18.1)	0.29
No asthma medication	39 (41.1)	38 (43.7)	77 (42.3)	0.44
Total house income CDN$				
<35,000	10 (10.5)	7 (8)	17 (9.3)	0.95
35,000–80,000	25 (26.3)	23 (26.4)	48 (26.4)	
>80,000	24 (25.3)	22 (25.3)	46 (25.3)	
Unknown	36 (37.9)	35 (40.2)	71 (39)	
Daily outdoor activity ⩾2 h	53 (55.8)	23 (26.4)	76 (41.8)	0.00
Weight kg				
<39	29 (30.5)	23 (26.4)	52 (28.6)	0.56
39 to <52	31 (32.6)	35 (40.2)	66 (36.3)	
⩾52	35 (36.8)	29 (33.3)	64 (35.2)	
Height cm				
<147	26 (27.4)	26 (29.9)	52 (28.6)	0.16
147 to <157	42 (44.2)	27 (31.0)	69 (37.9)	
⩾157	27 (28.4)	34 (39.1)	61 (33.5)	
Total	95 (100)	87 (100)	182 (100)	

Data are presented as n (%), unless otherwise stated. #: for seasonal differences.

TABLE 2 Morning and evening forced expiratory volume in 1 s (FEV_1) expressed and diurnal FEV_1 change among 182 asthmatic children, by season during the study period

Variables	Mean±SD	1st quartile	Median	3rd quartile
FEV_1 % pred				
Morning	83.8±18.1	73.5	85.3	95.3
Evening	84.5±18.3	74.0	85.8	95.9
Diurnal FEV_1 change# %	2.28±17.4	-5.6	0.4	7.6

% pred: % predicted. #: expressed as 100×(FEV_1 bedtime - FEV_1 morning)/FEV_1 morning.

three pollutants (table 4). The strongest correlation between two pollutants was 0.68 ($p<0.0001$), which was observed with NO_2, and $PM_{2.5}$.

Bedtime FEV_1

Adjusted for daily mean temperature and relative humidity, day of the week, duration of outdoor activity, sex and study period, an IQR increase (6.0 $\mu g \cdot m^{-3}$) in the previous 24-h (20:00 h to 20:00 h) mean concentration of $PM_{2.5}$ was associated with a 0.54% (95% confidence interval (CI) 0.06–1.02) decrease in bedtime FEV_1 % predicted ($p=0.03$) (table 5). No statistically significant associations were found between bedtime FEV_1 and prior $PM_{2.5}$ concentrations averaged over 24–48 h, 0–48 h or 0–72 h before lung function was measured. We found no statistically significant associations between evening

TABLE 3 Frequency distribution of the daily 24-h mean concentrations of selected outdoor air pollutants and meteorological characteristics in Windsor (ON, Canada) between October 11 and December 11, 2005

Pollution/weather variable	Days	Mean±SD	25th percentile	Median	75th percentile	Interquartile range
SO_2 ppb	56	6.0±4.8	2.3	4.5	8.8	6.5
NO_2 ppb	56	19.1±6.0	14.5	19.8	24.3	9.8
O_3 ppb	56	14.1±6.0	8.8	13.0	17.8	9.0
O_{3max} ppb	56	27.2±8.6	21.8	27.0	32.8	11.0
$PM_{2.5}$ μg·m^{-3}	56	7.8±5.0	4.0	6.5	10.0	6.0
Temperature °C#	56	5.3±7.2	-1.9	6.6	11.1	13.0
Relative humidity %	56	67.0±8.6	60.2	67.4	71.8	11.6

O_{3max}: maximum ozone; $PM_{2.5}$: particulate matter <2.5 μm in diameter. #: data were obtained from Environment Canada's National Air Pollution Surveillance network.

FEV1 and NO_2, SO_2 and O_3. In two-pollutant models with SO_2, NO_2 or O_3, the $PM_{2.5}$ effect remained significant at $p<0.05$ (fig. 2).

Morning FEV1

We found no associations between morning FEV1 % predicted and pollutant concentrations with averaging times of 08:00 h on the day before to 08:00 h on the test day, 20:00 h to 08:00 h and 24:00 h to 08:00 h (overnight period). For the latter, adjusted mean interquartile increases in air pollution were associated with changes of 0.41 (95% CI -0.18–0.99) for SO_2, 0.09 (95% CI -0.25–0.43) for NO_2, -0.17 (95% CI -0.69–0.35) for O_3 and 0.28 (95% CI -0.12–0.68) for $PM_{2.5}$.

Diurnal change in FEV1

An interquartile increase in daytime $PM_{2.5}$ (6.5 μg·m^{-3}) averaged between 08:00 h and 20:00 h was associated with a 0.73% (95% CI 0.10–1.37) decrease in diurnal FEV1 change, expressed as 100×(FEV1 bedtime - FEV1 morning)/FEV1 morning ($p=0.024$) (table 6). No statistically significant association was found between diurnal FEV1 and $PM_{2.5}$ concentrations averaged 24–48 h, 0–48 h or 0–72 h before lung function was measured. Diurnal declines in FEV1 during the daytime were also associated with increases in daytime NO_2 ($p=0.024$) and SO_2 (0.036) (table 6). In two-pollutant models with SO_2, NO_2 or O_3, the $PM_{2.5}$ effect remained statistically significant ($p=0.016$) only with O_3 (fig. 3).

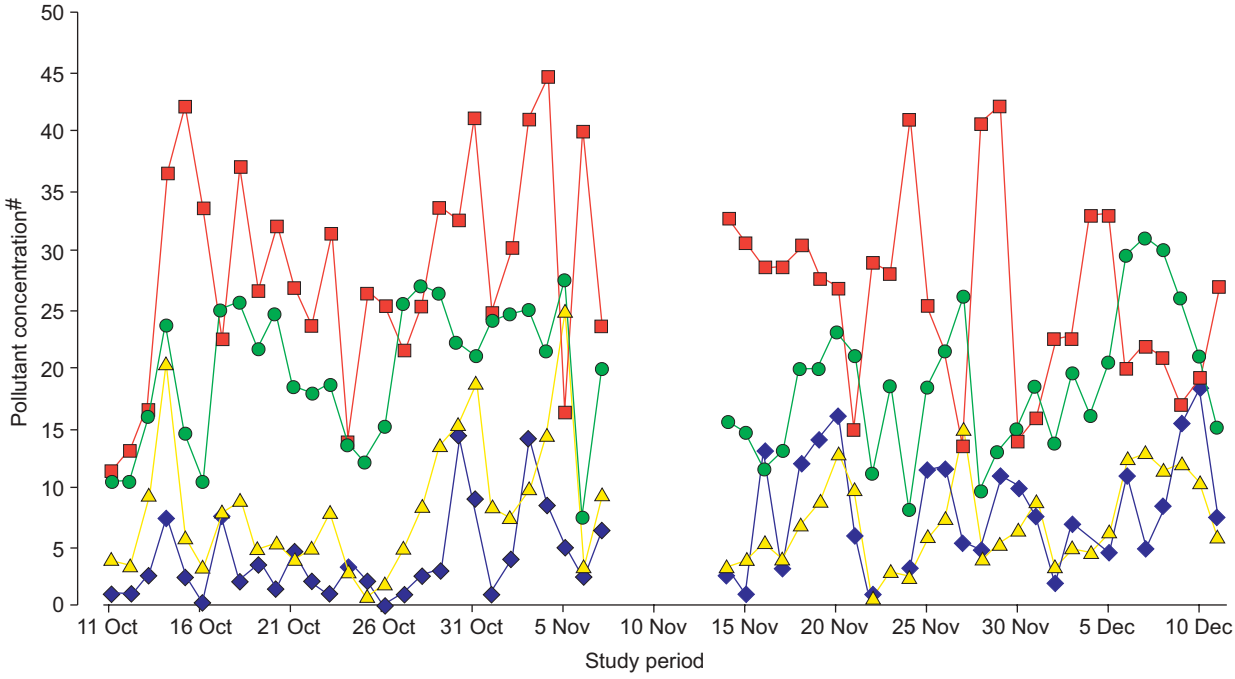

FIGURE 1. The 24-h mean concentrations of air pollutants during the study period October 11 to December 11, 2005, in Windsor, ON, Canada. ◆: sulphur dioxide; ●: nitrogen dioxide; ▲: particulate matter <2.5 μm in diameter ($PM_{2.5}$); ■: ozone. #: all pollutant concentrations are expressed in ppb except $PM_{2.5}$, which is in μg·m^{-3}.

TABLE 4 Pearson correlation coefficients (p-values) between daily mean measures of outdoor air pollution, temperature and relativity humidity in Windsor (ON, Canada) from October 11 to December 11, 2005

Pollutants	NO_2	O_3	O_{3max}	$PM_{2.5}$	Temperature	Relative humidity
SO_2	0.31 (0.02)	-0.05 (0.70)	-0.02 (0.90)	0.43 (<0.001)	-0.30 (0.03)	-0.19 (0.16)
NO_2	1	-0.50 (<0.001)	-0.18 (0.19)	0.68 (<0.001)	-0.11 (0.40)	0.00 (0.99)
O_3		1	0.81 (<0.0001)	-0.26 (0.05)	0.09 (0.51)	-0.55 (<0.001)
O_{3max}			1	-0.03 (0.82)	0.28 (0.04)	-0.51 (<0.001)
$PM_{2.5}$				1	0.17 (0.22)	0.14 (0.32)
Temperature					1	0.09 (0.51)

O_{3max}: maximum ozone; $PM_{2.5}$: particulate matter <2.5 μm in diameter.

Effect modification of the FEV1 response to air pollutants

For the association between FEV1 and $PM_{2.5}$, the first-order interaction term for corticosteroid use (on at least 50% of the study days *versus* less) was not significant, but power was poor with only 35 subjects reporting corticosteroids on at least half of the days. No significant differences in the FEV1–pollutant association were found for any of the pollutants and the following groups: male *versus* female subjects, those who spent at least 2 h outdoors daily *versus* those who spent less, and those whose baseline FEV1 was <85% *versus* ⩾85%. For the sex comparison, the change in FEV1 % predicted for an interquartile change in 24-h mean $PM_{2.5}$ was -0.54 (95% CI -1.13–0.04) for males and -0.54 (95% CI -1.37–0.28) for females. For baseline FEV1 level, the change in FEV1 % predicted was -0.88 (95% CI -1.53–-0.22) in the group with FEV1 ⩾85% and -0.19 (95% CI -0.89–0.52) in those with lower FEV1.

Other response variables

The presence or absence of difficulty breathing, cough, wheeze and chest tightness was indicated on the daily diary. The odds ratio for reporting chest tightness was 1.30 (1.06–1.58) for days with a mean SO_2 in the greatest quartile (⩾8.8 ppb) *versus* the lowest quartile (<2.3 ppb). No other similar contrasts between air pollutants and symptoms were significant at $p<0.05$. We did not find any significant effects of air pollutants on the peak expiratory flow measures but all point estimates were negative. For an interquartile increase in 24-h mean $PM_{2.5}$, percentage predicted peak flow decreased by -0.17 (95% CI -0.70–0.35).

DISCUSSION

Key findings

Among children with a history of asthma, bedtime lung function decreased with increased ambient concentrations of $PM_{2.5}$ even after adjustment for other pollutants. There was an approximate 0.5 percentage point decline in FEV1 % predicted for an interquartile increase in pollutant. FEV1 declines were associated with recent air pollution exposure, both the 24-h average before bedtime flows and the 12-h average during the day. Others have detected minimal or no effects within the past 24 h, although significant effects were detected from 5-day averaged particulate concentrations [9, 13]. Although both $PM_{2.5}$ and NO_2 may represent mobile combustion-related air pollution, two-pollutant models indicated that $PM_{2.5}$ had the most robust effect on lung function. The air pollution concentrations in Windsor were much lower than in many large US cities where particulate pollution has been associated with mortality [4]. We observed decreases in lung function at 24-h $PM_{2.5}$ concentrations approximately five times less than the US National Air Quality standard of 35 $\mu g \cdot m^{-3}$.

Significance of findings

We were able to detect an adverse biological effect on the lungs from air pollution at levels within currently accepted guidelines for public safety, suggesting that air pollution standards should be revisited. Although the FEV1 change during a clinically diagnosed asthma exacerbation is much larger than the 0.54% change observed in this study, the latter is of public health importance. All children in the community are exposed to the ambient air pollution, resulting in a large number of children affected. Assuming that there is a population distribution of asthma severity and of sensitivity to air pollution, children with severe disease and increased susceptibility to air pollution would be more likely to have a clinically important exacerbation of asthma on high-air pollution days. This argument is supported by the empiric evidence. NORRIS *et al.* [19] reported that a change in daily $PM_{2.5}$ of 11 $\mu g \cdot m^{-3}$ was associated with a relative risk estimate of 1.15 (95% CI 1.08–1.23) for a visit to the emergency department for asthma.

Strengths and limitations of the present study

We did not have objective measurements of asthma. The use of medication would be more likely among those with more severe asthma, but reported use was not an effect modifier, suggesting that asthma severity is not a determinant of the response to air pollution. A meta-analysis of air pollution studies in children did not find children with asthma to be more susceptible than children without diagnosed asthma, which also suggests that asthma severity is not a consistent effect modifier [20]. We do not know the reason for the stronger association between air pollution and bedtime flows compared with morning flows. Perhaps the children's air pollution ''dose'' would be less in the 12 h before the morning FEV1 measurement because they would be indoors and exposed to lower concentrations of ambient pollution. Also, minute ventilation would be less while sleeping than during wakefulness. We did not measure indoor air quality, but only children living in smoke-free homes were included. Associations between FEV1 and day-to-day changes in ambient air pollution would not be confounded by indoor air allergens

TABLE 5 Change in bedtime forced expiratory volume in 1 s (FEV_1) associated with an increase in daily air pollutant concentration averaged between 20:00 h the previous day and 20:00 h on the test day, among children with asthma in Windsor (ON, Canada) from October 11 to December 11, 2005#

Pollutants	Air pollution averaging time h	Change FEV_1 % pred	95% CI	p-value
NO_2	0–12	-0.10	-0.31–0.10	0.32
	12–24	-0.09	-0.41–0.23	0.58
	0–24	-0.24	-0.79–0.30	0.38
O_{3max}	0–12	0.31	-0.36–0.98	0.36
	12–24	-0.15	-0.61–0.32	0.54
	0–24	-0.13	-0.52–0.28	0.54
$PM_{2.5}$	0–12	-0.39	-0.79–0.01	0.06
	12–24	-0.32	-0.71–0.07	0.11
	0–24	-0.54	-1.02– -0.06	0.03
SO_2	0–12	-0.11	-0.64–0.41	0.67
	12–24	0.00	-0.60–0.60	0.99
	0–24	-0.09	-0.67–0.49	0.75

Associations were adjusted for daily mean temperature, relative humidity, day of the week, outdoor activity on the same day of at least 2 h and study period (October 11–November 7, 2005 and November 14–December 11, 2005). % pred: % predicted; CI: confidence interval; O_{3max}: maximum ozone; $PM_{2.5}$: particulate matter <2.5 μm in diameter. #: a mixed model was used with random intercept and fixed slope.

or irritants unless they changed on a day-to-day basis in concert with outdoor air pollution. JANSSEN *et al.* [21] studied the association between personal and outdoor concentrations of PM_{10} over time among 37 nonsmokers. The median Pearson correlation coefficient was 0.71 when not exposed to passive smoke, indicating that changes in outdoor levels reflect changes indoors. The forced vital capacity manoeuvre required for the FEV_1 measurement was observed only during the training period. Increased variability of the test could have reduced the power to detect a true association with air pollution. However, we did detect an adverse relation with particles. The Pearson correlation coefficient between morning and evening values was r=0.82 (p<0.0001), indicating a moderate degree of reproducibility.

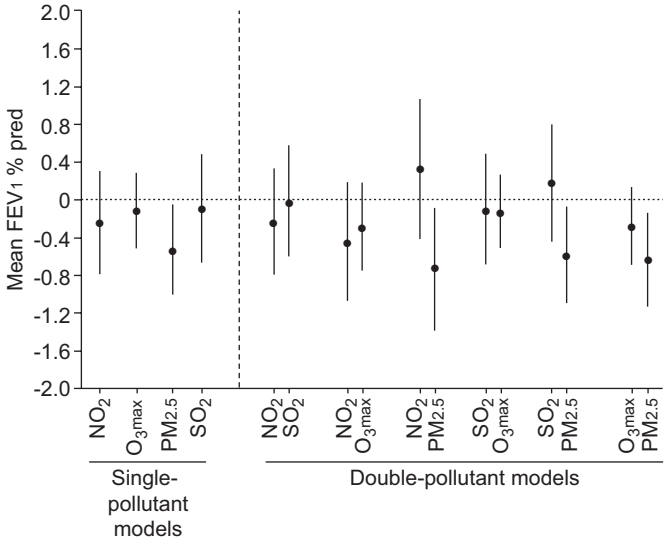

FIGURE 2. Mean (95% confidence interval) bedtime forced expiratory volume in 1 s (FEV_1) expressed as a percentage of predicted (% pred), associated with interquartile increase of air pollutant concentration. We used a mixed model with autoregressive covariance structure adjusted for daily mean temperature, relative humidity, day of the week and time for outdoor activity on the same day and study period (October 11–November 7, 2005 and November 14–December 11, 2005). $PM_{2.5}$: particulate matter <2.5 μm in diameter.

Comparison of the present results with previous panel studies of children with asthma

PETERS *et al.* [13] studied a panel of 82 Czech children with asthma between November 1991 and February 1992. An increase of 6.5 $mg \cdot m^{-3}$ in 5-day mean sulphate was associated with a 5.62 $L \cdot min^{-1}$ (95% CI -9.93– -1.30) decrease in peak flow. Another report from the Czech panel by PETERS *et al.* [13] showed significant associations between air pollution and peak flow during September 1991 and March 1992. MORTIMER *et al.* [10] also detected a negative association between ambient O_3 and morning peak flow among 846 children with a history of asthma recruited from eight US urban centres. Peak flow decreased by 0.59% (95% CI 0.13–1.05) for each 15 ppb increase in the 5-day moving average for O_3. In one panel study of 22 Hispanic children with asthma by DELFINO *et al.* [8], peak flows were not found to be associated with ambient ozone, NO_2 or SO_2. In another panel of 19 children with asthma by the same lead investigator, a 0.7% (95% CI -1.9–0.4) decrease in FEV_1 was associated with a 7.5 $\mu g \cdot m^{-3}$ increase in $PM_{2.5}$ averaged over the preceding 24 h at a central site [9]. Using a passive nephelometer for personal monitoring, the observed effect size was statistically significant with a -5.9% (95% CI -10.8–-1.0) change in FEV_1 for a 30 $\mu g \cdot m^{-3}$ change. Multiday moving averages for $PM_{2.5}$ resulted in larger effect sizes but these were not significantly different from those for the previous 24-h average. In our study, earlier changes were detected with significant effects seen between morning and evening lung function associated with same-day $PM_{2.5}$. The effect size per

TABLE 6 The diurnal change in forced expiratory volume in 1 s (FEV_1) associated with an interquartile increase in the daily air pollutant concentration averaged between 08:00 h and 20:00 h on the test day, among children with asthma in Windsor (ON, Canada) from October 11 to December 11, 2005[#]

Pollutants	Air pollution averaging time h	Diurnal change in FEV_1[¶]	95% CI	p-value
NO_2	0–12	-0.34	-0.64– -0.04	0.02
O_{3max}	0–12	0.75	-0.33–1.83	0.18
$PM_{2.5}$	0–12	-0.73	-1.37– -0.10	0.02
SO_2	0–12	-0.92	-1.78– -0.06	0.04

Associations are adjusted for daily mean temperature, relative humidity, day of the week, outdoor activity on the same day of at least 2 h and study period (Oct 11–Nov 7, Nov 14–Dec 11). CI, confidence interval; O_{3max}: maximum ozone; $PM_{2.5}$: particulate matter <2.5 μm in diameter. [#]: a mixed model was used with random intercept and fixed slope; [¶]: expressed as 100 × (FEV_1 bedtime - FEV_1 morning)/FEV_1.

$\mu g \cdot m^{-3}$ of $PM_{2.5}$ in our study was 0.08%, in close agreement with the 0.09% estimated in the study by DELFINO *et al.* [9] despite the mean $PM_{2.5}$ during the studies being 7.8 $\mu g \cdot m^{-3}$ and 10.3 $\mu g \cdot m^{-3}$, respectively. Whether exposed to higher or lower daily average concentrations of $PM_{2.5}$, it appears that equivalent changes in $PM_{2.5}$ have a similar magnitude of effect on lung function. TRENGA *et al.* [14] reported an adverse effect of centrally monitored $PM_{2.5}$ on the FEV_1 of children with asthma, only if they were not receiving anti-inflammatory medications. We did not detect a significant difference between those with and those without asthma medications. A study similar to ours took place in Detroit (MI, USA), which is connected to Windsor by the international Ambassador Bridge [22]. During six periods, each of 14 days, 86 children performed FEV_1 measurements using a portable device and recorded daily $PM_{2.5}$, PM_{10} and O_3. For the entire study group,

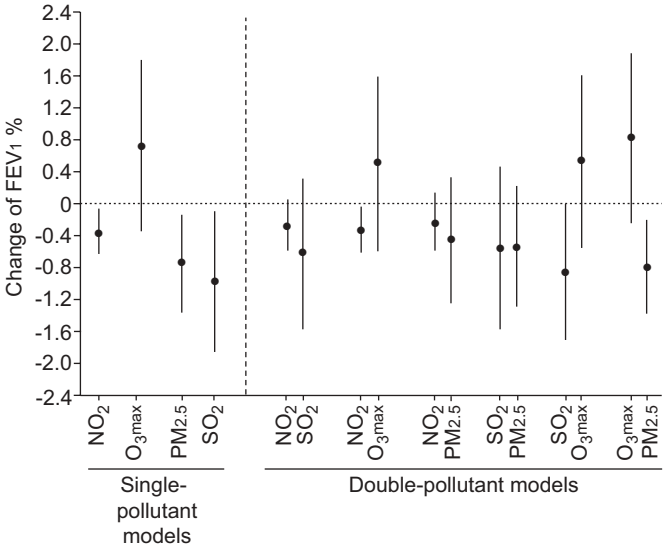

FIGURE 3. Mean (95% confidence interval) for diurnal change in forced expiratory volume in 1 s (FEV_1) associated with interquartile increases of air pollutant concentrations averaged from 08:00 h to 20:00 h on the test day. We used a mixed model with autoregressive covariance structure adjusted for daily mean temperature, relative humidity, day of the week and time for outdoor activity on the same day and study period (October 11–November 7, 2005 and November 14–December 11, 2005). $PM_{2.5}$: particulate matter <2.5 μm in diameter.

no significant associations were reported between FEV_1 and pollutants. Subgroup analyses restricted to those reporting maintenance inhaled corticosteroids, and using three different lags, revealed that four out of 24 associations tested were statistically significant between single pollutants and diurnal FEV_1 variation and/or lowest daily FEV_1. For the subgroup reporting upper respiratory symptoms, eight out of 24 associations with single pollutants were positive at $p \leqslant 0.05$. The air pollutant association with diurnal variation was positive, whereas it was inverse in our study. Whether or not an increase or decrease in diurnal variation is considered an adverse response depends on the reason. In our study, the morning flows did not change significantly with air pollution. Thus, the decreased diurnal variation was due to a smaller than expected FEV_1 improvement that normally occurs during the day and is unrelated to air pollution. A more recent study also compared air pollution levels with self-administered spirometry in a panel of children [23], in which 53 subjects with asthma were studied for 10 days. Peak hourly personal $PM_{2.5}$ (averaging 90 $\mu g \cdot m^{-3}$), but not ambient levels, were associated with decreased FEV_1. Maximum morning FEV_1 decreases were seen with approximate 8-h lags, and maximum afternoon and evening decreases were associated with 24-h lags. No air pollution effects were seen in a group of 16 children taking a β-agonist, theophylline, and/or an anti-cholinergic medication. In our study, with much lower concentrations of ambient $PM_{2.5}$ but 10 times the number of person-days of observation, we found maximum FEV_1 effects within a lag time of 24 h after exposure and also effects on diurnal variation within a 12-h period.

In summary, this study provides evidence that acute changes in urban air pollution, even within a day, at concentrations less than in many North American urban centres, worsens lung function in children with asthma.

STATEMENT OF INTEREST

None declared.

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REFERENCES

1 Health effects of outdoor air pollution. Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society. *Am J Respir Crit Care Med* 1996; 153: 3–50.
2 Brunekreef B, Holgate ST. Air pollution and health. *Lancet* 2002; 360: 1233–1242.
3 Dockery DW, Pope CA III. Outdoor particulates. *In*: Steenland K, Savitz DA, eds. Topics in Environmental Epidemiology. New York, Oxford University Press, 2002; pp. 119–166.
4 Samet JM, Dominici F, Curriero FC, *et al.* Fine particulate air pollution and mortality in 20 U.S. cities 1987–1994. *N Engl J Med* 2000; 343: 1742–1749.
5 Stieb DM, Judek S, Burnett RT. Meta-analysis of time-series studies of air pollution and morality: effects of gases and particles and the influence of cause of death, age, and season. *J Air Waste Manage Assoc* 2002; 52: 470–484.
6 Chan CC, Wu TH. Effects of ambient ozone exposure on mail carriers' peak expiratory flow rates. *Environ Health Perspect* 2005; 113: 735–738.
7 Delfino RJ. Association of asthma symptoms with peak particulate air pollution and effect modification by anti-inflammatory medication use. *Environ Health Perspect* 2002; 110: A607–A617.
8 Delfino RJ, Gong H Jr, Linn WS, *et al.* Asthma symptoms in Hispanic children and daily ambient exposures to toxic and criteria air pollutants. *Environ Health Perspect* 2003; 111: 647–656.
9 Delfino RJ, Penelope JEQ, Floro J, *et al.* Association of FEV_1 in asthmatic children with personal and microenvironmental exposure to airborne particulate matter. *Environ Health Perspect* 2004; 112: 932–941.
10 Mortimer KM, Neas LM, Dockery DW, *et al.* The effect of air pollution on inner-city children with asthma. *Eur Respir J* 2002; 19: 699–705.
11 Ostro B, Lipsett M, Mann J, *et al.* Air pollution and exacerbation of asthma in African-American children in Los Angeles. *Epidemiology* 2001; 12: 200–208.
12 Peters A, Dockery DW, Heinrich J, *et al.* Medication use modifies the health effects of particulate sulphate air pollution in children with asthma. *Environ Health Perspect* 1997; 105: 430–435.
13 Peters A, Dockery DW, Heinrich J, *et al.* Short-term effects of particulate air pollution on respiratory morbidity in asthmatic children. *Eur Respir J* 1997; 10: 872–879.
14 Trenga CA, Sullivan JH, Schildcrout JS, *et al.* Effect of particulate air pollution on lung function in adult and pediatric subjects in a Seattle panel study. *Chest* 2006; 129: 1614–1622.
15 The City of Windsor, Ontaria, Canada. Demographics. www.citywindsor.ca/002358.asp Last accessed: June 9, 2009.
16 Hankinson JL, Odencrantz JR, Fedan KB. Spirometric reference values from a sample of the general U.S. population. *Am J Respir Crit Care Med* 1999; 159: 179–187.
17 Lipfert FW, Wyzga RE. Statistical considerations in determining the health significance of constituents of airborne particulate matter. *J Air Waste Manage Assoc* 1999; 49: 182–191.
18 Fact sheet final revisions to the national ambient air quality standards for particle pollution (particulate matter). http://epa.gov/particles/pdfs/20060921_factsheet.pdf Last accessed: June 9, 2009.
19 Norris G, Young Pong SN, Koenig JQ, *et al.* An association between fine particles and asthma emergency department visits for children in Seattle. *Environ Health Perspect* 1999; 107: 489–493.
20 Ward DJ, Ayres JG. Particulate air pollution and panel studies in children: a systematic review. *Occup Environ Med* 2004; 61: e13.
21 Janssen NA, Hoek G, Brunekreef B, *et al.* Personal sampling of particles in adults: relation among personal, indoor, and outdoor air concentrations. *Am J Epidemiol* 1998; 147: 537–547.
22 Lewis TC, Robins TG, Dvonch JT, *et al.* Air pollution-associated changes in lung function among asthmatic children in Detroit. *Environ Health Perspect* 2005; 113: 1068–1075.
23 Delfino RJ, Staimer N, Tjoa T, *et al.* Personal and ambient air pollution exposures and lung function decrements in children with asthma. *Environ Health Perspect* 2008; 116: 550–558.