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Modification of Traffic-related Respiratory Response by Asthma Control in a Population of Car Commuters

Maria C. Mirabelli[a], **Rachel Golan**[c], **Roby Greenwald**[c], **Amit U. Raysoni**[c], **Fernando Holguin**[d], **Priya Kewada**[c], **Andrea Winquist**[c], **W. Dana Flanders**[b], and **Jeremy A. Sarnat**[c]

[a]Air Pollution and Respiratory Health Branch, Division of Environmental Hazards and Health Effects, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, GA

[b]Department of Epidemiology, Rollins School of Public Health, Emory University, Atlanta, GA

[c]Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA

[d]Division of Pulmonary, Allergy and Critical Care, Department of Medicine, University of Pittsburgh, Pittsburgh, PA

Abstract

Background—Effects of traffic-related exposures on respiratory health are well documented, but little information is available about whether asthma control influences individual susceptibility. We analyzed data from the Atlanta Commuter Exposure study to evaluate modification of associations between rush-hour commuting, in-vehicle air pollution, and selected respiratory health outcomes by asthma control status.

Methods—Between 2009 and 2011, 39 adults participated in Atlanta Commuter Exposure, and each conducted two scripted rush-hour highway commutes. In-vehicle particulate components were measured during all commutes. Among adults with asthma, we evaluated asthma control by questionnaire and spirometry. Exhaled nitric oxide, forced expiratory volume in 1 second (FEV_1), and other metrics of respiratory health were measured precommute and 0, 1, 2, and 3 hours postcommute. We used mixed effects linear regression to evaluate associations between commute-related exposures and postcommute changes in metrics of respiratory health by level of asthma control.

Correspondence: Maria C. Mirabelli, Air Pollution and Respiratory Health Branch, National Center for Environmental Health, Centers for Disease Control and Prevention, 4770 Buford Hwy NE, Building 106, Mailstop F-60, Atlanta, GA 30341. zif7@cdc.gov..

The ACE-1 study was developed and implemented by Drs. Sarnat, Flanders, Golan, Greenwald, Raysoni, Winquist, and Ms. Kewada. Dr. Mirabelli developed the analysis plan, analyzed the data, and led the writing for this paper. All authors reviewed interim results, contributed to the interpretation of the data, and approved the final paper for submission.

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

The authors report no conflicts of interest.

Results—We observed increased exhaled nitric oxide across all levels of asthma control compared with precommute measurements, with largest postcommute increases observed among participants with below-median asthma control (2 hours postcommute: 14.6% [95% confidence interval {CI} = 5.7, 24.2]; 3 hours postcommute: 19.5% [95% CI = 7.8, 32.5]). No associations between in-vehicle pollutants and percent of predicted FEV_1 were observed, although higher $PM_{2.5}$ was associated with lower FEV_1 % predicted among participants with below-median asthma control (3 hours postcommute: −7.2 [95% CI = −11.8, −2.7]).

Conclusions—Level of asthma control may influence respiratory response to in-vehicle exposures experienced during rush-hour commuting.

Individuals who commute by car are exposed to a mixture of exposures that includes particulate and gaseous pollutants, noise, and stress.[1] In-vehicle measurements of organic and inorganic particulate matter components indicate that drivers and passengers are exposed to exhaust, regardless of whether they use vehicle air filters or drive with the windows closed.[2] The effects of traffic-related air pollution on respiratory health, including on respiratory health of individuals with asthma, are well documented.[3-5] However, little information is available about the contribution of asthma to individual susceptibility or whether any such susceptibility may be affected by level of asthma control.

The Atlanta Commuter Exposure (ACE-1) pilot study was initiated in 2009 to evaluate associations between in-vehicle air pollutant mixtures and cardiorespiratory health responses among rush-hour automobile commuters. Recent findings from the ACE-1 study suggest that a 2-hour commute during morning rush-hour traffic is associated with increased pulmonary inflammation and reduced measures of heart-rate variability.[6] Increased concentrations of exhaled nitric oxide (NO) observed postcommute suggest that traffic-related exposures may lead to short-term inflammation in the lung. Variation in the magnitude of the responses among individuals with asthma may reflect differences in asthma phenotype or level of asthma control.[6] The ACE-1 study provides a unique opportunity to further investigate the extent to which observed associations between rush-hour automobile commuting, in-vehicle exposures, and respiratory health outcomes are modified by one's level of asthma control using a quasi-experimental study design to observe respiratory health outcomes before and after a 2-hour commute. Improving our understanding of the role of asthma control in modifying the impact of traffic exposures may provide valuable information about the susceptibility of adults with asthma, who commute by car during rush hour. Such improvements in our understanding of how asthma control affects susceptibility to adverse health effects of traffic-related exposures may have implications for the management of asthma, particularly for persons routinely exposed to traffic.

METHODS

Atlanta Commuter Exposure Study

We conducted an epidemiologic analysis using data collected for the ACE-1 pilot panel study.[2,6]

The ACE-1 study was conducted between December 2009 and June 2011 when 21 adults with self-reported asthma and 21 adults without self-reported asthma used their private vehicles to drive a scripted 2-hour commute along heavily used commuting roadways in the metropolitan Atlanta area.[6] The ACE-1 study protocol excluded a priori all potential study participants who reported the following: smoking, living in a home with a smoker, pregnancy, diabetes, previous myocardial infarction, implantable cardioverter-defibrillators or pacemakers, use of digoxin or beta blockers for treatment of hypertension or arrhythmias, or pulmonary disease other than asthma. We also excluded individuals with forced expiratory volume in 1 second (FEV_1) lower than 70% of age-, race-, and sex-specific predicted FEV_1,[7] which was assessed using precommute spirometry. Participants were recruited largely by word of mouth and flyers posted on the Emory University and Centers for Disease Control and Prevention campuses.[6] At the beginning of the study, all participants completed questionnaires to provide demographic and health-related information. Participants completed physical examinations pre- and postcommute. All commutes were conducted between 7:00 A.M. and 9:00 A.M. and began at the environmental health laboratory of the Rollins School of Public Health at Emory University. We excluded data from three participants who did not complete the questionnaire items used to categorize asthma control. Three participants withdrew from the study before completing the second study commute and the remaining 36 each completed two scripted commutes. Our final analyses were conducted using data collected from 39 participants and 75 commutes (Figure 1). The ACE-1 study protocol and materials were approved by the Institutional Review Board of the Rollins School of Public Health at Emory University. Office of Management and Budget approval was obtained by the Centers for Disease Control and Prevention (Control No. 0920-0859). All participants provided written informed consent.

Traffic-related Exposures

As in previous analyses,[6] traffic-related exposures were evaluated using two methods. First, we considered the entire 2-hour commute a complete exposure (i.e., “commute-as-exposure” models) and compared health measurements collected before the exposure (precommute) to those collected after the exposure (0, 1, 2, and 3 hours postcommute). Second, we assessed pollutant exposures during the commutes using 2-hour means of in-vehicle measurements of particulate matter ≤2.5 micrometers in diameter ($PM_{2.5}$), particle number concentration, and the following $PM_{2.5}$ components: elemental carbon, organic carbon, water-soluble organic carbon, particle-bound polycyclic aromatic hydrocarbons (PAHs), *n*-alkanes, and particulate iron (i.e., “pollutant-as-exposure” models). Pollutant data collection protocols, analytic methods, and data quality have been described in detail elsewhere.[2,6] A previously published matrix of Pearson correlation coefficients indicating correlations of the in-vehicle particulate components[6] also provides information about correlations in the data used for this analysis.

Respiratory Health Metrics

The concentration of exhaled NO in exhaled breath was measured using a portable NIOX MINO analyzer (Aerocrine, New Providence, NJ). The concentration of malondialdehyde in exhaled breath condensate was measured using high-performance liquid chromatography to assess the progression of airway lipid peroxidation reactions.[6,8] Spirometry was conducted

using OHD KoKo spirometers (Occupational Health Dynamics, Birmingham, AL). Spirometry measurements used in this analysis include FEV_1, forced vital capacity (FVC), and forced expiratory flow between 25% and 75% of vital capacity ($FEF_{25–75}$). Percentage of predicted values of FEV_1, FVC, and $FEF_{25–75}$ were calculated using standard reference equations published by Hankinson et al.[7] We measured exhaled NO, malondialdehyde, and spirometry precommute, immediately postcommute, and 1, 2, and 3 hours after the commute using methods described previously.[2,6]

Level of Asthma Control

For participants with asthma, levels of asthma control were evaluated using the seven-item Asthma Control Questionnaire.[9] The Asthma Control Questionnaire was adapted to collect information about experiences during the 3 months before data collection (e.g., “on average, during the past 3 months, how often were you woken by your asthma during the night?”). For six of the seven questionnaire items, respondents selected an answer along a seven-point scale that ranged from zero (e.g., “never”) to six (e.g., “unable to sleep because of asthma”). The seventh item was assigned using the percentage of predicted FEV_1 values and a similar range of values from zero, for >95% predicted, to six, for <50% predicted.[9] Percent of predicted FEV_1 values were computed using spirometry performed before the first study commute. For each participant with asthma, Asthma Control Questionnaire scores were calculated as the mean of the values assigned to the seven individual questionnaire items.[9] Scores were then categorized as lower or higher than the median of the distribution of scores of the 18 participants with asthma (median: 0.79; mean: 1.09 [SD: 0.71]). Because lower Asthma Control Questionnaire scores convey better levels of asthma control, scores ≤0.79 are hereafter referred to as “above-median asthma control” and scores >0.79 as “below-median asthma control.”

Statistical Analysis

We conducted descriptive analyses to summarize the demographic characteristics of the study population, commutes completed, and in-vehicle pollutants measured during completed study commutes. To assess the relations between the rush-hour commute exposures and biomarkers of respiratory health, we used mixed effects linear regression with random-participant intercepts, which accounted for the correlations between data collected at multiple time points per participant.

For commute-as-exposure analyses in which the entire 2-hour commute is considered a complete exposure, we compared metrics of respiratory health measured after the commute (0, 1, 2, and 3 hours postcommute) to values measured precommute using separate models for each postcommute time point. In these models, each mixed effects linear regression model was specified with a random intercept for each participant and a spatial power covariance structure.[10] The commute-as-exposure models that we used were variations of the generalized linear mixed model $E(Y) = \exp(\alpha + \Sigma\beta x)$ that modeled pre- and postcommute measurements of the respiratory health metric, precommute level of asthma control, and interaction terms to evaluate modification of the effect of the time point by level of asthma control, with no asthma considered the referent category. For models of the effect

of the commute on exhaled NO and malondialdehyde, we transformed concentrations using a natural log transformation, yielding a final model:

$$\begin{aligned} ln\left(Y_{ij}\right) = \quad & \beta_0 + \beta_1 \cdot time_{ij} + \beta_2 \cdot score1_{i0} \\ & + \beta_3 \cdot score2_{i0} + \beta_4 \cdot time_{ij} \cdot score1_{i0} \\ & + \beta_5 \cdot time_{ij} \cdot score2_{i0} + \left(u_i + e_{ij}\right), \end{aligned} \quad (1)$$

in which Y_{ij} is exhaled NO or malondialdehyde for individual i at time j, $time_{ij}$ is the postcommute indicator variable, $score1_{i0}$ indicates above-median asthma control, $score2_{i0}$ indicates below-median asthma control, β_0 is the fixed intercept term, and u_i is the random intercept term ~N(0, $\sigma^2_{\mu 0}$). Associations generated using Equation 1 are presented as the percentage change in biomarker concentrations at each postcommute time point relative to precommute concentrations. Percentage changes were calculated as $(\exp(\beta_1) - 1) \cdot 100$ among individuals without asthma, $(\exp(\beta_1 + \beta_4) - 1)\ 100$ among individuals with above-median asthma control, and $((\exp(\beta_1 + \beta_5) - 1) \cdot 100$ among individuals with below-median asthma control. Positive percentage changes in exhaled NO and malondialdehyde indicate adverse respiratory response among individuals with and without asthma. Associations generated using percentages of age-, race-, and sex-specific predicted spirometry values as dependent variables were based on similar models in which spirometry outcomes were not transformed:

$$\begin{aligned} Y_{ij} = \quad & \beta_0 + \beta_1 \cdot time_{ij} + \beta_2 \cdot score1_{i0} \\ & + \beta_3 \cdot score2_{i0} + \beta_4 \cdot time_{ij} \cdot score1_{i0} \\ & + \beta_5 \cdot time_{ij} \cdot score2_{i0} + \left(u_i + e_{ij}\right) \end{aligned} \quad (2)$$

For these models, associations are presented as mean changes in percent predicted values at each postcommute time point relative to precommute percent predicted values. Changes in percent predicted values were calculated as a linear combination of parameter estimates: ft among individuals without asthma, $\beta_1 + \beta_4$ among individuals with above-median asthma control, and $\beta_1 + \beta_5$ among individuals with below-median asthma control. For these results, negative changes in percent of predicted spirometry values indicate adverse respiratory response among individuals with and without asthma.

For pollutant-as-exposure analyses in which we evaluated effect of in-vehicle pollutant measurements, the mixed effects linear regression models were similarly specified with a random intercept for each participant and a spatial power covariance structure and interaction terms to evaluate modification of the effect of the in-vehicle pollutant exposures by level of asthma control. Estimates of the associations between each pollutant and respiratory health metric were generated using separate models for each postcommute time point and we estimated differences between post- and precommute measurements, controlling for precommute measurements, by adapting Equations 1 and 2 to the following, respectively:

$$\begin{aligned} \Delta ln\left(Y_{ij}\right) = \quad & \beta_0 + \beta_1 \cdot pollutant_{ij} + \beta_2 \cdot score1_{i0} \\ & + \beta_3 \cdot score2_{i0} + \beta_4 \cdot pollutant_{ij} \cdot score1_{i0} \\ & + \beta_5 \cdot pollutant_{ij} \cdot score2_{i0} + \beta_6 \cdot ln\left(Y_{i0}\right) + \left(u_i + e_{ij}\right) \end{aligned} \quad (3)$$

$$\Delta Y_{ij} = \beta_0 + \beta_1 \cdot pollutant_{ij} + \beta_2 \cdot score1_{i0} + \beta_3 \cdot score2_{i0} + \beta_4 \cdot pollutant_{ij} \cdot score1_{i0} + \beta_5 \cdot pollutant_{ij} \cdot score2_{i0} + \beta_6 \cdot Y_{i0} + (u_i + e_{ij}) \quad (4)$$

In equations 3 and 4, $\Delta\ln(Y_{ij})$ and $\Delta(Y_{ij})$ represent the differences between measurements at post- and precommute time points (i.e., $\ln(Y_{ij})$ - $\ln(Y_{i0})$ and Y_{ij} - Y_{i0} respectively). Associations are presented as the percentage change in biomarkers of inflammation or changes in the percent predicted at each postcommute time point associated with an interquartile range increase in pollutant concentration. For all commute-as-exposure and pollutant-as-exposure models, we evaluated the contributions of the interaction terms to the fit of the model to the data by contasting −2 Log Likelihood values of the models described above to those of models from which the two interaction terms were excluded. *P* values for interaction (P_{int}) <0.10 are presented.

Following our main analyses, we conducted sensitivity analyses to evaluate the impact on our results of our decision to dichotomize the distribution of Asthma Control Questionnaire scores at 0.79, the median score in our study population and therefore a cut-point that optimized the distribution of the observations in our study. These sensitivity analyses were conducted using identical models as those described above and an Asthma Control Questionnaire score cut-point of 1.00, where scores ≤1.00 were categorized as "well-controlled" and >1.00 were categorized as "not well-controlled."[11] For this sensitivity analysis, we selected the cut-point of 1.00 on the basis of a crossover point between well-controlled and not well-controlled reported by Juniper et al.[11] All analyses were performed using SAS version 9.3 (SAS Institute Inc., Cary, NC), and results are presented with 95% confidence intervals (CIs).

RESULTS

Characteristics of the 39 ACE-1 study participants included in our analysis are shown in Table 1 for participants without asthma and, for participants with asthma, by level of asthma control. Participants without asthma were older (mean: 35 years) than participants with above- (mean: 35 years) or below- (mean: 31 years) median asthma control. Participants' Asthma Control Questionnaire scores ranged from 0.29 to 0.71 among individuals categorized as having above-median level asthma control and from 0.86 to 2.43 among those categorized as having below-median asthma control (Table 2). Measured precommute, exhaled NO concentrations were lower among participants without asthma (mean [SD]: 22.7 [12.4] ppb) than those with asthma (mean [SD]: 43.2 [37.8] ppb, data not shown). Mean precommute malondialdehyde concentrations were also lower among participants without asthma (0.08 [SD: 0.03] μmol·L^{-1}) than participants with asthma (0.12 [SD: 0.07] μmol·L^{-1}, data not shown). Mean values of the spirometry measures were higher among participants with above-median levels of asthma control than those with below-median asthma control or without asthma.

Table 3 shows concentrations of $PM_{2.5}$ and its components measured inside participants' vehicles during the study commutes. Mean concentrations of $PM_{2.5}$, elemental carbon,

organic carbon, and particle-bound PAH were higher in vehicles driven by participants without asthma than in vehicles driven by participants with asthma; for these five pollutants, differences between the groups ranged from 18% higher for particle-bound PAH to 94% higher for elemental carbon. As described previously,[6] the observed differences in pollutant concentrations measured in vehicles driven by participants with and participants without asthma are believed to be random with respect to with the recruitment of participants and participant asthma status. Additional description of the concentrations of these in-vehicle pollutants have been published previously.[2]

Results of commute-as-exposure models in which we evaluated postcommute changes in exhaled NO, malondial-dehyde and percents of predicted FEV_1, FVC, and $FEF_{25–75}$ values are shown in Figure 2. Relative to precommute measurements, exhaled NO concentrations were higher at all postcommute time points. The largest postcommute increases in exhaled NO were observed among participants with below-median asthma control (0 hour: 9.1% [95% Cl = 2.1, 16.6]; 1 hour: 17.9% [95% Cl = 8.9, 27.7]; 2 hours: 14.6% [95% Cl = 5.7, 24.2]; 3 hours: 19.5 [95% Cl = 7.8, 32.5]). We observed no postcommute changes in malondialdehyde. Postcommute FEV_1 % predicted and $FEF_{25–75}$ % predicted were slightly elevated relative to precommute measurements, particularly among participants with below-median asthma control.

Associations between in-vehicle pollutant concentrations and exhaled NO concentrations measured pre- versus postcommute were generally stronger among individuals with below-median asthma control than among individuals without asthma or with above-median asthma control (Figure 3). Among respondents with below-median asthma control, an increase in $PM_{2.5}$ equal to the interquartile range of in-vehicle measurements was associated with a 22.6% (95% Cl = 5.5, 42.4) increase in exhaled NO measured 3 hours postcommute. Despite imprecision in estimates of the percent changes in malondialdehyde associated with in-vehicle pollutant measurements, we observed differences across asthma control categories at postcommute time points; these results are available in Online Supplement Figure S1 (http://links.lww.com/EDE/A906).

Pollutant-as-exposure models in which changes in FEV_1 % predicted were regressed on in-vehicle pollutant concentrations are shown in Figure 4. In contrast to the commute-as-exposure results, interquartile range increases in pollutant concentrations and FEV_1 % predicted were not consistently associated with elevations in FEV_1 % predicted 3 hours postcommute. Although the estimates were imprecise and largely consistent with the null, higher $PM_{2.5}$ levels were associated with declines in FEV_1 % predicted, particularly at the 2- and 3-hour-postcommute time points and among participants with above-median asthma control (2 hours: −0.8% [95% CI = −4.8, 3.2]; 3 hours: −3.1 [95% CI = −8.3, 2.1]) and below-median asthma control (2 hours: −3.1% [95% CI = 6.8, 0.6]; 3 hours: −7.2 [95% CI = −11.8, −2.7]). Estimates of the associations of in-vehicle pollutant measurements with changes in FVc % predicted and $FEF_{25–75}$ % predicted are available in Online Supplement Figures S2 and S3, respectively (http://links.lww.com/EDE/A906). Overall, estimates of these associations were imprecise, although greater decrements in lung function were generally observed among participant with below-median levels of asthma control than

participants with above-median asthma control or no asthma, and the observed differences generally increased with increasing time after the study commute.

Our sensitivity analyses, designed to evaluate the impact of changing the cut-point used to categorize Asthma Control Questionnaire scores from 0.79 to 1.00, resulted in a reclassification of two people and a final categorization of 21 individuals without asthma, 11 with well-controlled asthma, and seven with asthma not well controlled. Overall, estimates generated in these analyses were similar in magnitude and direction to those generated in our main analyses, though recategorization affected the precision of the estimates (data not shown).

DISCUSSION

Using data from the ACE-1 study, we examined asthma control as a potential modifier of the associations between exposures measured in personal passenger vehicles during morning rush-hour commutes and changes in exhaled NO, malondialdehyde, and three spirometric measures of pulmonary function. Despite the small number of participants in our study, these results identify variation in the associations between commuting and shortterm respiratory response by the presence of asthma and, among those with asthma, by level of asthma control and provide initial evidence about the influence that asthma control may have on susceptibility to adverse respiratory health outcomes after traffic-related exposures experienced during typical morning rush-hour commutes. Results of analyses of in-vehicle pollutant components as exposures further suggest that postcommute responses may be triggered by specific in-vehicle pollutant exposures. Estimated changes in spirometry generated from our pollutant-as-exposure models are notable for their contrasts with estimates of changes in spirometry when we examined the commute as a complete exposure, which did not indicate pre- to postcommute declines in FEV_P FVC, or $FEF_{25–75}$. However, for several pollutants, decrements in these lung function metrics were observed at higher levels of in-vehicle pollutants (e.g., $PM_{2.5}$), with the observed decrements largely driven by response among individuals with below-median asthma control. In our previous analysis in which asthma control was not considered, we did not observe pollutant-specific associations with lung function.[6] In this analysis, although no single pollutant was consistently associated with changes in our selected respiratory health outcomes, several ubiquitous particulate components were associated with measurable responses in one or more of the end points. For panel studies such as ours, this is not uncommon; and neither our study nor the few other published studies that have used similar research designs have conclusively identified a single causal pollutant or class of pollutants.[12,13] Nonetheless, findings from the AcE-1 study extend our initial observations about the role of specific chemical pollutants in eliciting respiratory response[6] and our current understanding of the potential respiratory health impacts of traffic-related air pollutants[3,4,12] by highlighting the potential influence of asthma control on individual-level susceptibility

Short-term response to air pollution has been investigated in previous epidemiologic studies, including a study of respiratory response after 2-hour walks along a busy London street (Oxford Street) and through nearby Hyde Park,[12] a study of health effects after a 2-hour car ride in which investigators reported modification of the effect of the highway exposure on

endothelial derived No by diabetic status,[14] and an evaluation of associations between urban air quality and weekly Asthma control Questionnaire scores among 36 school-age children that reported a suggestion of positive associations between $PM_{2.5}$ and asthma control Questionnaire score.[15] after an evaluation of exhaled NO response among school children affected by air pollution before and during the 2008 Olympics in Beijing, Lin et al.[16] reported robust associations between $PM_{2.5}$ and exhaled NO, which were, broadly speaking, modestly stronger among children with asthma than among children without asthma. From a case-crossover study in which participants completed 2-hour walks along the heavily trafficked Oxford Street and in Hyde Park, London, McCreanor et al.[12] reported larger respiratory responses after the Oxford Street route than after the Hyde Park route and among participants with moderate asthma than among those with mild asthma; such differences in respiratory response were observed up to 7 hours after the start of the exposure and, in some cases, even 22 hours after the start of the exposure. In contrast, the follow-up in our study was limited to 3 hours postcommute and therefore cannot be used to draw conclusions about the role of asthma control in observed respiratory health effects of longer duration. Despite this limitation, our findings contribute to a growing body of literature about the role of individual-level susceptibility to ambient air quality exposures.

The effects of exposure to ambient air pollution, including to traffic-related air pollution, on the airways are well documented to include changes in biomarkers of oxidative stress and inflammation and decrements in lung function.[17-21] Our finding of elevated exhaled NO concentrations at all postcommute time points and variation across levels of asthma control support the hypothesis that acute inflammatory response may be modified by asthma control. Results from our pollutant-as-exposure models further suggest that the inflammatory response, including variation by level of asthma control, may be differentially affected by specific particulate components. In contrast, our results do not support this hypothesis for malondialdehyde, a biomarker of oxidative stress, and results for spirometric measurements are inconsistent. Evaluated in total, differences between effects generated using commute-as-exposure models and pollutant-as-exposure models may suggest that individual particulate components may not affect the same biologic pathways to respiratory response. Indeed, although individual commuters have little control over the outdoor air quality and particulate components present during morning rush hour, evidence that asthma control may affect individual susceptibility may provide commuters who have asthma and their health care providers an opportunity to lessen the extent to which their asthma may be exacerbated by their daily activities.

In this analysis, we used mixed-effects linear regression models to account for correlations in outcomes measured in the same individuals over time and in other unmeasured, individual-level characteristics. Our ability to construct similar models for these analyses as those developed by Sarnat et al.[6] is a notable strength of our analysis. Our study population included 18 participants with asthma and 21 participants without asthma, 17 and 19 of whom, respectively, completed two study commutes each. Despite measurements provided by each participant at up to 10 time points, the relatively small number of observations in our analysis, and missing data for several measures limit our ability to conduct additional analysis to explore the roles of body mass index, medication use, general health status, automobile characteristics, in-vehicle ventilation, temperature, humidity, rainfall, season,

multipollutant exposures or other factors that may influence susceptibility to in-vehicle air pollutants.[3] additional information about these and other factors may further improve our ability to draw conclusions about the extent to which relations between commuting-related exposures and respiratory health outcomes are modified by individual-level and environmental factors. In particular, additional information about the types and frequencies of medications used by individuals with asthma may improve our understanding of how asthma medications affect individual-level susceptibility to traffic-related exposures. The small size of our study precluded evaluation of the extent to which the effect modification observed in our study may have been driven by individual components or clusters of components of the seven-item asthma control Questionnaire. Despite the lack of information about medication use, the small number of observations in the ACE-1 study, and the limited statistical power to detect exposure–outcome associations, the associations generated by our analysis suggest effect measure modification by level of asthma control. The extent to which demographic, socioeconomic, health, and other characteristics of the ACE-1 study population differ from those of the general population limits our ability to generalize our findings to populations external to the ACE-1 cohort.

Individual-level characteristics, including asthma status and six of the seven components of the Asthma Control Questionnaire, were self-reported by study participants at the beginning of the study. If participants experienced changes in their asthma status, symptoms, or level of control between the time of enrolling in the study and the time of completing the second study commute, our results may not reflect the true extent to which level of asthma control affects susceptibility to commute-related exposures. Despite including FEV_1 % predicted as one element of the Asthma control Questionnaire, our analyses included evaluation of the effect of commute-related exposures on FEV_1 % predicted as an independent variable. Because the Asthma control Questionnaire and spirometry data were collected before each participant's first commute, the FEV_1 component of the Asthma Control Questionnaire and the spirometry outcomes in our analysis are correlated (e.g., Pearson correlation coefficient for correlation between Asthma control Questionnaire score and FEV_1 % predicted = −0.43; $P = 0.08$). In our commute-as-exposure analyses, we evaluated changes in lung function relative to precommute measurements to minimize the impact of precommute measures on our results. In these models, lower precommute measures of spirometry in the group with below-median asthma control could plausibly limit the magnitude of potential postcommute declines in each of the three lung function measurements. In fact, our commute-as-exposure models generated estimated increases in postcommute FEV_1 and $FEF_{25–75}$ among participants with below-median asthma control. The interpretation of these improvements as an indicator that participants' abilities to perform forced exhalation maneuvers may improve over time is not supported by previous research designed to evaluate learning effects and variation in spirometry among healthy adults.[22] The objective measures of respiratory health measured in the AcE-1 study strengthen the interpretation of our findings.

As noted previously,[6] pollutant concentrations varied across the three asthma control categories. For six of the eight $PM_{2.5}$ components included in our analysis, mean and median concentrations were higher during commutes completed by individuals without asthma. If the relation between the measured pollutants and metrics of respiratory health

evaluated in our study is not linear, but instead has a threshold level of effect, for example, then the differences in pollutant concentrations during commutes completed by participants without asthma and those present during commutes completed by the remaining participants may have meaningfully affected our findings. In such a scenario, the observed exposure differences may result in an underestimation of the true differences between the exposure–outcome relations of participants with asthma and those without asthma. The lack of days without in-vehicle exposures with which to compare our data is a notable limitation. However, the relatively large number of distinct study commutes (n = 75) is a strength of our study.

Overall, and in combination with previous findings,[6] these results extend our understanding of the effect of traffic-related exposures on respiratory health by evaluating potential short-term and adverse impacts on metrics of respiratory health. These findings may be of interest to health care providers, public health personnel, commuters, and others interested in attenuating adverse health effects experienced by individuals with asthma.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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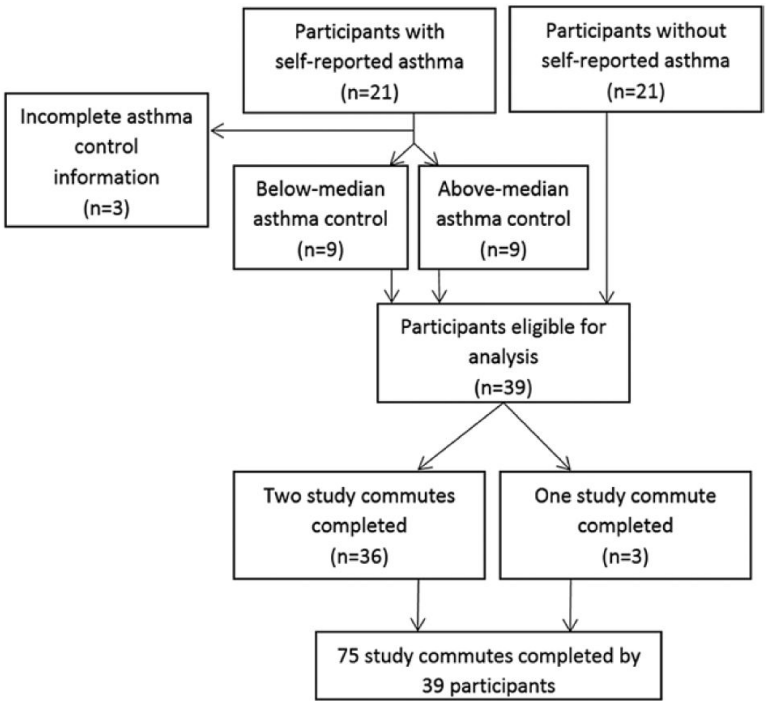

FIGURE 1.
Selection of the final ACE-1 study population for analysis.

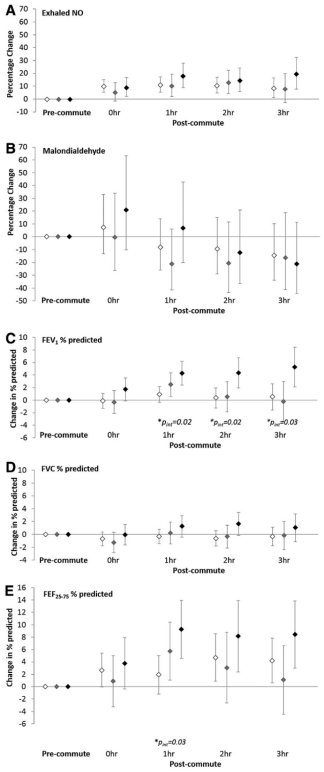

FIGURE 2.

Change (with 95% CI) in exhaled NO, malondialde-hyde, FEV_1 % predicted, FVC % predicted, and $FEF_{25–75}$ % predicted among ACE-1 study participants. Postcommute changes shown are relative to precommute concentrations among participants without asthma (*white diamond*), above-median asthma control (*gray diamond*), and below-median asthma control (*black diamond*). *Asterisks P* value for interaction (P_{int}) <0.10.

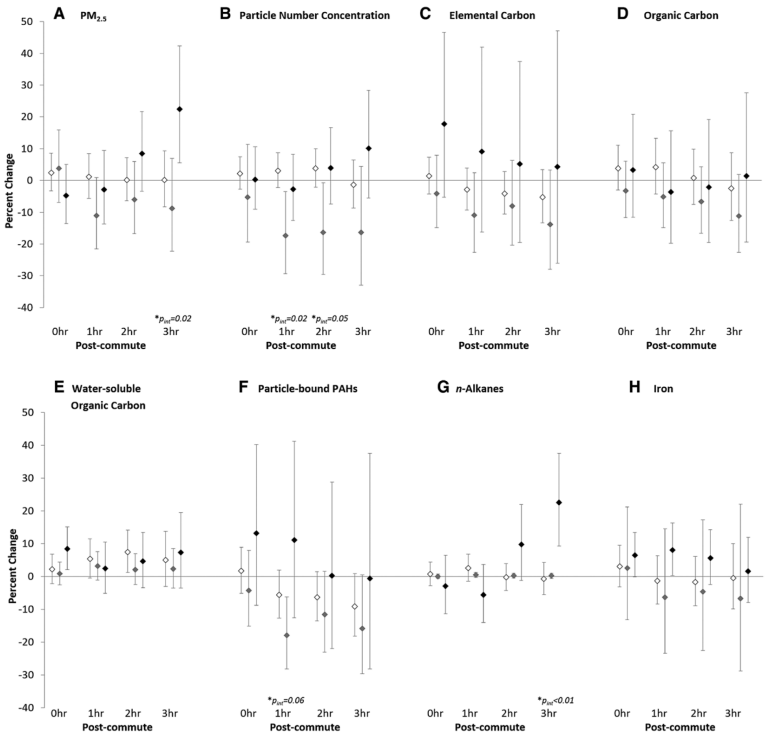

FIGURE 3.

Percentage change (with 95% CI) in exhaled NO concentration associated with each interquartile range increase in pollutant concentration among participants without asthma (*white diamond*), above-median asthma control (*gray diamond*), and below-median asthma control (*black diamond*). *Asterisks P* value for interaction (P_{int}) <0.10.

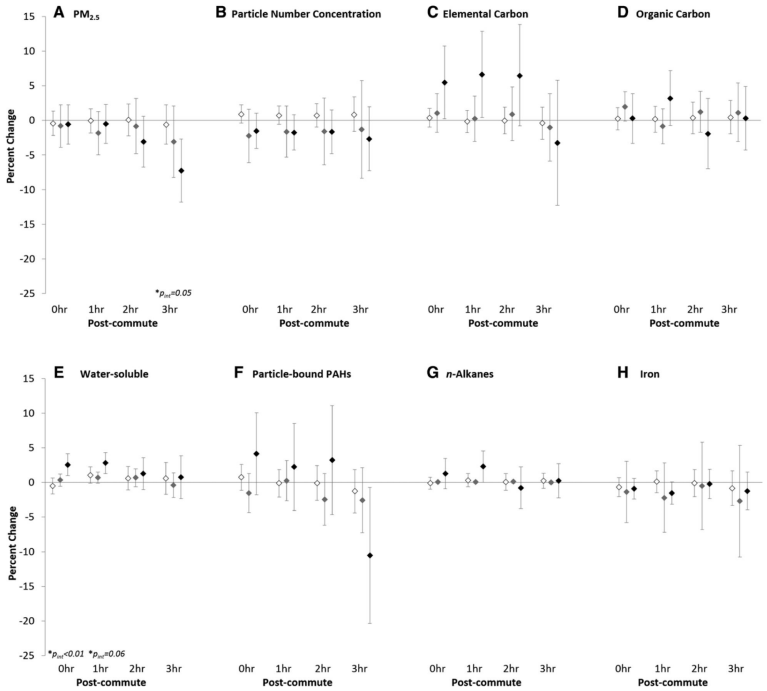

FIGURE 4.

Change (with 95% CI) in FEV_1 % predicted values associated with each interquartile range increase in pollutant concentration, by level of asthma control. Postcommute changes in FEV_1 % predicted shown are percentage points above or below precommute % predicted values among participants without asthma (*white diamond*), above-median asthma control (*gray diamond*), and below-median asthma control (*black diamond*). *Asterisks P* value for interaction (P_{int}) <0.10.

TABLE 1

Characteristics of the ACE-1 Study Population (N = 39) and Completed Study Commutes (N = 75)

	Level of Asthma Control		
	No Asthma	Above-median Asthma Control	Below-median Asthma Control
Characteristics	**No. (%)[a]**	**No. (%)[a]**	**No. (%)[a]**
No. participants	21 (54)[b]	9 (23)[b]	9 (23)[b]
Demographic characteristics			
Race			
White	13 (62)	5 (56)	5 (56)
Not white	8 (38)	4 (44)	4 (44)
Sex			
Female	8 (38)	3 (33)	8 (89)
Male	13 (62)	6 (67)	1 (11)
Commute characteristics			
Total commutes completed			
1	2 (10)	0 (0)	1 (11)
2	19 (90)	9 (100)	8 (89)
Date ranges of commutes			
1st commute	Dec 2009–Apr 2011	May 2010–Mar 2011	Oct 2010–Apr 2011
2nd commute	Apr 2010–Jun 2011	Mar 2011–Jun 2011	Apr 2011–May 2011
Interval between commutes[c,d]			
Mean (SD)	24.8 (16.9)	21.7 (15.1)	14.3 (8.5)
Median	19	17	13

[a] No. (column %), unless otherwise specified.

[b] Row %.

[c] In weeks.

[d] Among participants who completed two commutes.

TABLE 2

Indicators of Respiratory Health Measured Before the First ACE-1 Study Commute

	Level of Asthma Control		
	No Asthma	**Above-median Asthma Control**	**Below-median Asthma Control**
Asthma control score			
No. observations		9	9
Mean (SD)		0.51 (0.05)	1.68 (0.17)
Minimum, maximum		0.29, 0.71	0.86, 2.43
Exhaled NO (ppb)			
No. observations	21	9	9
Mean (SD)	22.7 (12.4)	36.4 (22.3)	49.9 (49.4)
Median	20.0	30.0	29.0
Malondialdehyde ($\mu mol \cdot l^{-1}$)			
No. observations	16	8	9
Mean (SD)	0.08 (0.03)	0.13 (0.08)	0.11 (0.06)
Median	0.07	0.10	0.10
FEV_1, % predicted			
No. observations	20	9	9
Mean (SD)	101.5 (14.0)	108.1 (13.8)	93.1 (15.2)
Median	98.9	112.9	90.1
FVC, % predicted			
No. observations	20	9	9
Mean (SD)	101.2 (17.0)	108.6 (8.3)	103.4 (13.1)
Median	99.9	108.1	101.6
$FEF_{25–75}$, % predicted			
No. observations	20	9	9
Mean (SD)	101.9 (19.0)	112.7 (35.5)	78.6 (31.5)
Median	104.9	108.4	69.2

TABLE 3

In-vehicle Air Pollutant Measurements Collected During Rush-hour Automobile Commutes Completed by ACE-1 Study Participants

In-vehicle Air Pollutant Measurements	Level of Asthma Control		
	No Asthma	Above-median Asthma Control	Below-median Asthma Control
No. eligible commutes	39	18	17
$PM_{2.5}$ ($\mu g \cdot m^{-3}$)			
No. commutes measured	36	18	17
Mean (SD)	28.8 (14.4)	23.8 (11.7)	21.0 (12.8)
Median	27.5	21.5	18.9
Interquartile range	20.9	20.9	13.1
Particle number concentration	a		
(No. particles per cm^3)			
No. commutes measured	36	18	16
Mean (SD)	28.4 (14.4)	26.3 (6.9)	21.5 (11.1)
Median	27.3	25.0	20.5
Interquartile range	19.5	7.2	17.8
Elemental carbon[b] ($\mu g \cdot m^{-3}$)			
No. commutes measured	39	18	13
Mean (SD)	3.5 (2.0)	2.0 (1.4)	1.6 (0.9)
Median	3.2	1.7	1.4
Interquartile range	3.5	1.0	0.8
Organic carbon[b] ($\mu g \cdot m^{-3}$)			
No. commutes measured	38	18	13
Mean (SD)	22.0 (6.5)	16.0 (7.4)	15.7 (5.1)
Median	21.0	16.1	13.8
Interquartile range	9.0	7.6	4.6
Water-soluble organic carbon			
(μg-m^{-3})			
No. commutes measured	35	18	13
Mean (SD)	6.5 (3.1)	5.5 (5.7)	6.7 (3.9)
Median	6.7	4.6	6.3
Interquartile range	2.9	3.2	2.5
Particle-bound PAHs ($ng \cdot m^{-3}$)			
No. commutes measured	39	18	15
Mean (SD)	128.1 (33.8)	118.2 (34.5)	97.1 (17.8)
Median	128.0	103.9	96.1
Interquartile range	50.8	51.9	28.2
n-alkanes[a,c] ($pg \cdot m^{-3}$)			
No. commutes measured	37	15	11

In-vehicle Air Pollutant Measurements	Level of Asthma Control		
	No Asthma	Above-median Asthma Control	Below-median Asthma Control
Mean (SD)	49.2 (34.5)	117.4 (316.5)	37.5 (25.6)
Median	40.9	32.2	34.8
Interquartile range	23.0	46.7	17.3
Iron ($ng \cdot m^{-3}$)			
No. commutes measured	38	18	13
Mean (SD)	310.6 (224.1)	176.7 (115.0)	225.5 (356.4)
Median	273.0	178.4	136.0
Interquartile range	289.8	96.7	181.4

[a] In thousands.

[b] Elemental and organic carbons measured using filter-based thermal-optical transmittance.

[c] Sum of *n*-Alkanes with 23–27 carbons.