Health Services Utilization in Asthma Exacerbations and PM₁₀ Levels in Rural Colorado

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Abstract

Rationale: The San Luis Valley in rural Colorado often has elevated levels of ambient particulate matter. To date little is known about the impact of ambient particulate matter levels and medical care utilization due to asthma exacerbation in rural communities.

Objectives: We investigated the impact of ambient particulate matter concentrations on emergency/urgent visits and hospitalizations for asthma in a rural community.

Methods: Daily ambient particulate matter concentrations from an air quality monitor in the San Luis Valley (2003–2012) were obtained from the state health department. Deidentified data for emergency/urgent visits with a diagnosis code for asthma were collected from the local health care system organization. A generalized linear model using splines and employing generalized estimating equations for correlated measures over time was used to examine the association between daily counts of emergency/urgent visits for asthma and 3- to 5-day averaged ambient particulate matter concentrations.

Results: For each 15- $\mu\text{g}/\text{m}^3$ increase in 3-day averaged ambient particulate matter, there was an associated 3.1% increase in hospital counts for all patients with asthma (95% confidence interval, 0.3–5.9%; $P = 0.03$). When the 3-day average exceeded 50 $\mu\text{g}/\text{m}^3$, asthma hospital visits increased by 16.8% ($P = 0.03$), and when it exceeded 100 $\mu\text{g}/\text{m}^3$, visits increased by 65.8% ($P = 0.002$). In children, the odds of one asthma event requiring an emergency/urgent care visit increased 5.0% with each 15- $\mu\text{g}/\text{m}^3$ increase in 3-day averaged ambient particulate matter ($P = 0.22$).

Conclusions: We observed associations between ambient air levels of particulate matter with a diameter less than 10 μm and emergency/urgent care visits and hospitalization counts in a rural U.S. community prone to dust storms and Environmental Protection Agency exceedances.

Keywords: ambient particulate matter; rural; asthma; children; exacerbations

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Particulate matter with a diameter less than 10 μm (PM₁₀) is a heterogeneous mixture composed of hydrocarbons, transition metals, and endotoxins (1). In rural areas, 80% of PM₁₀ is composed of windborne crustal elements, whereas in urban areas it consists primarily of automobile pollution and products of combustion (2).

Long-term exposure to particulate matter air pollution has been associated with premature mortality in those affected by respiratory and cardiovascular diseases (3, 4). Elevated PM₁₀ levels are associated with exacerbations of respiratory conditions including chronic obstructive pulmonary disease and bronchitis (5, 6), and are recognized to worsen asthma symptoms

(5, 7–9). Among people with asthma experiencing higher exposure to PM₁₀, studies have found increased physician consultations for worsening asthma (10), greater use of asthma reliever medications, increased emergency room visits for asthma exacerbations (5, 7–9), and increased asthma-related hospitalizations with the association strongest in infants (11).

Childhood asthma prevalence in the rural community observed in this study, the San Luis Valley (SLV), is 14% (12, 13), which is higher than the U.S. average of 12% (8), and it is therefore of public health importance to identify potential sources of asthma exacerbations in this community. In addition, PM₁₀ levels in rural areas, similar to the SLV, have more frequent days on which levels exceed the Environmental Protection Agency (EPA) maximum contaminant level of 150 µg/m³ (14).

Research has shown that asthma admission rates are more associated with PM₁₀ levels than with fine particles (15). Studies have reported an increased risk for medical visits for asthma exacerbations of 3–6% for every 10-µg/m³ increase in PM₁₀ (15, 16). PM₁₀ has been identified as an environmental trigger for asthma but in limited studies conducted in populations residing in urban areas and over short periods of time (7, 8, 11, 17). A review by Tzivian (8) calls for rigorous studies over longer periods of time and expanding to include rural and minority populations; this study addresses these identified limitations. Our current research is one of the first to examine the association between outdoor PM₁₀ levels and emergency/urgent visit and hospitalization (EUH) counts related to asthma exacerbation over a 10-year period in a rural, biethnic, underserved community.

Methods

Study Population

The SLV is a high-altitude (~7,500 ft) rural community located in south central Colorado covering approximately 8,000 square miles. It has a biethnic population of about 48,000 that is both white and Hispanic/Latino. The median income is approximately \$29,650 with 25% living below the poverty level (18). The primary economic components are tourism and agriculture (ranching and potato crops) (18). The SLV has an arid climate with an average PM₁₀ level of 25 µg/m³ (range, 6–484 µg/m³) between 2001 and 2011 (19). On average the SLV has two times the number of average daily PM₁₀ levels that exceed the EPA maximum contaminant level of 150 µg/m³ (14), relative to other areas of Colorado, including mountain, industrial, and urban areas (19).

Study Sample

We obtained data for all respiratory-related EUH records from the regional medical center serving all of the SLV population (see the online supplement) for the years 2003 through 2012. We requested visit records limited to those with *International Classification of Diseases*, version 9 (ICD-9) codes for asthma (493.x), pneumonia (481, 485, 486), acute respiratory illness (460.x, 462.x), and chronic obstructive pulmonary disease with bronchitis (490.x). Each record included patient age at the time of the visit, ICD-9 code, and visit date. Patient sex was not included in the data set because past research has not indicated that sex modifies the association between PM₁₀ levels and asthma exacerbation (20). This study was approved with waiver of consent by the Colorado Multiple Institutional Review Board for human research.

Meteorological Data

The National Oceanic Atmospheric Association's publicly available meteorological data for 2003 to 2012 were obtained from the one meteorological station in the community, located at the regional airport, 2 miles south of the two monitors in Alamosa. Data included daily average temperature, daily total precipitation, daily average barometric pressure, and daily average wind speed. These variables were selected because of the strong association with elevated PM₁₀

levels in ambient air (21). Each meteorological variable was incorporated into the statistical analysis in the original form (daily average or daily total).

Daily PM₁₀ Levels

In the SLV, there are two ambient air monitoring stations, one at Adams State University and the second at a municipal building, located 2 miles apart in the city of Alamosa, which is where the largest portion of the population resides. Monitors are maintained by the Colorado Air Pollution Control Division (CAPCD) of the Colorado Department of Public Health and Environment (CDPHE) (22). PM₁₀ levels were measured daily throughout the 10-year study period (2003–2012) from high-volume canister samples that use quartz filters (8 × 10 in.), using the protocol established by the U.S. National Ambient Air Quality Standards for particulate matter. Filters were collected daily and sent to the CDPHE in a manila envelope for laboratory analysis. The laboratory used the standards of protocol for PM₁₀ gravimetric analysis that determines particulate concentration based on weight difference (22). PM₁₀ level data are reported to the CAPCD and stored in the environmental data warehouse within the CDPHE. The CAPCD analyzes the PM₁₀ levels to identify samples with levels exceeding 150 µg/m³, which are further analyzed for elemental and chemical composition (22). Data from the monitor at the municipal

Table 1. Demographic distribution for the San Luis Valley population (2010) and study cohort (2003–2012)

	San Luis Valley (n = 46,173)*	Study Cohort (3,376 Asthma-related EUH Counts)
Age group		
<5 yr	1,755 (3.8%)	384 (11.4%)
5–14 yr	3,114 (6.7%)	487 (14.4%)
15–64 yr	36,086 (78.1%)	2,062 (61.1%)
≥65 yr	5,218 (11.3%)	443 (13.1%)
Race/ethnicity		Not available
White non-Hispanic	23,087 (50%)	
Hispanic	21,701 (47%)	
Other	1,385 (3%)	
Sex		
Male	22,625 (49%)	
Female	23,548 (51%)	

Definition of abbreviation: EUH = emergency/urgent visit and hospitalization. Entries represent count (percentage).

*Data from Reference 18.

site were more complete (11.2% of daily values missing for Adams, 6.7% for the municipal building, with no apparent trend for missing data for either site), and the PM₁₀ concentrations from these monitors were well correlated ($r = 0.88$ on untransformed scale and $r = 0.81$ on natural log of concentrations) over the study period, based on days when both had readings. Because of the strong agreement between monitors and because the municipal monitor data were more complete, the statistical modeling incorporated PM₁₀ concentrations from the municipal monitor only.

PM_{2.5} is not monitored in the San Luis Valley and therefore was not included in this study.

Statistical Analyses

For each count outcome, a generalized linear model was fit using a log link, including a scale parameter for dispersion, and employing generalized estimating equations to account for serial correlations in hospital counts over time. The m -dependent working covariance structure with $m = 4$ was selected as the best available structure, allowing a flexible correlation structure between counts for days up to 4 days apart (23). Cubic b-splines were used to model the mean number of counts over time, using evenly spaced knots 1 year apart. Model predictors included class variables for day of the week and month, and continuous variables for daily temperature, pressure, and humidity. Wind speed was initially included but dropped because of weaker significance. Daily visit counts were determined by counting the number of visits per day in total and then by key strata (age category: 5–14, 15–64, 65+; disease category: asthma [493.x]). We examined 1-, 3-, and 5-day moving averages of regular or log-transformed PM₁₀ concentrations. For the 3- and 5-day moving averages, models related the count outcome on a given day to the average PM₁₀ concentration over days up to and including that day (e.g., a count today was related to the average of PM₁₀ today, yesterday, and 2 d ago, for the lagged 3-d moving average [MA]). For individual-day PM₁₀ (i.e., 1-d average), we examined up to lag 4 of the pollutant. Models were also fit using indicators for 1-, 3-, or 5-day averages that exceeded 50- and 100- $\mu\text{g}/\text{m}^3$ thresholds. Model-based standard errors were used, as the empirical standard

errors could not be estimated for these data. For specific counts of children with asthma, the outcome was modeled as binary (0 vs. at least 1) because counts were rare and a logit link was used. The online supplement describes sensitivity analyses for models using 3- or 5-day MA pollutant variables that consider different ways of handling missing data.

Results

Emergency/Urgent Visit and Hospitalization Counts

From 2003 through 2012, there were 6,958 total urgent and emergency visits; 3,376 (48.5%) were associated with asthma, 2,006 (28.8%) with pneumonia, 1,345 (19.3%) with pharyngitis/nasopharyngitis, and the remaining 231 (3.3%) with bronchitis. The

median number of visits per day was 2 for all respiratory conditions (1 for asthma) with a range of 0 to 11 (0 to 7 for asthma). The mean age of patients was 35.7 years; 15.6% were less than 5 years, 13.1% were 5–14 years, 52.4% were 15–64 years, and 18.9% were 65 years or older. The distribution of patients by age was similar to the age distribution in the SLV (Table 1). Our data set did not include race/ethnicity or sex; however, given that the data set included all EUH counts from the region's only emergency/urgent care provider and hospital, it is expected that the study cohort is representative of the patient population of the region. Urgent and emergency care visits due to asthma had the highest occurrence on Sunday and Monday and during the months of February, September, and October. Table 2 shows means and SD for hospital counts and PM concentrations for the two

Table 2. Total and asthma-related emergency/urgent and hospital visits: mean (SD)

			PM ₁₀ (µg/m ³)	
Total EUH Counts	Asthma EUH Counts		Adams	Municipal
Day of week				
Sunday	2.26 (1.65)	1.00 (1.13)	15.4 (1.84)	18.3 (1.84)
Monday	2.01 (1.59)	0.99 (1.06)	18.5 (1.82)	22.6 (1.70)
Tuesday	1.86 (1.52)	0.94 (1.09)	19.2 (1.74)	24.9 (1.66)
Wednesday	1.86 (1.47)	0.93 (1.00)	20.4 (1.81)	25.4 (1.78)
Thursday	1.74 (1.51)	0.91 (1.09)	20.0 (1.84)	25.2 (1.78)
Friday	1.84 (1.64)	0.89 (1.09)	19.1 (1.78)	24.7 (1.71)
Saturday	1.76 (1.43)	0.81 (0.96)	17.3 (1.85)	21.5 (1.71)
Month				
January	2.03 (1.44)	0.89 (0.97)	19.9 (1.78)	24.4 (1.78)
February	2.78 (1.91)	1.15 (1.22)	16.1 (1.91)	22.2 (1.80)
March	2.44 (1.67)	0.97 (1.09)	16.6 (1.91)	21.4 (1.75)
April	1.95 (1.53)	0.88 (1.03)	19.8 (2.15)	24.4 (2.10)
May	1.84 (1.37)	0.85 (0.92)	19.2 (1.96)	24.1 (1.84)
June	1.66 (1.36)	0.80 (0.93)	23.2 (1.78)	28.8 (1.67)
July	1.38 (1.24)	0.76 (0.93)	17.9 (1.50)	22.5 (1.51)
August	1.47 (1.31)	0.78 (0.90)	16.6 (1.40)	19.1 (1.49)
September	1.88 (1.48)	1.10 (1.13)	16.5 (1.51)	19.6 (1.51)
October	1.95 (1.72)	1.10 (1.29)	17.2 (1.86)	20.7 (1.80)
November	1.81 (1.51)	0.95 (1.13)	21.2 (1.90)	27.7 (1.80)
December	1.75 (1.52)	0.89 (1.09)	18.8 (1.91)	23.8 (1.77)
Year				
2003	1.91 (1.54)	0.84 (0.98)	20.5 (1.79)	22.7 (1.71)
2004	1.56 (1.28)	0.74 (0.90)	18.5 (1.66)	20.6 (1.71)
2005	2.00 (1.48)	0.89 (0.94)	16.9 (1.84)	20.6 (1.72)
2006	1.93 (1.50)	0.81 (0.98)	16.8 (1.91)	21.4 (1.80)
2007	2.27 (1.56)	1.00 (1.06)	18.3 (1.77)	24.2 (1.79)
2008	1.82 (1.61)	0.71 (0.95)	16.8 (1.86)	23.1 (1.75)
2009	2.07 (1.68)	1.01 (1.15)	17.2 (1.80)	21.3 (1.69)
2010	1.74 (1.29)	0.84 (0.94)	18.4 (1.93)	22.1 (1.75)
2011	2.45 (1.70)	1.61 (1.36)	20.5 (1.77)	30.8 (1.77)
2012	1.31 (1.55)	0.79 (1.01)	21.3 (1.79)	26.0 (1.73)

Definition of abbreviations: EUH = emergency/urgent visit and hospitalization; PM₁₀ = particulate matter with a diameter less than 10 μm , SD = standard deviation. Shown is the arithmetic mean (SD) for emergency/urgent and hospital visits, and geometric mean (geom. SD) for PM₁₀ concentrations ($\mu\text{g}/\text{m}^3$), by day of week, month, and year, 2003–2012.

monitors, by day of week, month, and year. Preliminarily, we fit the daily all respiratory-related EUH count data and daily PM₁₀ levels using local polynomial regression (a type of nonparametric regression; Figure 1). The data show mean trends that coincided for the most part, and hospital count peaks that tended to occur every other year. Figure 2 shows estimated (mean) visit counts over time, adjusted for PM₁₀, meteorological, and seasonal variables. The fitted curve is consistent with the descriptive curve for counts in Figure 1 and generally reflects a 2-year cycle in count behavior.

PM₁₀ and Meteorological Data

The interquartile ranges (IQRs) of 1-, 3-, and 5-day averaged PM₁₀ values from the municipal monitor were 16.0, 14.7, and 14.4, respectively. Both 3- and 5-day averaged PM₁₀ exceeded 50 $\mu\text{g}/\text{m}^3$ on 6.0% of days during the study period and exceeded 100 $\mu\text{g}/\text{m}^3$ on 0.7% of days. Geometric mean and geometric SD of PM₁₀ concentrations by year, month, and day of week are shown in Table 2, and Table 3 shows

a composite summary of pollution and meteorological variables.

Relationships between All Respiratory EUH Counts and PM₁₀

We completed an initial analysis of all respiratory conditions for patients of all ages with PM₁₀ untransformed, which showed that for each IQR increase (15 $\mu\text{g}/\text{m}^3$) of 3-day average PM₁₀ in outdoor air there was an associated increase of 1.8% ($P = 0.09$) in daily hospital visit counts. For 5-day averaged PM₁₀, the findings were similar, with a 2.3% ($P = 0.07$) increase in daily hospital visit counts for all respiratory disease. When the 3-day average PM₁₀ exceeded 100 $\mu\text{g}/\text{m}^3$ (modeling pollutant as binary), the number of hospital visits for all respiratory diseases was 32.6% ($P = 0.03$) higher than when it did not. Similarly, when the 5-day average exceeded 100 $\mu\text{g}/\text{m}^3$, the number of hospital visits for all respiratory diseases was 40.0% ($P = 0.01$) higher than when it did not. Analyses using individual-day pollutant variables up to lag 4 or log scale of pollutant variables

did not yield significant results at the $\alpha = 0.05$ level.

Relationships between EUH Counts for Asthma and PM₁₀

In models for patients of all ages with PM₁₀ untransformed, we observed that for each IQR increase (15 $\mu\text{g}/\text{m}^3$) in lagged 3-day average PM₁₀ there was an associated increase of 3.1% ($P = 0.03$) in daily EUH counts for asthma (Table 4). For 5-day moving average PM₁₀, the findings were similar, with a 3.1% ($P = 0.06$) increase in asthma-attributable EUH counts (Table 4). When the 3-day moving average was log transformed, the direction of the findings remained, although it was not statistically significant.

When the association was examined using binary PM₁₀ concentrations, where the 3-day average PM₁₀ exceeded 50 $\mu\text{g}/\text{m}^3$, there were 16.8% ($P = 0.03$) more asthma-related EUH counts (Table 5). Similarly, when the 3-day average PM₁₀ exceeded 100 $\mu\text{g}/\text{m}^3$, asthma visits were 65.8% ($P = 0.002$) higher. When the 5-day

Figure 1. Local polynomial regression for daily PM₁₀ (solid line, left y axis) and hospital counts (dashed line, right y axis) over a 10-year period (2003–2012). (First-degree polynomial, with a smoothing parameter of 0.15 for both variables.) EUH = emergency/urgent visit and hospitalization; PM₁₀ = particulate matter with a diameter less than 10 μm .

Figure 2. Estimated mean emergency/urgent visit and hospitalization (EUH) counts from 2003 to 2012, based on nonparametric regression fit (dashed line) and via generalized linear model (GzLM) fit (solid line). The GzLM fit accounted for variables as described in the section STATISTICAL ANALYSES.

pollution average exceeded $50 \mu\text{g}/\text{m}^3$, there were 14.1% ($P = 0.10$) more asthma-related EUH counts than when it did not (Table 5). Similarly, when the 5-day average exceeded $100 \mu\text{g}/\text{m}^3$ asthma-related EUH counts were 45.0% ($P = 0.03$) higher (Table 5). Analyses using individual-day pollutant variables up to lag 4 or log scale of pollutant variables did not yield significant results at the $\alpha = 0.05$ level.

Discussion

In this longitudinal study, increased PM_{10} levels were associated with an increase in EUH counts related to respiratory conditions, especially asthma, for individuals 5 years of age and older. The greater significance of these binary variables at specific cut points compared with the continuous variables suggests that there may be a threshold effect, below which little or no pollution effect occurs. This was confirmed in follow-up analyses with change-point models, where the linear relationship between hospital counts and PM_{10} below $50 \mu\text{g}/\text{m}^3$ was very weak and

insignificant. Both of the cut points used in our analyses are at an ambient air concentration less than the current EPA air quality standard for PM_{10} of $150 \mu\text{g}/\text{m}^3$. Our observations in those affected by asthma were supported by similar findings in EUH counts related to all forms of respiratory conditions, suggesting that elevated PM_{10} levels in ambient air are associated with compromised lung health.

Plausible mechanisms for PM_{10} provoking respiratory illnesses are related to its proinflammatory properties. In asthma, this proinflammatory response causes increased airway hyperresponsiveness culminating in airway narrowing and the experience of asthma symptoms (24, 25). Experimental studies reveal that exposure to PM_{10} can cause alveolar cytokine release responsible for bronchospasm and reduced pulmonary function (26) and also known to cause epithelial injury resulting from its oxidative properties (24). It is suggested that this is because PM_{10} , in contrast to gaseous pollutants, can induce oxidative reactions by crossing the fluid in the respiratory tract lining (27).

Epidemiologic research suggests that large (PM_{10}) particles can become lodged in the airways of the lungs, causing compromised breathing inevitably leading to worsening asthma and the possible need for medical intervention. Studies have documented an association between higher PM_{10} levels in ambient air and an increased number of emergency room visits (5, 11, 20, 28); a systematic review of 25 studies (8) also corroborated an association between PM_{10} levels in ambient air and an increased number of emergency room visits, and a second review found 2% increases in asthma-related hospitalizations for every $10\text{-}\mu\text{g}/\text{m}^3$ increase in PM_{10} (29), which was substantiated in another large systemic review by Weinmayr and colleagues, which found PM_{10} significantly increased risk for asthma symptoms (odds ratio, 1.028; 95% confidence interval, 1.006–1.051) (30). Last, a study by Canova and colleagues found that an increase in PM_{10} levels by $10 \mu\text{g}/\text{m}^3$ was associated with an 35% increase in emergency room visits due to asthma lagged 0–3 days (for lag 0–3: odds ratio, 1.35; 95% confidence interval, 1.04–1.76) similar to findings in this study (29).

Table 3. Descriptive statistics for particulate matter with a diameter less than 10 μm and meteorological variables

Variable	Mean	SD	Minimum	25th Percentile	50th Percentile	75th Percentile	Maximum
Temperature, °F	42.7	18.2	−12	29	44	59	74
Pressure, altimeter in.	22.8	0.16	22.06	22.68	22.81	22.9	23.17
Precipitation, in.	0.019	0.074	0	0	0	0.005	1.49
Wind, mph	7.2	3.91	0	4.4	6.4	8.9	27.4
PM ₁₀ , $\mu\text{g}/\text{m}^3$							
1-d	27.5	24.7	2	16	23	32	635
3-d	27.7	18.1	4	17.7	24	32.3	337.5
5-d	27.8	16.2	4.5	18.3	24.6	32.7	266
Log 1-d PM ₁₀ , $\mu\text{g}/\text{m}^3$	3.14	0.57	0.69	2.77	3.14	3.47	6.45
Log 3-d PM ₁₀ , $\mu\text{g}/\text{m}^3$	3.14	0.47	1.39	2.82	3.14	3.44	5.47

Definition of abbreviations: PM₁₀ = particulate matter with a diameter less than 10 μm , SD = standard deviation.

Several factors place children at greater risk for asthma exacerbations due to elevated PM₁₀ levels in ambient air and include the following: rapid growth and development during childhood (31); immature and underdeveloped lungs (32–34); higher inhaled air capacity, which can potentially lead to higher doses of PM₁₀ (35); and a corresponding higher volume-to-body weight ratio than adults (34). Because of their smaller airways the disposition of pollutants, especially PM₁₀, is greater in children than adults (33, 34), thus further supporting the significance of the findings that ambient PM₁₀ levels increase EUH counts in children, especially in rural areas where dust levels are elevated.

This study is not without limitations. It is expected that the use of a single monitor can approximate the individual-level potential for exposure; however, it does not account for individual dose, which is variable due to volume of air intake, spatial variability in dust concentrations, indoor air PM₁₀ concentration, time spent indoors versus outdoors, and time spent at other locations such as school, day care, or work. However, given the concordance between the two PM₁₀ monitors present in Alamosa, the use of the municipal monitor for a population-level approximation of exposure is appropriate. In addition, we considered only PM₁₀ concentrations and did not consider other pollutants with known

association with asthma exacerbations in urban populations, including nitrogen oxide (NO_x) and sulfur oxide (SO_x) (36, 37). These other pollutants were not included because PM₁₀ is the predominant ambient air pollutant of concern in this rural community, with no exceedances of NO_x or SO_x reported during the 10-year study period, whereas PM₁₀ had 72 exceedances.

Another limitation is that our statistical models did not account for individual-level confounders that could influence the need for an EUH for worsening asthma. Such factors include underlying severity of chronic respiratory illnesses, smoke exposure, adherence to treatment plans, genetic susceptibility, respiratory infections (viral and bacterial), other household exposures, residential distance from clinic or hospital, and access to transportation, all of which can increase the risk of exacerbations and were not included as part of the data ascertainment. These data were not included as part of the data-sharing agreement with the regional medical facility as a means to preserve confidentiality because the data included individual records with some days having only one record. Future research in the area should collect individual-level data that include these other known triggers of asthma exacerbation as part of the prospective study that concurrently tracks air quality and medical care utilization related to asthma.

Another limitation is that PM_{2.5} was not included in this analysis because it is not measured in the San Luis Valley. PM_{2.5} has been associated with asthma exacerbation; however, it is inconclusive as to whether asthma outcomes are worse with PM₁₀ or with PM_{2.5} or whether the mixed effects of both have even worse outcomes (38). It is possible that the exclusion of PM_{2.5} from the statistical analysis induced bias; however, it is not expected that this bias was differential. In rural areas during dust storms particulate matter of all sizes has been shown to increase; however, PM₁₀ increases the most at a factor of 4.7 whereas PM_{2.5} and PM₁ increase by a factor of only 2, suggesting that in rural dust storms similar to the ones that plague the San Luis Valley, PM₁₀ will increase more than other particulate matter (39). In a pilot study as part of this research, we completed a chemical composition analysis of PM₁₀ quartz filters ($n = 75$) with daily average levels greater than 75 $\mu\text{g}/\text{m}^3$. Results found

Table 4. Generalized estimating equation estimates (95% confidence interval) of change in asthma-related emergency/urgent and hospitalization visit count as a function of particulate matter with a diameter less than 10 μm , (measured in $\mu\text{g}/\text{m}^3$)

Lag Structure for PM ₁₀ *	Records Available for Analysis	Relative Increase in Hospital Count per IQR Increase in Pollutant† (%)	95% CI	P Value
3-d MA	3,445	3.1	0.3 to 5.9	0.03
3-d MA‡	3,444	3.9	0.9 to 6.8	0.01
5-d MA	3,512	3.1	−0.1 to 6.4	0.06
1-d, lag 0	3,112	1.0	−1.1 to 3.1	0.40
1-d, lag 1	3,112	1.5	−0.6 to 3.4	0.17
1-d, lag 2	3,111	1.5	−0.6 to 3.6	0.17
1-d, lag 3	3,111	0.0	−2.2 to 2.3	0.99
1-d, lag 4	3,110	−0.3	−2.5 to 2.1	0.81

Definition of abbreviations: CI = confidence interval; IQR = interquartile range; MA = moving average; PM₁₀ = particulate matter with a diameter less than 10 μm .

*Averaged days starting from current day, for example, lagged 3-day MA includes current day plus previous 2 days.

†IQR, 16, 14.7, and 14.4 for 1-day, 3-day, and 5-day moving averages, respectively.

‡Without outlier (1 value that exceeded 300 $\mu\text{g}/\text{m}^3$).

Table 5. Estimates of change in asthma-related emergency/urgent and hospital visit counts for high versus low particulate matter with a diameter less than 10 μm (measured in $\mu\text{g}/\text{m}^3$)

Lag Structure for PM ₁₀ *	Cut Point for PM ₁₀ ($\mu\text{g}/\text{m}^3$)	Records Available for Analysis	Relative Increase in Hospital Count for "High" versus "Low" Pollution (%)	95% CI	P Value
3-d MA	50	3,445	16.8	1.2 to 34.8	0.03
3-d MA	100	3,445	65.8	20.2 to 128.7	0.002
5-d MA	50	3,512	14.1	-2.3 to 33.3	0.10
5-d MA	100	3,512	45.0	2.7 to 104.8	0.03

Definition of abbreviations: CI = confidence interval; MA = moving average; PM₁₀ = particulate matter with a diameter less than 10 μm .

*Averaged days start from current day, for example, lagged 3-day MA includes current day plus previous 2 days.

that 16.5% of the filters had no detectable levels of polyaromatic hydrocarbons, a known pollutant due to traffic and wood burning, and in 85% of samples only one polyaromatic hydrocarbon metabolite was detected. Results suggested that traffic and wood burning were not major contributions to air pollution, which are also common sources of smaller particulate matter.

A final limitation is the defining of our cases on the basis of ICD-9 codes that were listed at time of discharge and then as the primary ICD-9 code during the visit.

ICD-9 codes have been shown to underrepresent asthma cases, especially in young children, due to complexity and misdiagnoses with lower respiratory infections, which is why we excluded children under 5 years of age (40). Bias due to case identification through ICD-9 code is more readily noted in children less than 5 years old due to the apprehension of labeling a child of this age with asthma (41). However, a strength of this work is that the study did not involve children under the age of 5, for this reason, and limits this potential issue.

Even with these limitations, this study provides significant results and insights in that asthma exacerbations were associated with PM₁₀ levels in a rural population and the association is strongest in the pediatric population. Our work suggests that exposure to PM₁₀ at thresholds lower than those currently set by the EPA (150 $\mu\text{g}/\text{m}^3$) may contribute to greater EUH counts related to asthma over a 24-hour period of time. This suggests the need for continued evaluation of the public health relevance of clean air standards. In conclusion, we observed an association between EUH and hospitalization counts and ambient air PM₁₀ levels in a rural community prone to dust storms and EPA exceedances. Because PM₁₀ in ambient air remains a common exposure in the United States, the impact on asthma and lung health should provide motivation to public health officials to conduct further research to elucidate the role of PM₁₀ in respiratory health for individuals of all ages. ■

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