RESEARCH AND PRACTICE
The Influence of Socioeconomic Markers on the Association Between Fine Particulate Matter and Hospital Admissions for Respiratory Conditions Among Children

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Objectives. We evaluated the influence of socioeconomic status (SES) on hospital admissions for respiratory conditions associated with ambient particulate matter that is 2.5 micrometers or less in aerodynamic diameter (PM2.5) in children aged 1 to 9 years in 12 California counties, from 2000 to 2005.

Methods. We linked daily hospital admissions for respiratory conditions (acute respiratory infections, pneumonia, and asthma) to meteorological, air pollution, and census data.

Results. In San Diego, San Bernardino, Riverside, and Los Angeles counties, the admission rates for children associated with PM2.5 ranged from 1.03 to 1.07 for combined respiratory conditions and 1.03 to 1.08 for asthma in regions with lower SES. We observed 2 distinct patterns of the influence of the composite SES Townsend index. In lower-SES South Coast areas, PM2.5-associated hospital admission rates for all respiratory outcomes were predominantly positive whereas results in the Central Valley were variable, often tending toward the null.

Conclusions. These distinct patterns could be attributed to the heterogeneity of regional confounders as well as the seasonal variation of emission sources of PM2.5. Composite SES is one potential factor for increasing susceptibility to air pollution. (Am J Public Health. 2013;103:695-702. doi:10.2105/AJPH.2012. 300945)

Growing evidence demonstrates that exposure to ambient particulate matter that is 2.5 micrometers or less in aerodynamic diameter (PM2.5) may be associated with increases in respiratory symptoms and prevalence of asthma in children.1-4 Children, especially those with preexisting respiratory conditions, may be more affected by ambient PM2.5 than adults.5 Children are more active and spend more time outdoors, which contributes to their potential for breathing a greater amount of polluted air per pound of body weight than adults.5,6 Biologically, the peripheral airways in children are more susceptible to inflammation when exposed to polluted air, which leads to greater airway obstruction than in adults.7

Adding to the public health concern for children and their vulnerability to air pollution, epidemiological studies have revealed that low socioeconomic status (SES) may be associated with different air pollution impacts. A study by Lynch et al.8 found that persons of lower SES have a generally higher mortality rate than more advantaged persons. To date, most of the epidemiological studies on air pollution exposures have mainly focused on adult mortality rates9-12 and childhood asthma hospital admissions.13-16 Studies have shown that low-income families have a higher likelihood of living in older areas and live in high-traffic areas, leading to an increased likelihood of exposure to air toxins and higher ambient PM2.5 compared with high-income families.17 Questions, however, still remain regarding the role SES plays in the association between ambient PM2.5 and poor respiratory health. For children, a key question is the contribution of low SES to a child’s respiratory health in conjunction with a higher rate of exposure to ambient air pollution.5-7 Few studies have focused on morbidity among children in relation to ambient concentrations of PM2.5 using a time-series approach. This is probably because the number of hospital admissions for pediatric morbidity is often insufficient for such an analysis.

To assess the relationship among SES, acute PM2.5 exposure, and childhood morbidity, we obtained daily hospital admissions and PM2.5 data for the Central Valley and the South Coast regions of California. We also explored which single or composite socioeconomic measures can be used to evaluate socioeconomic inequality in children. We then evaluated the modifying effect of the selected single or composite socioeconomic variables.
on the association between daily ambient PM2.5 and hospital admissions for respiratory conditions among
children from ages 1 to 9 years in 12 counties in the Central Valley and the South Coast regions from 2000 to
2005.

METHODS
The focus of our analysis was the 12 counties in the Central Valley and South Coast regions of California:
Sacramento, San Joaquin, Stanislaus, Fresno, Kings, Tulare, and Kern counties in the Central Valley and San
Bernardino, Los Angeles, Orange, Riverside, and San Diego counties in the South Coast region. We obtained
pollutant data (PM2.5) for 2000 through 2005 from the California Air Resources Board, which maintains
information from the National Air Monitoring Stations and State and Local Air Monitoring Stations
(http://www.arb.ca.gov/aqd/almanac/ almanac.htm).

Data on PM2.5 are reported as the 24-hour average mass concentration, based on measurements taken every 1,
3, or 6 days depending on the station and time frame of the measurements. There were 39 and 34 PM2.5
monitoring sites in the Central Valley and the South Coast regions, respectively, during the study period.

For counties with more than 1 monitoring site, we calculated the daily average PM2.5 by taking the average
across sites within the county. To account for missing daily PM2.5 data among monitoring sites, we used the
following logic: (1) If observations were missing at a site, but the nearest monitoring sites in the same county or
air basin had measured values for the missing day, we performed linear regression to predict the missing values
by using measured values at 1 or more nearest monitoring sites. A predictive power (R2) of 0.7 or more was
required to apply this method. (2) If observations were missing at all monitoring sites for a day, we computed the
missing observations by using linear interpolation between successive measured values. (3) If observations were
still missing and neither of the previously described approaches were possible, we computed the missing
observations by using the concept of ratios. This assumed that an observation is proportional to the annual site
mean and the average ratio concentration over the means across other nearby monitoring sites in the same or
nearest counties in proportion to their respective averages (see appendix available as a supplement to the online
version of this article at http://www. ajph.org).

After these steps, data used in this analysis contained 73% measured and 27% computed daily average PM2.5
values for the 12 counties from 2000 to 2005. To control for possible confounding effects from temperature and
relative humidity, we used daily meteorological data obtained from the California Irrigation Management
Information System (http://www.cimis.water.ca.gov/ cimis/data.jsp).

Data Sources for Area-Based Socioeconomic Status Measures
We obtained census and zip code tabulation areas (ZCTAs) data from the US Census 2000.18 Typically, a 5-digit
ZCTA is approximately equal to a 5-digit zip code but there are important distinctions: ZCTAs follow census block
boundaries, whereas zip codes serve US Postal Service addresses. Therefore, a ZCTA can include several zip
codes and a zip code can include several ZCTAs.19,20

For these analyses, we linked the 5-digit ZCTAs to 5-digit zip codes for the location of the residence for the 12
counties in the Central Valley and the South Coast regions by using ArcGIS 9.3 (ESRI, Redlands, CA) to overlay
shape files of the zip codes and ZCTAs. Zip code centroids most proximal to the centroid of a ZCTA were
identified as the ZCTA. Using this criterion, we successfully matched 70% of ZCTAs to zip codes within 1
kilometer of the centroid of the ZCTA. We excluded zip codes with poor matches with ZCTAs from our analyses.

We derived single SES variables, at the ZCTA level, based on US Census 2000 data.18 The decision to use
these variables was based on similar work conducted in the Public Health Disparities Geocoding Project
Monograph. 20-22 Each ZCTA corresponds to both single and composite SES variables. The selected single and
composite SES variables used in our analysis are shown in Table A (available as a supplement to the online
version of this article at http://www.ajph.org).

Based on Krieger's approach,20,22-24 we generated 2 composite SES variables from single SES variables. We
generated the first composite SES variable by performing factor analysis with varimax rotation on the 9 single
SES variables (Table A, available as a supplement to the online version of this article at http://www.ajph.org). Our
second composite SES variable was the Townsend index, devised by Townsend et al. to provide a material
measure of deprivation and disadvantage.25 We generated the Townsend index by calculating the Z-score for
each of the 4 census variables: percentage crowding, percentage unemployment, percentage of individuals who
do not own cars, and percentage of renters. Subsequently, we created the Townsend index by summing the
Z-score values from each of the 4 census variables.21,25 The higher the Townsend index score, the more
disadvantaged an area is thought to be.
For our analysis, we dichotomized each single and composite SES into either higher or lower SES, based on their 50th percentile. Higher scores on the index denoted lower SES.

We obtained data on daily hospital admissions for respiratory conditions among children from the California Office of Statewide Health Planning and Development for the period 2000 through 2005. The hospital admissions records included the date of admission, place of residence (zip code and county), and primary diagnoses. Our analysis focused on 4 respiratory conditions among children: combined respiratory conditions (International Classification of Diseases, Ninth Revision [ICD-9] codes 460-519), acute respiratory infections including pneumonia (ICD-9 codes 460-466, 480-486), pneumonia (ICD-9 codes 480-486), and asthma (ICD-9 code 493).26 We obtained the daily counts for each category of hospital admissions by totaling the number of hospital admissions for respiratory conditions among children in ZCTAs with low and high SES, by county in a SAS database (SAS Institute Inc, Cary, NC).

Statistical Analysis

We performed generalized additive Poisson regression models27 to estimate the association among the single or composite SES variables, PM2.5 concentrations at different lags, and daily hospital admissions of childhood respiratory illnesses. We performed analyses that accounted for longer-term patterns in the health outcomes data (i.e., time trends and seasonality, day of the week,28 and smoothing splines with different lags for temperature29). We then examined the effect of PM2.5 in the model by investigating exposure lags of zero to 6 days. Based on Akaike’s Information Criterion (AIC), the 3-day-lag PM2.5 exposure yielded the best fit and was used in all subsequent analyses.

Lastly, we examined the modifying effect of single or composite area-based SES variables. Of notable interest for main-effect models, although the effects of single or composite area-based SES variables were strong risk factors for the 4 respiratory outcomes, the point estimates of PM2.5 on childhood respiratory illnesses did not appear to be attenuated. We also performed stratified models on the single and composite area-based SES variables, and the strength of association between PM2.5 and the 4 respiratory outcomes remained unchanged. Therefore, we decided to present models that yielded a good fit based on AIC. Among the models with SES variables, the Townsend index had the lowest AIC based on goodness of fit and the strongest parameter estimate for our models. Table B (available as a supplement to the online version of this article at http://www.ajph.org) shows the summarized basic statistics for the Townsend index by counties.

RESULTS

Table B (available as a supplement to the online version of this article at http://www.ajph.org) shows that the median of the Townsend index varied from -0.67 (San Diego County) to -0.08 (Tulare County). Table 1 summarizes the descriptive results of the daily mean for hospital admission rates for respiratory conditions per 1 000 000 children aged 1 to 9 years per county for 2000 through 2005. The daily mean hospital admission rates for combined respiratory conditions ranged from 11.2 per 1 000 000 (San Diego County) to 20.8 per 1 000 000 (San Bernardino County). Among the 12 counties, Fresno had the highest rate of hospital admissions for childhood asthma (8.8 per 1 000 000), with San Bernardino second at 7.6 per 1 000 000 children. More than 40% of the total number of pediatric respiratory hospital admissions in Sacramento, Fresno, Los Angeles, Orange, and San Diego counties were for asthma.

Over the study period, the daily mean PM2.5 concentration ranged from a low of 12.8 micrograms per cubic meter in Sacramento County to a high of 24.6 micrograms per cubic meter in Riverside County (Table 2). Although our investigation used the daily PM2.5 levels in the analysis, none of the 12 counties had annual averages below the current California annual PM2.5 standard (12 lg/m3), and only Sacramento, San Joaquin, and San Diego counties had annual averages below the federal annual PM2.5 standard (15 lg/m3; data not shown). The PM2.5 levels of the 12 counties were in compliance with the federal daily PM2.5 standard (35 lg/m3).

Figure 1a-b shows the county-level adjusted relative rates (RRs) and their confidence intervals. For combined respiratory conditions, the adjusted RR for hospital admissions were significantly increased in Fresno, Tulare, Los Angeles, Riverside, Orange, San Bernardino, and San Diego counties per 10 micrograms per cubic meter increment of PM2.5. For acute respiratory infections, including pneumonia, the hospital admission RR ranged from 1.03 to 1.07 in Los Angeles, Riverside, San Bernardino, and San Diego counties per 10 micrograms per cubic meter change in PM2.5. For pneumonia, the adjusted RR for hospital admissions increased significantly per 10 micrograms per cubic meter increment of PM2.5 with a RR of 1.02 and 1.05 observed only in Los Angeles and San Diego counties, respectively. In addition, for childhood asthma, the estimated RRs for hospital admissions were also significantly increased and ranged from 1.03 to 1.08 in Riverside, Orange, Tulare, Los Angeles, San Diego, San Bernardino, San Joaquin, and Fresno counties per 10 micrograms per cubic meter increments of PM2.5 exposure.
In the South Coast region, we observed a clear pattern in the relationship between PM2.5 exposure and the 4 different outcomes in the model stratified by SES (Figure 2). In Los Angeles, Riverside, Orange, San Bernardino, and San Diego counties, the RRs for hospital admission rates per 10 micrograms per cubic meter increments of PM2.5 ranged from 1.03 to 1.07 for respiratory conditions, 1.03 to 1.08 for respiratory infections, 1.01 to 1.07 for pneumonia, and 1.03 to 1.08 for asthma in regions with lower SES. In higher-SES regions of Los Angeles, Riverside, Orange, San Bernardino, and San Diego counties, the RRs for hospital admissions ranged from 1.01 to 1.05 for respiratory conditions, and 1.03 to 1.05 for asthma. Although the differences in the interaction terms of SES and PM2.5 were not statistically significant, in the South Coast region, the rates of hospital admissions of the 4 outcomes per 10 micrograms per cubic meter of PM2.5 were generally higher in areas with lower SES.

We observed no clear pattern in the Central Valley for the influence of SES on the relationship between PM2.5 and the 4 outcomes. In the Central Valley, the RR for hospital admissions for asthma per every 10 micrograms per cubic meter of PM2.5 in Sacramento County was 1.06 for regions with low SES (high Townsend index score). This was particularly true for the 2 respiratory subtypes: pneumonia and acute infections. The estimated RR for hospital admissions for pneumonia was 1.04 in Kern County for regions with low SES. The estimated RR for hospital admissions for asthma was 1.18 in San Joaquin County for regions with high SES (low Townsend index score). In Fresno County, the rates of hospital admissions for respiratory conditions, respiratory infections, pneumonia, and asthma per 10 micrograms per cubic meter increments in PM2.5 were higher for regions with high SES.

DISCUSSION

In this study, we performed daily time-series analysis to investigate the impact of short-term PM2.5 concentration on hospital admissions for 4 respiratory conditions among children aged 1 to 9 years in 12 counties in 2 different regions of California. Our results suggest that exposure to ambient levels of PM2.5 is associated with hospital admissions for respiratory conditions with lower-SES children at higher risk for all outcomes examined in nearly all counties even though only a few models were statistically significant. Results also showed that the magnitude of the associations varies depending on the outcome and the county. In one of the study regions (the South Coast region) SES modified the relationship of PM2.5 on the effects on respiratory conditions. These findings are consistent with previous studies that investigated the relationship between acute nitrogen dioxide exposure, socioeconomic deprivation, and hospital admissions for respiratory illnesses in children.30 These findings, similar to ours, showed that the effects of air pollution exposure and SES were independent predictors for hospital admission rates for childhood respiratory illnesses.

To date, most of the time-series studies reporting that short-term exposure to PM2.5 increases risk of hospital admissions for respiratory conditions were based on adult data,31-34 with few studies on children.35-37 An epidemiological study conducted in Zonguldak, Turkey, reported a significant relationship between exposure to PM2.5 and childhood asthma with an odds ratio of 1.15 for increments of 10 micrograms per cubic meter.35 Case-crossover studies in Australia and New Zealand also found that exposure to PM2.5 was associated with increased hospital admissions for bronchitis and pneumonia in children.36 Our findings not only provide evidence for the impact of PM2.5 exposure on hospital admission rates for childhood respiratory illnesses but also suggest the modifying effects of area-based socioeconomic measures on the impact of PM2.5 exposure, especially in the South Coast region of California.

The associations between ambient PM2.5 and increased hospital admission rates of childhood respiratory conditions, respiratory infections, pneumonia, and asthma were stronger in lower-SES areas of the South Coast region, (i.e., Los Angeles, Riverside, Orange, San Bernardino, and San Diego counties) than in higher-SES areas, with the only exceptions being asthma in Orange and Riverside counties. These differences may suggest that the heterogeneity of the effect of PM2.5 on childhood respiratory morbidity in the South Coast region and the Central Valley possibly reflect the inter- and intracounty differences in demographical characteristics of both regions. In the Central Valley the results were less consistent, in that PM2.5 was positively associated with the asthma admissions rate in lower-SES areas of Sacramento County but negatively associated with the asthma admissions rate in lower-SES areas of Fresno, San Joaquin, and Tulare counties. Recent San Joaquin Valley research indicates that the trends and patterns of health outcomes vary by the conditions in the communities.38 Community conditions in the Central Valley are complexly interrelated so perhaps more information on each community's characteristics in the Central Valley could explain the inconsistency of the current models and guide future research.

We observed 2 distinct patterns of association between PM2.5 concentrations and respiratory conditions (Figures 1 and 2). In the South Coast region, the PM2.5 effects on the 4 respiratory outcomes tended away from the null, whereas the PM2.5 effects observed in the Central Valley tended toward the null for the 4 respiratory outcomes. One possible explanation is the fact that PM concentrations in California regions vary seasonally depending on
the nature of the predominant emission sources and meteorological factors. The Central Valley contains more area sources such as field preparation, road dust, and agricultural burning and the South Coast is more dominated by mobile sources or stationary sources (industry). In California, organic carbon, elemental carbon, nitrate, sulfate, and ammonium are the most abundant components of PM2.5. The distribution of these components in PM2.5 varies seasonally and with meteorological conditions. Seasonality is more pronounced in the Central Valley where PM2.5 concentrations are high when stagnant conditions cause ambient pollution to be trapped in the valley during the winter months. In the Central Valley, organic carbon is significantly higher during the winter season because of agricultural burning and residential wood-burning.

Compared with other areas in California, the South Coast region is rather unique in that PM2.5 concentrations are high throughout the year. However, seasonal variations are observed. For example, nitrate production in the South Coast region is greatest during the winter months, although it remains statistically significant during summer months. Sulfate concentrations are highest during summer months in the South Coast region, and the overall sulfate concentrations in the South Coast region are the highest in California. Therefore, the roles nitrate and sulfate might play in the association between PM2.5 and hospital admissions for respiratory conditions among children is an important issue that needs further investigation. So far, 1 study of hospital admissions for respiratory conditions among children in 6 counties of California concluded that PM2.5 components such as elemental carbon, organic carbon, nitrates, and sulfate were associated with higher proportions of respiratory conditions such as pneumonia, asthma, and bronchitis. However, in our study, we did not examine the relationship between the composition of particulate matter and the various respiratory health outcomes because of the lack of daily particulate matter component data. This study suggests that the heterogeneity of PM2.5 effects on hospitalizations may reflect seasonal and regional differences in emissions and in particles' chemical constituents.

Alternatively, the distinct patterns may also suggest that there are differences between many confounders and potential effect modifiers in the Central Valley and South Coast regions. The Central Valley is a highly productive agricultural area on both a national and international scale and its economy is dependent on agricultural and related sectors, which is also highly seasonal and subject to variability because of changes in markets and crops. In addition, many farm workers are transient or part-time workers. Therefore, the unstable wage conditions might contribute to problems in accessing health care.

By contrast, the industries in the South Coast region are highly diverse and provide a more stable job market than in the Central Valley. The distinct pattern might be explained by variations in exposure such as indoor exposures related to housing conditions and personal exposures such as active and passive cigarette smoking. For example, the Townsend index attempts to directly measure material deprivation by factors that include employment status, car ownership, house occupancy, and overcrowding. Each of these factors has been shown to increase adverse health outcomes in several studies. The inclusion of car ownership reflects that poorer people are less likely to own cars and may use public transportation instead. One study has shown that people using public transportation such as buses can have higher exposure to traffic-related pollution as buses can contain more pollutants and move more slowly through traffic, thus exposing the rider for longer periods of time.

Nevertheless, the inclusion of employment status, house occupancy, and overcrowding reflects the circumstances that a low-SES population might be more susceptible to poor lifestyle conditions than higher-SES populations. For example, lower-SES populations receive less-adequate health care (e.g., accessibility and quality of care) have poorer living conditions, and have a poorer diet (e.g., consuming less fruit and vegetables while consuming more fat) compared with high-SES populations. As a consequence, compared with the individual-level Townsend index, the area-based Townsend index may not adequately capture the environmental determinants of health related to personal exposure patterns. In addition, the relationship is more complex and influenced by other factors that determine access to health care such as distance or drive time to care facilities, rural or urban area, and ethnic distribution of the area. These issues could not be explored further because of the lack of population or individual information.

Limitations

Because of unsuccessful linkage of ZCTAs and zip codes, we excluded 30% of the zip codes from our analysis. Because the exclusion was unrelated to the status of respiratory outcomes and exposure assignment, in general, this type of systematic bias should not influence the association between hospital admissions of respiratory illnesses and PM2.5, although in some circumstances it might bias the association away from the null.

Another limitation of our study is the ecological design, in which we evaluated the association between SES, PM2.5, and different respiratory outcomes in different counties, because we have only population information in
our study. However, despite its weaknesses, an ecological study is useful for a quick and inexpensive method of research using data that are readily available. In our study, the ecological design found an interesting association between the modifying effect of SES on the relationship between PM2.5 and hospital admissions for childhood respiratory conditions, providing impetus for more specific and detailed research. As such, more studies of the relationship among area-based SES, PM2.5, and childhood respiratory health are needed. Nevertheless, our results are consistent with findings in previous studies that reported that PM2.5 levels are positively associated with hospital admissions of respiratory conditions among children.

Conclusions

This study shows differences, according to area SES levels, in the impacts of PM2.5 on hospital admissions for respiratory conditions in 5 California South Coast counties, with lower SES areas showing a stronger association of PM2.5 with hospital admissions for acute respiratory conditions, pneumonia, and asthma. By contrast, in the Central Valley of California, the association of PM2.5 with hospital admissions was not influenced by area SES levels. Socioeconomic effects appeared to be independent of and modified by the impact of PM2.5 on children's hospital admissions. Because of the nature of this study design and the difficulty of accessing individual information, further confirmatory studies of the relationship among area-based SES, PM2.5, and childhood respiratory health are needed.

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