Race/Ethnicity, Residential Segregation, and Exposure to Ambient Air Pollution: The Multi-Ethnic Study of Atherosclerosis (MESA)

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Objectives. We described the associations of ambient air pollution exposure with race/ethnicity and racial residential segregation.

Methods. We studied 5921 White, Black, Hispanic, and Chinese adults across 6 US cities between 2000 and 2002. Household-level fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_X) were estimated for 2000. Neighborhood racial composition and residential segregation were estimated using US census tract data for 2000.

Results. Participants in neighborhoods with more than 60% Hispanic populations were exposed to 8% higher $PM_{2.5}$ and 31% higher NO_X concentrations compared with those in neighborhoods with less than 25% Hispanic populations. Participants in neighborhoods with more than 60% White populations were exposed to 5% lower $PM_{2.5}$ and 18% lower NO_X concentrations compared with those in neighborhoods with less than 25% of the population identifying as White. Neighborhoods with Whites underrepresented or with Hispanics overrepresented were exposed to higher $PM_{2.5}$ and NO_X concentrations. No differences were observed for other racial/ethnic groups.

Conclusions. Living in majority White neighborhoods was associated with lower air pollution exposures, and living in majority Hispanic neighborhoods was associated with higher air pollution exposures. This new information highlighted the importance of measuring neighborhood-level segregation in the environmental justice literature. (*Am J Public Health.* 2014;104:2130–2137. doi:10.2105/AJPH.2014.302135)

In the United States, race/ethnicity is highly correlated with residential location, with Whites and minorities often living segregated from one another.[1,2] Differential residential location can result in important racial/ethnic differences in environmental exposures, such as air pollution.[1,3–6] Epidemiological studies have consistently shown increased risk for morbidity and mortality from cardiovascular[7–10] and respiratory diseases (chronic obstructive pulmonary disease, asthma, and lung cancer)[8,11–14] associated with exposure to ambient air pollution, including exposure to fine particulate matter (particles < 2.5 μm in aerodynamic diameter [$PM_{2.5}$]) and nitrogen oxides (NO_X; sum of nitric oxide, nitrogen dioxide, nitrous acid, and nitric acid).[15–21] Predominantly minority areas are more likely to have[22,23] or be more proximal[4,24,25] to hazardous sites or air pollution sources, including point sources and roadway traffic. However, few studies have investigated how individual- or household-level exposure estimates are associated with race/ethnicity.

In addition to proximity to pollution sources, poor enforcement of environmental regulations in minority communities and inadequate response to community complaints may also contribute to higher exposure to environmental hazards in minority communities.[1] These institutional factors reflect physical, political, social, and economic characteristics of neighborhoods that are often correlated with their racial/ethnic composition and the level of racial residential segregation. For these reasons, measures of neighborhood racial/ethnic composition and racial residential segregation may be associated with environmental exposures independently of the individual race/ethnicity of residents. Despite the importance of contextual information for advancing research for environmental justice, few studies have simultaneously examined how neighborhood characteristics and the race/ethnicity of study participants are related to environmental exposures or examined racial residential segregation as it relates to air pollution exposure.[6,26]

Also, most studies have compared exposure among Whites and Blacks with few studies including other races/ethnicities.[4,24,27–29] Our objective in this study was to describe associations of exposure to ambient air pollution, estimated by annual average $PM_{2.5}$ and NO_X concentrations at the household level, with race/ethnicity, neighborhood racial/ethnic composition, and racial/ethnic residential segregation in White, Black, Hispanic and Chinese adults who participated in the Multi-Ethnic Study of Atherosclerosis (MESA) in 6 US communities.

METHODS

MESA, a longitudinal study of subclinical cardiovascular disease, enrolled 6814 White, Black, Hispanic, and Chinese participants ages 45 to 84 years from Forsyth County (Winston-Salem), North Carolina; New York, New York; Baltimore, Maryland; St. Paul, Minnesota; Chicago, Illinois; and Los Angeles, California between 2000 and 2002.[30] White participants were recruited from all 6 study sites; Black participants were recruited from all sites except Minnesota; Hispanic participants were only recruited in California, New York, and Minnesota; and Chinese participants were only recruited in Illinois and California. Of the 6814 participants who completed the baseline MESA examination, 6000 consented to participate in the MESA Air study. We excluded 5 participants who were enrolled from sites with few participants of the same race/ethnicity (2 Chinese Americans in New York and 3 Hispanics in Winston-Salem), 60 participants missing data for racial residential segregation measures, and 19 participants missing other relevant covariates; this left a total of 5921 participants distributed across 1147 census tracts for this analysis.

Ambient Air Pollution Exposures

Concentrations of $PM_{2.5}$ and NO_X at individual residence locations were predicted by MESA Air for the MESA cohort using area-specific hierarchical spatio-temporal models.[31–33] These models used spatially varying long-term average concentrations and seasonal and long-term trends, as well as spatially correlated, but temporally independent, residuals. The MESA Air exposure models were built using monitoring data from the US Environmental Protection Agency (EPA) Air Quality System, supplemented with data collected specifically for the MESA Air study. The study-specific data were collected from 27 fixed-site monitors situated in MESA communities that collected more than 100 consecutive 2-week integrated air samples during the course of the study. Monitors were placed at a subset of nearly 700 participant homes, and for NO_X monitoring, the monitors were placed during simultaneous deployment ("snapshot" campaigns) of more than 100 samples in each MESA region during 3 sampling periods (December through February; May through August; and October/November or March/April). This sampling was described in more detail by Cohen et al.[34]

Each model also used geographic variables, including roadway density, land use, and outputs from dispersion models, among others. To characterize residence-specific ambient air pollution exposure, we used likelihood-based annual average concentrations of $PM_{2.5}$ and NO_X for 2000 that were estimated for each participant based on the location(s) lived during that year.

Race/Ethnicity and Racial/Ethnic Residential Segregation

Participant race/ethnicity was assessed by self-report and categorized as non-Hispanic White ("White"), non-Hispanic Black ("Black"), Hispanic, and Chinese. We used census-tract level data from the 2000 Census to characterize participant neighborhoods. We estimated the census tract racial/ethnic composition using the percentage of the census tract population who identified themselves as White, Black, Hispanic, or Asian (the US Census does not collect information for Chinese individuals separately). This variable was categorized as less than 25%, 25% to 60%, or more than 60% of a given racial/ethnic group.

Although racial/ethnic composition is often used as a proxy for racial residential segregation, it does not take into account information about the composition of the larger spatial area or adjacent census tracts. Thus, we further assessed racial residential segregation using the Getis and Ord G_i* statistic[35,36] ("G statistic") calculated separately for Whites, Blacks, Hispanics, and Asians. The G statistic yields a *Z*-score for each census tract that estimates the extent to which the racial/ethnic composition in that tract and neighboring tracts deviates from the mean racial/ethnic composition of the county overall. A nonstatistically significant G statistic indicates no clustering of tracts that significantly deviate from the racial/ethnic composition of the county. A statistically significant positive G statistic indicates clustering of census tracts with that race/ethnicity overrepresented (greater percentage of race/ethnicity) compared with the county overall. A statistically significant negative G statistic indicates clustering of census tracts with that race/ethnicity underrepresented (lower percentage of race/ethnicity) compared with the county overall. An alpha level of .1 was set for the G statistic, corresponding to a G statistic of ± 1.645. We identified neighborhoods with no clustering ($-1.645 >$ G statistic < 1.645), clustering characterized by underrepresentation of a race/ethnicity ("underrepresented" [G statistic ≤ -1.645]), and clustering characterized by overrepresentation of a race/ethnicity ("overrepresented" [G statistic ≥ 1.645]).

Other Variables

We used self-reported educational attainment and annual family income at baseline as primary measures of participant socioeconomic status (SES). We measured participant education as the highest level completed and categorized the levels as less than high school, high school, some college or technical school, and college or graduate degree. Annual family income was collected in 13 categories. We categorized annual family income as unknown, $24 999 or less, $25 000 to $49 999, $50 000 to $74 999, and $75 000 and greater. We also included data on census tract population size and median family income in the census tract from the 2000 Census as covariates. We treated the study site as a categorical variable.

Statistical Analysis

We stratified descriptive statistics by participant race/ethnicity (White, Black, Hispanic, and Chinese). Air pollution concentrations were log-transformed for the analyses. Using mixed-effects models, we computed crude and adjusted ratios of the ambient air pollution ($PM_{2.5}$ and NO_X concentrations) geometric means by comparing the following: (1) Black, Hispanic, and Chinese participants with White participants; (2) levels of census tract racial composition (25%–60% and > 60% vs < 25% for each race/ethnicity); and (3) categories of racial residential segregation (G statistic, over- or underrepresentation of a racial/ethnic group vs no clustering). Mixed-effect models included a census-tract specific random intercept to account for the clustering of individuals. We adjusted the multivariable models for gender (dichotomous), age (continuous), education (categorical) and annual family income (categorical), neighborhood median family income (continuous), and neighborhood population size (log-transformed). We also adjusted models that included racial composition and racial residential segregation participant race/ethnicity. Second, we further adjusted for study site (categorical). For racial composition, we also evaluated the dose–response relationship between the measures of air pollution and percentage of race/ethnicity in the census tract, stratified by participant race/ethnicity, and we formally evaluated race*site interactions. All statistical analyses were performed using R software (version 2.14.2, R Project for Statistical Computing, Vienna, Austria). All statistical tests were 2-sided, and confidence intervals (CIs) were set at 95%.

RESULTS

Among the study participants, 40% were White, 28% were Black, 21% were Hispanic, and 11% were Chinese (Table 1). Forty-eight percent of participants were men, and the mean age was 62 years, with no differences by race/ethnicity. Educational attainment and family income were higher among Whites and lower among Hispanic participants. The geometric means of ambient air pollution was 16.5 micrograms per cubic meter for $PM_{2.5}$ and 43.2 parts per billion for NO_X. $PM_{2.5}$ concentrations were higher in Chinese participants compared with other races/ethnicities, and NO_X concentrations were higher in Hispanics and Chinese, intermediate in Blacks, and lower in Whites (data available as a supplement to the online version of this article at http://www.ajph.org). In unadjusted models, air pollution concentrations were similar across other participant characteristics, except study site (data available as a supplement to the online version of this article at http://www.ajph.org). Median $PM_{2.5}$ concentrations were highest in Los Angeles (21.5 μg/m^3) and lowest in St. Paul (12.9 μg/m^3). Median NO_X concentrations were highest in New York (81.5 ppb) and lowest in Winston-Salem (21.3 ppb).

Census Tract Characteristics

Participants were more likely to reside in census tracts where more than 60% of the residents were of their race/ethnicity than in census tracts where they were the minority, except for Chinese participants, who were most likely to reside in census tracts with 25% to 60% Asian populations (Table 2). Participants were also more likely to reside in census tracts with high values for the spatial clustering of their race/ethnicity than in areas with spatial clustering of another race/ethnicity (Table 2). Compared with other races/ethnicities, White participants lived in census tracts with higher median family incomes and were least likely to live in a predominately Hispanic census tract. Black participants were less likely to live in predominately Asian census tracts compared with other races/ethnicities. Hispanic participants lived in census tracts with the largest population size and lowest median family incomes. Chinese participants resided in the least populated census tracts and were less likely to live in a predominately Black census tract.

Air pollution concentrations were similar across census tract characteristics, except census tract median family income, percentage Hispanic, and percentage Asian in the census tract, and were positively associated with air pollution concentrations (data available as a supplement to the online version of this article at http://www.ajph.org).

TABLE 1—Characteristics of Participants Stratified by Race/Ethnicity: Multi-Ethnic Study of Atherosclerosis, 6 US Communities, 2000–2002

Characteristic	White	Black	Hispanic	Chinese
No. of participants	2361	1629	1266	665
Gender, %				
Female	52.0	54.8	51.9	50.1
Male	48.0	45.2	48.1	49.9
Age, y, mean (SD)	62.4 (10.1)	61.9 (9.9)	61.4 (10.3)	61.9 (10.2)
Education, %				
< high school	4.7	11.4	42.1	21.4
High school	17.0	19.0	21.3	16.1
Some college/technical	27.5	34.7	26.1	21.4
College/graduate degree	50.9	34.9	10.4	41.2
Family income, $, %				
≤ 24 999	15.2	26.7	46.5	45.4
25 000–49 999	26.3	29.8	33.4	23.3
50 000–74 999	19.9	19.3	10.5	12.3
≥ 75 000	36.3	16.9	7.8	18.5
Unknown	2.2	7.3	1.8	0.5
Study site, %				
Winston-Salem, NC	21.4	26.0	0.0	0.0
New York, NY	8.7	20.8	35.2	0.0
Baltimore, MD	19.6	28.5	0.0	0.0
St. Paul, MN	23.6	0.0	29.1	0.0
Chicago, IL	21.5	16.6	0.0	41.5
Los Angeles, CA	5.2	8.0	35.8	58.5
Air pollution exposure, GM (95% CI)				
$PM_{2.5}$ concentration, μg/m^3	15.7 (15.6, 15.8)	16.5 (16.4, 16.6)	16.9 (16.8, 17.1)	19.2 (19.0, 19.4)
NO_X concentration, ppb	33.6 (33.0, 34.4)	43.3 (42.2, 44.4)	58.7 (57.1, 60.4)	58.5 (56.3, 60.8)

Note. CI = confidence interval; GM = geometric mean; NO_x = nitrogen oxides; $PM_{2.5}$ = fine particulate matter.

Air Pollution Differences

After adjustment for age, gender, education, family income, census tract median family income, population size, and for study site, $PM_{2.5}$ concentrations were 1% higher for Hispanic participants compared with White participants (Figure 1). Black and Hispanic races/ethnicities were associated with 2% higher NO_X concentrations (95% CI = 0%, 3% and 95% CI = 1%, 4%, respectively) compared with White participants (Figure 1). We found significant geographic heterogeneity in racial/ethnic differences in exposure to ambient air pollution (all *P* values for race*site interactions < .001). Compared with Whites, Blacks had higher $PM_{2.5}$ concentrations in New York and higher NO_X concentrations in Winston-Salem; Hispanics had higher $PM_{2.5}$ and NO_X exposures than Whites in New York and Los Angeles; and Chinese had similar $PM_{2.5}$ and NO_X levels to Whites in Los Angeles, but lower $PM_{2.5}$ and NO_X exposures than Whites in Chicago.

After adjustment for participant and neighborhood characteristics, and study site, participants living in census tracts with more than 60% Whites were exposed to 2% lower $PM_{2.5}$ and 8% lower NO_X compared with participants living in census tracts with less than 25% Whites (Table 3). Participants living in census

TABLE 2—Characteristics of Census Tracts Stratified by Participant Race/Ethnicity: Multi-Ethnic Study of Atherosclerosis, 6 US Communities, 2000–2002

Characteristic	White (n = 2361), Mean (SD) or %	Black (n = 1629), Mean (SD) or %	Hispanic (n = 1266), Mean (SD) or %	Chinese (n = 665), Mean (SD) or %
Population size	5072 (2170)	4841 (2447)	5905 (2865)	4785 (1768)
Median family income, $	70 843 (34 470)	42 919 (19 881)	42 741 (22 873)	59 602 (31 173)
Racial/ethnic composition, %				
White				
< 25	9.3	71.7	60.9	52.8
25–60	31.0	16.6	19.8	21.4
> 60	59.7	11.7	19.3	25.9
Black				
< 25	78.4	16.8	88.7	98.5
25–60	15.8	25.9	10.1	1.4
> 60	5.9	57.3	1.2	0.2
Hispanic				
< 25	81.4	82.8	26.4	61.7
25–60	17.0	11.9	31.5	30.5
> 60	1.5	5.3	42.1	7.8
Asian				
< 25	97.6	99.3	90.4	38.8
25–60	2.3	0.6	8.1	41.1
> 60	0.2	0.1	1.4	20.2
Residential segregation, %				
White				
Underrepresented	22.9	70.7	63.3	49.6
No clustering	58.4	24.7	32.5	34.9
Overrepresented	18.7	4.5	4.2	15.5
Black				
Underrepresented	12.6	3.0	3.2	10.6
No clustering	80.5	34.4	92.4	88.6
Overrepresented	6.9	62.6	4.4	0.8
Hispanic				
Underrepresented	8.9	9.4	2.7	11.0
No clustering	62.9	72.1	29.4	75.3
Overrepresented	28.2	18.5	67.9	13.7
Asian				
Underrepresented	1.7	35.4	13.5	0.6
No clustering	79.4	56.1	69.0	18.2
Overrepresented	18.9	8.5	17.5	81.2

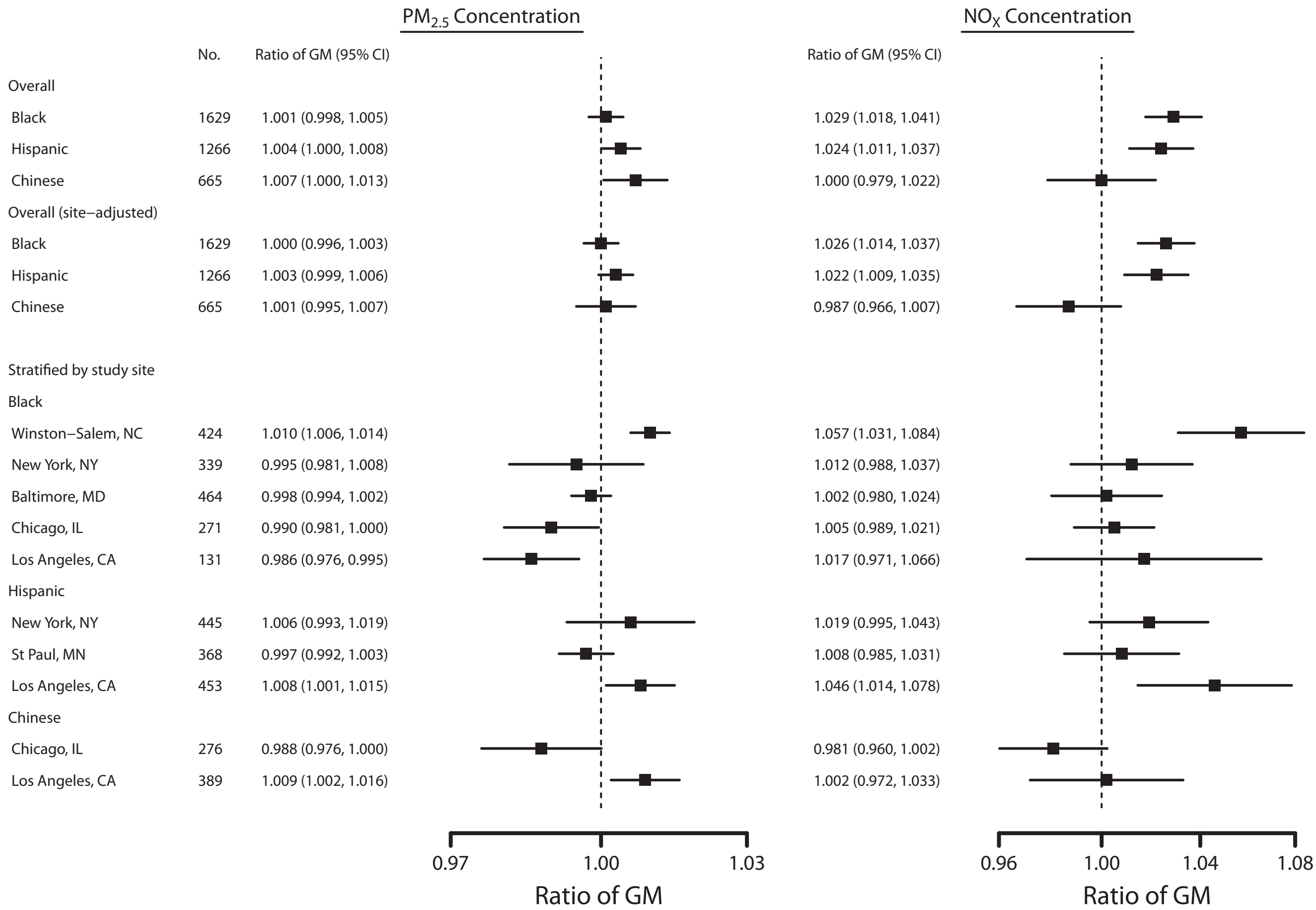
Note. The 6 US communities were Forsyth County (Winston-Salem), NC; New York, NY; Baltimore, MD; St. Paul, MN; Chicago, IL; and Los Angeles, CA.

tracts with more than 60% Blacks were exposed to 5% lower NO_X compared with participants living in census tracts with less than 25% Black (Table 3). After adjustment, participants living in census tracts with more than 60% Hispanics were exposed to 3% higher $PM_{2.5}$ concentrations and 14% higher NO_X concentrations compared with census tracts with less than 25% Hispanics (Table 3). Participants living in census tracts with more than 60% Asians were exposed to 3% higher $PM_{2.5}$ concentrations compared with census tracts with less than 25% Asians (Table 3). Associations between census tract racial composition and $PM_{2.5}$ and NO_X concentrations were similar across participant race/ethnicity (data available as a supplement to the online version of this article at http://www.ajph.org).

Consistent with our racial/ethnic composition findings, compared with participants living in census tracts without clustering, participants living in clusters of census tracts where Whites were significantly underrepresented or Hispanics were overrepresented were exposed to higher $PM_{2.5}$ and higher NO_X concentrations (Table 3). There were no differences comparing participants living in clusters of census tracts with Blacks over- or underrepresented. After adjustment for site, participants living in a cluster of census tracts where Hispanics were overrepresented had 4% higher $PM_{2.5}$ and 13% higher NO_X concentrations compared with participants in census tracts without clustering. Participants living in a cluster of census tracts where Whites were underrepresented were exposed to higher $PM_{2.5}$ and NO_X concentrations (1% and 12%, respectively) compared with participants in census tracts without clustering. Living in a cluster of census tracts where Asians were underrepresented was associated with 8% higher NO_X concentrations compared with living in census tracts without clustering. Site-specific analyses for associations of racial/ethnic composition and residential segregation with air pollution were not possible because some categories of racial/ethnic composition or segregation were not represented at all sites (data available as a supplement to the online version of this article at http://www.ajph.org).

DISCUSSION

Compared with White participants, Black and Hispanic participants were exposed to higher air pollution concentrations, although these differences were small. In addition, living in majority White neighborhoods was associated with lower household-level $PM_{2.5}$ and NO_X concentrations, and living in majority Hispanic neighborhoods was associated with higher air pollution exposures, as measured by household-level measures of $PM_{2.5}$ and NO_X concentrations. The racial composition and segregation of a neighborhood were associated with air pollution exposure independent of an individual's race/ethnicity. Our findings



Note. Points represent the ratio of GM of fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_X) concentrations comparing participants of each race/ethnicity to White participants. Horizontal lines represent 95% confidence intervals (CIs). Results were adjusted for age, gender, education, participant annual family income, census tract, median family income, and population size. Text provided for ratio of GM was rounded to 2 decimal places.

FIGURE 1—Ratio of geometric means (GM) of air pollution by race/ethnicity stratified by study site: Multi-Ethnic Study of Atherosclerosis, 6 US communities, 2000–2002.

highlighted the importance of measuring neighborhood-level segregation in the environmental justice literature.

We focused this analysis on 2 types of air pollutants, $PM_{2.5}$ and NO_X. While $PM_{2.5}$ reflects overall exposure to fine particles from stationary and mobiles sources, NO_X is a good marker of traffic-related air pollution and has the advantage of characterizing within-city variability while also allowing for consistency of exposure across sites and populations because the chemical composition of particulate matter can vary geographically.[37–39] As a result of evidence of the health effects of air pollution, the EPA set the National Ambient Air Quality Standards for $PM_{2.5}$ and NO_2 at 15 micrograms per cubic meter and 53 parts per billion, respectively, during 2000.[40] In our study, concentrations of $PM_{2.5}$ and NO_X at participant residences exceeded this standard for 79% of participants for $PM_{2.5}$ and for 38% of participants for NO_X.

Previous research evaluated racial/ethnic differences in air pollution exposure. In 25 064 individuals in California's South Coast Air Basin, geometric mean concentrations of $PM_{2.5}$ emitted from diesel engines were higher for non-White people than for Whites, after accounting for population density and daily travel distance.[28] A few other studies examined racial/ethnic differences using direct measures or estimates of air pollution concentrations, but additional studies showed racial/ethnic differences using other markers of air pollution. Studies of children in Florida[24] and California[41,42] found consistent differences in the spatial distribution of sources of air pollution by race/ethnicity (based on proximity to pollutant sources and high traffic density), with minority children facing higher potential exposure compared with their White counterparts. Proximity to a major roadway was used as a marker of long-term exposure to traffic-related air pollution. Consistent with our study, Black and Hispanic MESA participants who underwent cardiac magnetic resonance imaging were more likely to live near major roadways than participants of other races.[43] A study of 3886 individuals hospitalized for acute myocardial infarction in 64 centers across the United States from 1989 to 1996

TABLE 3—Ratio of Geometric Means of Air Pollution Exposure by Census Tract Racial/Ethnic Composition and Residential Segregation: Multi-Ethnic Study of Atherosclerosis, 6 US Communities, 2000–2002

Characteristic	No.	$PM_{2.5}$ Concentration (95% CI)		NO_X Concentration (95% CI)	
		Model 1	Model 2	Model 1	Model 2
Racial/ethnic composition, %					
White					
< 25	2510	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
25–60	1395	0.99 (0.98, 1.00)	1.00 (0.99, 1.01)	0.91 (0.89, 0.94)	0.96 (0.94, 0.99)
> 60	2016	0.95 (0.94, 0.96)	0.98 (0.97, 0.99)	0.82 (0.79, 0.85)	0.92 (0.89, 0.95)
Black					
< 25	3902	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
25–60	931	0.99 (0.98, 1.00)	0.99 (0.98, 1.00)	0.96 (0.93, 0.99)	0.96 (0.93, 0.98)
> 60	1088	0.98 (0.97, 0.99)	0.99 (0.98, 1.00)	0.93 (0.90, 0.97)	0.95 (0.92, 0.98)
Hispanic					
< 25	4015	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
25–60	1198	1.05 (1.04, 1.06)	1.02 (1.02, 1.03)	1.12 (1.09, 1.15)	1.03 (1.01, 1.05)
> 60	708	1.08 (1.07, 1.09)	1.03 (1.02, 1.04)	1.31 (1.26, 1.36)	1.14 (1.10, 1.18)
Asian					
< 25	5324	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
25–60	439	1.03 (1.02, 1.04)	1.02 (1.01, 1.03)	1.10 (1.06, 1.14)	1.04 (1.01, 1.07)
> 60	158	1.03 (1.01, 1.05)	1.03 (1.01, 1.04)	1.08 (1.01, 1.16)	1.03 (0.97, 1.09)
Residential segregation, %					
White					
Underrepresented	2823	1.13 (1.10, 1.15)	1.01 (1.00, 1.02)	1.59 (1.49, 1.69)	1.12 (1.08, 1.15)
No clustering	2426	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
Overrepresented	672	1.06 (1.03, 1.10)	1.02 (1.01, 1.04)	1.24 (1.13, 1.36)	1.03 (0.98, 1.08)
Black					
Underrepresented	452	0.96 (0.92, 0.99)	1.01 (0.99, 1.03)	0.86 (0.77, 0.96)	1.03 (0.98, 1.08)
No clustering	4226	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
Overrepresented	1243	0.97 (0.94, 0.99)	0.98 (0.97, 1.00)	0.96 (0.89, 1.03)	1.00 (0.96, 1.03)
Hispanic					
Underrepresented	470	1.16 (1.12, 1.20)	1.01 (0.99, 1.03)	1.40 (1.27, 1.54)	1.01 (0.96, 1.06)
No clustering	3532	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
Overrepresented	1919	1.09 (1.06, 1.11)	1.04 (1.02, 1.05)	1.55 (1.46, 1.65)	1.13 (1.09, 1.16)
Asian					
Underrepresented	791	1.08 (1.05, 1.11)	1.01 (1.00, 1.03)	1.38 (1.27, 1.49)	1.08 (1.04, 1.12)
No clustering	3783	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)	1.00 (Ref)
Overrepresented	1347	1.09 (1.06, 1.12)	1.01 (1.00, 1.02)	1.02 (0.94, 1.09)	1.02 (0.98, 1.05)

Note. CI = confidence interval; NO_x = nitrogen oxides; $PM_{2.5}$ = fine particulate matter. Model 1 adjusted for age, gender, race/ethnicity, education, family income, census tract, median family income, and population size. Model 2 further adjusted for study site. The 6 US communities were Forsyth County (Winston-Salem), NC; New York, NY; Baltimore, MD; St. Paul, MN; Chicago, IL; and Los Angeles, CA.

also found individuals living closer to a major roadway were more likely to be of non-White race/ethnicity.[44]

Living in census tracts with higher percentages of Hispanics was associated with higher exposures to $PM_{2.5}$ and NO_X, independently of individual race/ethnicity. These findings were largely consistent with a few previous studies of racial/ethnic composition and air pollution exposure. In metropolitan Phoenix, Arizona, census block groups with higher proportions of Hispanic immigrants were exposed to higher levels of nitrogen dioxide; however, no statistically significant differences were observed with the proportion of Blacks and air pollution exposures.[45] In a study of public parks and park-adjacent neighborhoods in Los Angeles, $PM_{2.5}$ concentrations were positively associated with percentage of Hispanic, Asian, and Black races/ethnicities, and NO_2 concentrations with percentage of Hispanic and Asian races/ethnicities.[4] In urban census tracts located in the northeastern United States, annual concentrations of $PM_{2.5}$ in the census tract increased for each interquartile range increase in census tract percentage Black, Asian, and other non-White race, respectively.[27]

Little is known regarding the association between racial segregation and air pollution exposures. In a study of exposure to air toxins, Morello-Frosch and Jesdale found that more segregated neighborhoods had higher concentrations and that racial/ethnic disparities in air toxin exposure were more pronounced in segregated areas.[26] In our study, after adjusting for study site, living in clusters of census tracts where Whites were underrepresented or Hispanics were overrepresented was associated with higher air pollution exposure. This was consistent with the observation that census tracts with a lower percentage of Whites and higher percentages of Hispanics had higher exposures. No differences were seen for racial/ethnic composition or residential segregation for Blacks; these findings might be related to other sociodemographic characteristics, such as a higher SES of participants and neighborhoods in the study. Studies showed that Blacks with higher SES were less segregated from Whites, as measured by the dissimilarity index, than those with lower SES.[46–49] Also, segregation of Blacks from Whites was shown to be lower in multiethnic areas because Hispanic and Asian/Pacific Islanders might serve as buffer populations between Whites and Blacks.[50,51] It will be important to evaluate the consistency of our findings for racial residential segregation and air pollution exposure in other studies that include White, Black, Hispanic, and Asian populations.

In addition, we found substantial geographic heterogeneity in racial/ethnic differences in exposure to ambient air pollution, and adjustment for the study site attenuated associations of race/ethnicity with air pollution exposure.

Differences in air pollution associations by site were also shown in a study conducted in MESA that examined differences in air pollution exposure by individual and neighborhood SES.[52] In that study, after adjusting for participant age, gender, and race/ethnicity, higher SES was associated with higher air pollution concentrations in New York, but not in other sites. Similar to our study, that study also found that neighborhood-level characteristics were more strongly associated with air pollution exposures than were individual-level factors. Because of the association between race/ethnicity and SES, these findings indicated that differences in air pollution exposures by race/ethnicity were complex and might not be the same for all locations in the United States.

Strengths and Limitations

Our study benefitted from individual-level estimates of air pollution exposure, the multicity study design, and the high quality standardized protocol. The state-of-the-art air pollution exposure estimates our study used provided a level of spatial resolution and sophisticated statistical modeling not previously available in epidemiological analysis. The use of a multiethnic cohort designed to recruit a large proportion of participants from non-White groups, including Black, Chinese, and Hispanic participants, allowed us to assess exposure to air pollution in previously unexplored racial groups. Our study was also strengthened by the assessment of racial/ethnic differences in air pollution exposure at the individual and neighborhood levels.

A few limitations should be taken into account. MESA recruitment methods did not ensure the representativeness of the source population. MESA participants were enrolled at each study site with the intent of having specific distributions across strata defined by race/ethnicity, gender, and age group, and not by random sample; because of this sampling strategy, MESA participants and their neighborhoods might not be representative of the race/ethnicity or spatial distribution of the populations at each site (data available as a supplement to the online version of this article at http://www.ajph.org). Because of the sampling methodology, the major sources of ambient air pollution, and the population demographic characteristics in this study, our findings might not be generalizable to other populations, including rural populations. Also, data for some races/ethnicities were unavailable for some study sites, and we were unable to evaluate associations comparing all races/ethnicities in all cities. Models were conducted with and without adjustment for study site; however, there was the potential for residual confounding and our associations could potentially be underestimated, but could also be overestimated. Lastly, we used mixed models with census tract specific intercepts. However, some spatial autocorrelation might not be fully captured by these models. In a study conducted in MESA that examined differences in air pollution exposure by individual and neighborhood SES, findings from mixed effect models with census tract intercepts were similar to those from spatial intrinsic conditional autoregressive models that further accounted for similarities between neighboring census tracts.[52] In addition, although residual spatial autocorrelation might be problematic, spatial autocorrelation could also reflect the social, political, and economic influences that tended to group populations with common features.

Conclusions

In our multiethnic study, the racial composition and segregation of a neighborhood were associated with air pollution exposure independently of individual race/ethnicity. Our findings highlighted the importance of measuring neighborhood-level segregation in the environmental justice literature. The higher levels of exposure to ambient air pollution among ethnic minorities and minority communities in this study, which in some cases exceeded the EPA standards, contributed to environmental injustice and highlighted the need for additional strategies for reducing racial/ethnic disparities in air pollution exposure and air pollution-related morbidity and mortality. ■

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M. R. Jones, A. Navas-Acien, J. D. Kaufman, A. Hajat, and A. V. Diez-Roux conceptualized the study and its design. A. V. Diez-Roux, K. N. Kershaw, J. D. Kaufman, and W. S. Post acquired data and performed quality control. M. R. Jones performed the statistical analysis. M. R. Jones and A. Navas-Acien drafted the article. All of the authors participated in the interpretation of data and critical revision of the article.

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Note. This research has not been formally reviewed by the EPA. The views expressed in this document are solely those of the authors and the EPA does not endorse any products or commercial services mentioned in this publication.

Human Participant Protection

Institutional review board approval was granted at each study site, and written informed consent was obtained from all participants.

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