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Air Pollution, Cardiovascular Outcomes, and Social Disadvantage: The Multi-ethnic Study of Atherosclerosis

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Abstract

Background—Social factors may enhance health effects of air pollution, yet empirical support is inconsistent. The interaction of social and environmental factors may only be evident with long-term exposures and outcomes that reflect long-term disease development

Methods—We used cardiac magnetic resonance imaging data from the Multi-Ethnic Study of Atherosclerosis to assess left-ventricular mass index (LVMI) and left-ventricular ejection fraction (LVEF). We assigned residential concentrations of fine particulate matter (PM_{2.5}), oxides of nitrogen (NO_x), and nitrogen dioxide (NO₂) in the year 2000 to each participant in 2000 using prediction models. We examined modifying roles of four measures of adversity: race/ethnicity, racial/ethnic residential segregation, and socioeconomic status (SES) and psychosocial adversity as composite indices on the association between air pollution and LVMI or LVEF.

Results—Compared to whites, blacks showed a stronger adjusted association between air pollution and LVMI. For example, for each 5 µg/m³ greater PM_{2.5} level, whites showed a 1.0 g/m² greater LVMI (95%CI: -1.3, 3.1) while blacks showed an *additional* 4.0 g/m² greater LVMI

(95%CI: 0.3, 8.2). Results were similar for NO_x and NO₂ with regard to black race and LVMI. However, we found no evidence of a modifying role of other social factors or ethnic groups. Furthermore, we found no evidence of a modifying role for any social factors or racial/ethnic groups on the association between air pollution and LVEF.

Conclusions—Our results suggest that racial group membership may modify the association between air pollution and cardiovascular disease.

Background

Researchers have documented the associations between various social, psychosocial, and environmental factors and health, but usually not in the same study or even in the same disciplinary. Because these factors are often spatially correlated and have common biological mechanisms (e.g., inflammation and oxidative stress (1-3)), they may act jointly to affect health (4-6). Furthermore, the United States Air Pollution Prevention and Control Act requires that the National Ambient Air Quality Standards protect populations that may be particularly vulnerable (i.e., responsive) to the health effects of air pollution (7). Hence, it is a public health imperative to understand the factors, including the social and psychosocial factors that alter vulnerability to air pollution.

Not only can social and psychosocial factors independently affect health, but they may also modify the association between environmental hazards and health such that the most disadvantaged also are most detrimentally affected. Investigations into vulnerability (or modifying effects) however, have produced mixed results (8-11). This may be due to the social, psychosocial, and health measures examined. First, single social or psychosocial measures may not adequately capture vulnerability to environmental hazards. Rather, researchers note the importance of examining the cumulative effects of numerous social and psychosocial factors when investigating vulnerability to environmental health (12, 13). Neighborhood measures like racial/ethnic residential segregation may capture the accumulation of multiple adverse social and psychosocial exposures. In the joint effects of racial segregation and air pollution on health, the association between air pollution and cancer risk was found to increase with higher levels of segregation (14). Furthermore, multi-item indices may also capture information from different domains of life that play a role in vulnerability. For example, researchers recently reported evidence of a modifying role of social stress, modeled as an index of multiple social scales, on the association between short-term PM_{2.5} exposure and blood pressure (15).

Second, it is plausible that the interacting effects of social/psychosocial and environmental factors are more consistently evident for adult health outcomes that reflect chronic, long-term exposure (6). While there is evidence suggesting the importance of short-term exposures and acute outcomes with regard to respiratory health, the evidence is mixed with regard to cardiovascular health (8-10, 15). Two cardiovascular outcomes that reflect long-term cardiac overload, commonly due to hypertension, are left-ventricular mass index (LVMI) and ejection fraction (LVEF). Lower LVED and greater LVMI, in particular, is an independent predictor of cardiovascular disease (16-18). PM_{2.5} and traffic exposures have been found to be associated with LVMI (but not LVEF) (19). However, to our knowledge,

the modifying effects of social disadvantage or psychosocial adversity have not been examined for this outcome.

We used data from the Multi-Ethnic Study of Atherosclerosis (MESA), the MESA Air Pollution Study (MESA Air), and the MESA Neighborhood Study to examine vulnerability, in terms of additive interactions, between social/psychological factors and air pollution on LVMI and LVEF. We extend the literature in this area in different ways. First, we examine the additive interactions between social/psychological factors and air pollution on LVMI and LVEF in a racially and ethnically diverse population-based epidemiologic study using state-of-the-art air pollution exposure estimates. Second, we examine both individual and neighborhood measures of social disadvantage and psychological adversity. Specifically, we examine four measures of cumulative social disadvantage and psychological adversity: race/ethnicity, an individual socioeconomic status (SES) composite index, racial/ethnic residential segregation, and a psychological adversity composite index. Each of these encompasses multiple forms of disadvantage or adversity that accumulates either over time or across multiple domains.

Methods

Health and social data came from the baseline examination of MESA, a longitudinal study of cardiovascular disease in six sites (Baltimore, Maryland; Chicago, Illinois; Forsyth County, North Carolina; Los Angeles County, California; Northern Manhattan, New York; and St. Paul, Minnesota). Details of the MESA cohort have been published elsewhere (20). Briefly, 6,814 adults of white or black race or Hispanic or Chinese ethnicity who were between the ages of 45–85 years and free of clinical CVD were recruited for the study in 2000–2002. Institutional review board approval was granted at each study site, and written informed consent was obtained from all participants. Individuals with complete information on outcome, exposures, and covariates were included in our analytic sample ($n=4424$)

Outcome measures

Left ventricular mass, left ventricular end diastolic volume, and left ventricular end systolic volume were obtained by cardiac magnetic resonance imaging, measured at the baseline examination (2000–2002). All magnetic resonance imaging data were submitted to the MESA Magnetic Resonance Imaging Reading Center at Johns Hopkins Hospital for centralized processing using MASS software, version 4.2 (Medis, Leiden, Netherlands). LVMI, in g/m^2 , was calculated by dividing left ventricular mass by body surface area using the DuBois formula (21). LVEF, in %, was calculated by dividing stroke volume (the difference between left ventricular end systolic volume and left ventricular end diastolic volume, divided by left ventricular end diastolic volume).

Air pollution measures

We used hierarchical spatio-temporal models (described in detail in (22)) to estimate year 2000 (Jan 1–Dec 31) average residential ambient concentrations of fine particulate matter ($\text{PM}_{2.5}$) and oxides of nitrogen (NO_x) and, including nitrogen dioxide (NO_2) specifically, as indicators of traffic-related pollution, for each participant. Annual air pollution estimates

were derived using spatial and temporal information from numerous sources, including land use data such as, such as proximity to major roadways, and measurements from United States Environmental Protection Agency Air Quality System monitoring stations and supplemental monitoring stations specific to this study, as described elsewhere (23). Temporal information included long-term averages and seasonal and long-term trends. We used the fixed calendar year to reduce potential bias due to secular declines in air pollution levels and the differential study recruitment of areas and racial/ethnic groups within each study site. One-year averages were considered proxies of long-term exposures, as there is evidence of high correlation between one-year and 20-year air pollution levels in MESA Air (24).

Social disadvantage and psychological adversity measures

We expand this work in this area by examining the modifying role of factors that may mark cumulative social or psychosocial processes on the association between long-term air pollution exposure and long-term disease development. We measured cumulative social disadvantage in three ways. First, we examined race/ethnicity, which was self-reported in a questionnaire and categorized as: non-Hispanic white, Chinese, non-Hispanic black, and Hispanic. Second, we examined individual-level SES as a composite index of education, income, paternal education, and wealth (an index itself created from responses to questions on assets) collected by questionnaire. Following the literature (25, 26), an index, ranging from 0 to 14, was created as the sum of: quintiles (0 to 4) of the number of years of education, quintiles (0 to 4) of family income for the previous 12 months, wealth (0 to 4) as marked by ownership of home, car, land, or investments, and categories of paternal education (<high school, high school=0, high school=1, >high school=2).

Third, we examined racial/ethnic residential segregation using a dyadic (e.g, black versus non-black) spatial measure that reflects the extent to which racial/ethnic groups are clustered together in contiguous neighborhoods (census tracts). This local G_i^* statistic (27) yields a z-score for each census tract, which indicates the extent to which the racial composition of that tract and rook-based adjacent tracts deviated from the mean racial composition of the counties where MESA participants reside. The tract a participant lives in is given a weight of 1 and all adjacent tracts are given a weight of $1/n$, where n is the number of adjacent tracts, following the literature (28). A greater positive score reflects a greater clustering of that racial/ethnic group in an area of a metropolitan statistical area (i.e., a geographic entity consisting of one or more counties around a core urban area that have a high degree of social and economic integration) while a greater negative score reflects under-representation of that racial/ethnic group. Segregation may proxy a constellation of factors that alter vulnerability.

Finally, we examined psychological adversity as a composite index of five measures of psychological adversity: depressive symptoms, trait anger, trait anxiety, lack of emotional support, and chronic stress, all collected via questionnaire. Depressive symptoms were measured as the sum of responses to 20 questions about the frequency of depressive feelings and behaviors over the previous week, from the Center for Epidemiological Studies-Depression inventory (29). Trait anger and trait anxiety were measured as the sum of the responses to ten questions each, from the Spielberger Trait Anger Expression Inventory and

Spielberger Trait Anxiety Inventory, about the current frequency with which the participant has anger-related or anxiety-related feelings and behaviors, respectively (30). Emotional support was measured using the Emotional Social Support Index as the sum of the responses to six questions about the frequency of respondent's perceived availability of current emotional support. We reverse coded this measure so that higher values represented lower emotional support (i.e., greater adversity) (31). Chronic stress was measured using the Chronic Burden of Stress scale, five items about ongoing health, work, personal or financial problems (32). Following the literature (15, 33), an indicator variable was created as the high quartile for each measure and these indicators were then summed for an adversity score ranging from 0 to 4.

Analytic approach

To examine the descriptive characteristics of the sample, we estimated the means and standard deviations of continuous variables and percentages of categorical variables by quartile of PM_{2.5} level. To examine the independent and interactive associations between social/psychosocial factors and air pollution on LVMI or LVEF, we regressed LVMI or LVEF (in separate models) on air pollution (PM_{2.5}, NO_x, or NO₂, in separate models), before and after interactions based on the conceptual model in Figure 1. Based on this figure and the four modifiers we examined, each of the four sets of models differs slightly. However, all models include adjustment for age, sex, and study site. Furthermore, whenever we modeled segregation, we modeled only one dyadic type (e.g., white/non-white, Asian/non-Asian, etc) at a time as they were highly collinear and we always included controls for census tract poverty and length of residence in order to better isolate the role of racial segregation. Furthermore, while there is only a median of 2 MESA participants within any given tract, we used clustered robust standard errors whenever we modeled segregation measures. When modeling statistical interactions with air pollution, the air pollution variables were mean-centered.

First, we examined the role of race/ethnicity by regressing outcomes on air pollution and race/ethnicity, adjusting for confounders of the main effect as shown in Figure 1: the SES index and racial/ethnic segregation. We then introduced a statistical interaction between air pollution and race/ethnicity. Finally, we included adjustment for potential mediators/confounders of the race/ethnicity modifier as interactions between air pollution and each of the following: the SES index and racial/ethnic segregation (see Figure 1). Note that while we conceptualize psychological adversity as a mediator at the effect modification scale, it is a collider as well and including it may introduce bias. Therefore, we do not model it when we model segregation and SES.

Second, we examined the role of racial/ethnic segregation by regressing outcomes on air pollution and racial/ethnic segregation, adjusting for confounders of the main effect as shown in Figure 1: race/ethnicity and SES. We then introduced statistical interactions between air pollution and each segregation dyadic measure, adjusting for the interaction between air pollution and both Census tract poverty and length at address.

Third, we examined the role of individual SES by regressing outcomes on air pollution and the SES index, adjusting for the confounder of the main effect as shown in Figure 1: race/

ethnicity and racial/ethnic segregation. We then introduced statistical interactions between air pollution and the SES index.

Fourth, we examined the role of psychological adversity by regressing outcomes on air pollution and the psychosocial adversity index, adjusting for confounders of the main effect as shown in Figure 1: race/ethnicity, SES, and racial/ethnic segregation. We then introduced statistical interactions between air pollution and the psychosocial adversity index.

In sensitivity analyses, we explored more fully-adjusted models, as had been done previously (19), by regressing LVMI and LVEF on health behavior and clinical variables (both before and after the inclusion of statistical interactions), with additional adjustment for: systolic and diastolic blood pressure, low- and high-density lipoprotein cholesterol, lipid-lowering medication use, anti-hypertensive medication use, physical activity, body mass index, weekly alcohol use, diabetes status (by fasting blood glucose and self-report of diabetes medication use), and a variable that combines smoking status with hours per week of exposure to second hand smoke. Note that it is likely that these measures represent both confounders and mediators and may even introduce issues of reverse causality, and the inclusion of these variables further reduces the sample size to 3668.

We examined the possibility that there were racial/ethnic differences in the recruitment timing within each site, as air pollution levels had declined over the recruitment period which might confound our results. Therefore, we estimated models with adjustment for a race-by-site interaction rather than site alone. We also examined the possibility that adversity for a level of SES might differ based on the household size by adjusting for household size. We examined the potential for nonlinear associations by estimating models with quadratic interaction terms for each of the social and psychosocial measures. We tested for the possibility that there were systematic differences in the indexed measure of LVM (i.e., LVM indexed to body surface area) that would bias our results by re-estimating all models using the non-indexed LVM, adjusting for height and weight in addition to all other variables. All analyses were conducted in STATA 12.0 (StataCorp, College Station, TX).

Results

LVMI and LVEF were inversely and positively related, respectively, to $PM_{2.5}$ (see Table 1). NO_x and NO_2 were both positively related to both LVEF and LVMI (results not shown). Racial/ethnic differences in $PM_{2.5}$ quartile are an artifact of differential recruitment by site (e.g., Chinese recruitment in Los Angeles, the site with highest $PM_{2.5}$). $PM_{2.5}$ was not related to the SES index but was inversely related to the psychosocial adversity index (see Table 1).

Race/ethnicity, air pollution, and cardiovascular health

In models without statistical interactions, none of the three measures of air pollution were associated with LVMI (Table 2, Models 1a, 2a, and 3a). In models with interactions, compared to white race, black race showed a stronger association between air pollution and LVMI. Specifically, whites showed a 1.0 g/m^2 greater LVMI for each $5 \text{ } \mu\text{g/m}^3$ increase in $PM_{2.5}$ (95%CI: -1.3, 3.1; Table 2, Model 1b) while blacks showed an *additional* 4.0 g/m^2

greater LVMI for each 5 $\mu\text{g}/\text{m}^3$ greater level of $\text{PM}_{2.5}$ (95%CI: -0.3, 8.2). Similarly, whites showed a 0.5 g/m^2 greater LVMI (95%CI: -1.3, 2.4; Table 2, Model 2b) for each 40 ppb greater level of NO_x while blacks showed an *additional* 2.4 g/m^2 greater LVMI for each 40 ppb greater level of NO_x (95%CI: 0.2, 4.6). Finally, whites showed a 0.2 g/m^2 lower LVMI (95%CI: -2.8, 2.4; Table 2, Model 2b) for each 17 ppb greater level of NO_2 , while blacks showed an *additional* 2.3 g/m^2 greater LVMI for each 17 ppb greater level of NO_2 (95%CI: -0.4, 4.9). The race/ethnicity-specific associations between air pollution and LVMI are shown in Figure 2.

After adjustment for potential mediators/confounders on the effect modification level (i.e., SES and Black racial segregation, modeled as interactions with air pollution), the association between air pollution and LVMI did not change appreciably for blacks (see Figure 2).

Specifically, regarding $\text{PM}_{2.5}$, before adjustment, blacks showed a 5.0 g/m^2 greater LVMI for each 5 $\mu\text{g}/\text{m}^3$ greater level of $\text{PM}_{2.5}$ (95%CI: 0.8, 9.1; calculated post-estimation, with covariates held at their means, from coefficients in Table 2, Model 1b). After adjustment, blacks showed a 5.5 g/m^2 greater LVMI for each 5 $\mu\text{g}/\text{m}^3$ greater level of $\text{PM}_{2.5}$ (95%CI: 1.4, 9.6, calculated post-estimation, with covariates held at their means, from coefficients in Table 2, Model 1c with additional coefficients as outlined in the methods section).

Regarding NO_x , blacks showed a 3.0 g/m^2 greater LVMI (95%CI: 0.7, 5.2; calculated as described above) for each 40 ppb greater level of NO_x . After adjustment, blacks showed a 3.1 g/m^2 greater LVMI (95%CI: 1.0, 5.3; calculated as described above) for each 40 ppb greater level of NO_x . Regarding NO_2 , blacks showed a 2.0 g/m^2 greater LVMI (95%CI: -1.1, 5.2; calculated as described above) for each 17 ppb greater level of NO_2 . After adjustment, blacks showed a 1.6 g/m^2 greater LVMI (95%CI: -1.5, 4.7; calculated as described above) for each 17 ppb greater level of NO_2 .

In general, in models without statistical interactions, none of the three measures of air pollution was associated with LVEF (Table 3). Furthermore, there was no evidence of additive interactions between air pollution and race/ethnicity with respect to LVEF (Table 3).

Other social/psychosocial factors, air pollution, and cardiovascular health

There was no consistent evidence of additive interactions between air pollution and SES, psychological adversity, or any measure of racial/ethnic segregation with regard to either LVMI or LVEF (eTables 2 through 7).

In other sensitivity analyses, we do not find evidence of nonlinear associations for the continuous measures SES, racial/ethnic segregation, or psychosocial adversity. Furthermore, our results were not qualitatively different when adjusting for race*site rather than site alone, for household size, or when using non-index LVM. Adjustment for the health behavior and clinical markers did not qualitatively alter our results.

Discussion

We examined whether social disadvantage or psychological adversity were interactively associated with air pollution and cardiovascular health in a healthy, population-based, multi-ethnic sample. Most consistently, compared to whites, blacks showed a stronger association

between all three measures of air pollution and LVMI. However, these results should be interpreted with caution, as one takes note of the confidence intervals and the overall number of statistical tests. Nevertheless, we observed a difference in the association between PM_{2.5} and LVMI of 4.0 g/m² between blacks and whites. The size of this difference corresponds to a black–white difference in the association between PM_{2.5} and systolic blood pressure of 18 mmHg in this cohort, an important disparity, given that LVMI is an independent predictor of future cardiovascular events (16-18).

Empirical research on the modifying role of race/ethnicity in the association between air pollution and cardiovascular health has yielded mixed results. This may be due to differences in the temporal aspects of the air pollution measure used. No evidence was found for a modifying role of race/ethnicity on the association between short-term exposures to PM_{2.5} and cardiovascular outcomes in the MESA sample (8, 10). It may be that racial/ethnic group membership, with its relation to multiple social/psychosocial adversities, confers vulnerability to long-term rather than short-term air pollution exposures in relation to health measures that reflect long-term disease development. However, past findings have been mixed, with some indicating that, compared to whites, non-whites show stronger (34), weaker (35), or similar (10) associations between long-term PM_{2.5} exposure and cardiovascular health. Furthermore, there is no evidence of these differential associations when examining either abdominal aortic calcification (34) or retinal vasculature diameter (10) in the MESA sample.

Yet, LVMI represents long-term cardiac workload, increased, for example, with increased vascular resistance found in hypertension. Because of the earlier development and greater prevalence of hypertension in blacks compared to whites (36), LVMI may better capture the interactive effects of air pollution and racial/ethnic group membership on cardiovascular health than LVEF. That LVEF did not show the same pattern of results suggests that it may not be as sensitive to the long-term cardiac effects of chronic hypertension (19).

We did not find evidence that psychosocial adversity alters vulnerability. These results are consistent with an earlier study showing no evidence of a modifying effect on these associations between short-term PM_{2.5} exposure and blood pressure (8). It may be that these measures do not adequately capture long-term or chronic adversity that may be necessary for vulnerability to air pollution. Researchers suggest using measures of psychological trauma to capture chronic adversity (6). It may also be that the measures included in the index do not encompass an adequate breadth of psychosocial domains. Because the MESA study does not contain such measures, future work with other datasets could explore this possibility.

We also did not find evidence that SES or neighborhood segregation altered vulnerability. The empirical literature on the modifying role of neighborhood social disadvantage has yielded inconsistent results, with some reporting that socially disadvantaged neighborhoods show stronger (37-39), weaker (40), or no difference in (41, 42) associations between air pollution and health. The lack of consistency may have to do with different neighborhood samples which would yield differences in the balance of factors that promote resiliency and vulnerability.

The stronger association between air pollution and LVMI for black, compared to white race, may reflect the higher exposure to socioeconomic and psychosocial adversity disproportionately borne by blacks. Although our study adjusted for a number of these factors, not all factors could be controlled and the higher vulnerability found for blacks may be capturing factors not included in our models. Furthermore, there may be residual confounding even with adjustment for these factors, as research indicates that many of these measures are incommensurate across racial group (43). These types of adversity are related to systemic inflammation and oxidative stress (44, 45) that may result in chronic hypertension or may damage cardiac tissue directly (2, 46). Likewise, research has shown that air pollution is related to increased systemic inflammation and oxidative stress (1, 47). It may be that social/psychosocial factors and environmental exposures patterned by race, increase the risk of cardiovascular outcomes.

While this study is among the first to examine the joint associations between social and psychosocial factors, particularly racial/ethnic residential segregation, and air pollution with LVMI and LVEF, it is not without limitations. Because we used cross-sectional data, we cannot make causal determinations on the effects of these social factors, air pollution, and LVMI or LVEF. In the future, it may be possible to link these social and environmental exposures to the development and progression of these cardiovascular conditions. Also, while we measured psychosocial factors through questionnaires, biological measures of stress may provide more insight into potential interactive associations. While we based our analyses on a conceptual model informed by the extant literature, it may be that more complex statistical approaches (e.g., structural equation modeling) could clarify the role of numerous factors simultaneously and better clarify any modifying role of these social and psychosocial factors. Similarly, while we did not find evidence of a nonlinear modifying role of the factors we examined, it may be that any nonlinear associations are more complex in nature.

It may be that one-year average air pollution exposures do not adequately capture long-term exposures important for these types of additive interactions. As air pollution levels have been decreasing at MESA sites since baseline and this may reflect a long-term trend extending before baseline. Using one-year exposure estimates may, therefore, underestimate associations. However, research suggests a high correlation between one-year and 20-year exposure estimates in MESA (24).

Despite these limitations, our results indicate that blacks may be particularly vulnerable to the cardiovascular health effects of air pollution. Future research in this area is needed to address the causal mechanisms that link race/ethnicity, air pollution, and cardiovascular disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Conceptual model linking air pollution, social and psychosocial factors, and LVMI/LVEF

Notes: Not all variables are shown for figure clarity; only the main exposure, outcome, and modifiers are shown. Variables omitted from this figure are related to those in the figure as follows: sex and age are related to the outcome only; study site are related to race/ethnicity and air pollution only; neighborhood poverty is related to air pollution and outcomes (and is thus a confounder) and is a known link between racial/ethnic segregation and any outcome related to racial/ethnic segregation (e.g., air pollution, the relation between air pollution and outcome). Rectangles represent variables in the main association and ovals represent modifiers. Modifiers also may serve as confounders, as shown.

Abbreviations: LVEF, left ventricular ejection fraction; LVMI, left ventricular mass index; SES, socioeconomic status.

Figure 2. Mean difference in left ventricular mass index (LVMI) in g/m² and 95% confidence intervals associated with year 2000 average air pollution exposure by race/ethnicity (n=4424), Multi-Ethnic Study of Atherosclerosis, 2000-2002^a

Notes:

^a Models correspond to data in Table 2 and were adjusted for: age, sex, study site, SES index, black census tract segregation, census tract poverty, and length of residence at address. Models 1c, 2c, and 3c include additional adjustment for interactions between air pollution and both SES index and black census tract segregation. Air pollution measures were modeled as continuous and mean-centered before interactions. All estimates were modeled with clustered robust standard errors with respect to Census tract.

^b PM_{2.5} units are per 5µg/m³; NO_x units are per 40 ppb; NO₂ units are per 17 ppb
Abbreviations: PM_{2.5}, particulate matter air pollution 2.5µm; NO_x, oxides of nitrogen; NO₂, nitrogen dioxide

Table 1
Sociodemographic, psychosocial, segregation, and health characteristics by levels of one-year average 2000 PM_{2.5} exposure, The Multi-Ethnic Study of Atherosclerosis, 2000-2002

	Quartile of PM _{2.5} exposure, averaged over 2000			
	Quartile 1 ($<15.3\mu\text{g}/\text{m}^3$)	Quartile 2 ($15.3-<16.2\mu\text{g}/\text{m}^3$)	Quartile 3 ($16.2-<17.7\mu\text{g}/\text{m}^3$)	Quartile 4 ($17.7\mu\text{g}/\text{m}^3$)
Sociodemographic characteristics				
Age, years (mean)	59.7 (10.0)	62.1 (10.0)	62.6 (9.9)	62.0 (10.2)
Female (%)	51	53	56	51
Race/ethnicity (% distribution)				
White	52	40	46	21
Chinese	7	6	4	32
Black	12	45	35	14
Hispanic	29	9	15	34
SES index (mean)	1.3 (1.2)	1.3 (1.1)	1.3 (1.1)	1.2 (1.1)
Site (% distribution)				
Forsyth County	3	23	27	1
New York City	15	22	25	11
Baltimore	14	30	17	2
St. Paul	59	0	0	0
Chicago	9	24	30	8
Los Angeles	0	0	0	77
Psychosocial characteristics				
Psychosocial adversity index (mean)	7.5 (3.6)	7.9 (3.6)	7.3 (4.0)	6.1 (4.0)
Segregation				
White Gi* score (mean)	-1.0 (1.9)	-0.8 (1.9)	-0.7 (2.0)	-1.5 (1.9)
Asian Gi* score (mean)	0.4 (1.7)	0.0 (2.0)	0.3 (2.8)	2.6 (4.4)
Black Gi* score (mean)	-0.3 (1.3)	0.7 (2.0)	0.4 (2.0)	0.1 (3.4)
Hispanic Gi* score (mean)	3.7 (4.3)	0.0 (1.7)	0.3 (2.3)	0.6 (2.3)
Cardiovascular outcomes				
LVMI, g/m ² (mean)	80.0 (15.5)	78.1 (16.5)	77.1 (16.3)	76.9 (16.7)
LVEF, % (mean)	68.3 (7.3)	68.6 (7.8)	69.4(7.1)	69.9 (7.4)

Abbreviations: LVEF, left ventricular ejection fraction; LVMI, left ventricular mass index; PM_{2.5}, particulate matter air pollution 2.5 μm ; SES, socioeconomic status

Table 2
Mean difference in left ventricular mass index (LVMI) in g/m² and 95% confidence intervals associated with year 2000 average air pollution exposure, race/ethnicity, and their additive interactions (n=4424), Multi-Ethnic Study of Atherosclerosis, 2000-2002^a

	--PM _{2.5} --			--NO _x --			--NO ₂ --		
	--1a--	--1b--	--1c--	--2a--	--2b--	--2c--	--3a--	--3b--	--3c--
	MD (95%CI)	MD (95%CI)	MD (95%CI)	MD (95%CI)	MD (95%CI)	MD (95%CI)	MD (95%CI)	MD (95%CI)	MD (95%CI)
Air pollution ^b	1.3 (-0.8, 3.5)	1.0 (-1.3, 3.1)	-0.3 (-3.3, 2.7)	0.9 (-0.7, 2.4)	0.5 (-1.3, 2.4)	-1.6 (-4.2, 1.0)	-0.7 (-2.8, 1.4)	-0.2 (-2.9, 2.4)	-2.5 (-6.0, 1.1)
Race/ethnicity									
White	ref	ref	ref	ref	ref	ref	ref	ref	ref
Chinese	-1.4 (-3.1, 0.3)	-0.7 (-2.5, 1.1)	-0.6 (-2.4, 1.3)	-0.7 (-2.2, 0.8)	-0.4 (-2.0, 1.2)	-0.3 (-1.9, 1.3)	-1.6 (-3.2, 0.1)	-0.6 (-2.3, 1.0)	-0.5 (-2.2, 1.1)
Black	6.3 (5.0, 7.6)	6.2 (4.6, 7.7)	6.1 (4.6, 7.7)	5.5 (4.0, 6.9)	5.6 (4.2, 7.1)	5.8 (4.3, 7.2)	6.2 (4.9, 7.4)	5.5 (4.1, 7.0)	5.6 (4.1, 7.1)
Hispanic	1.8 (0.4, 3.2)	2.1 (-0.6, 3.6)	2.1 (0.6, 3.6)	1.9 (0.4, 3.3)	2.6 (1.1, 4.1)	2.8 (1.3, 4.3)	1.8 (0.3, 3.2)	2.6 (1.0, 4.1)	2.7 (1.1, 4.2)
Interactions									
Air pollution*White	ref	ref	ref	ref	ref	ref	ref	ref	ref
Air pollution*Chinese	0.1 (-2.5, 2.8)	0.1 (-2.6, 3.0)	0.2 (-2.6, 3.0)	-1.1 (-3.5, 1.3)	-1.1 (-3.5, 1.3)	-0.5 (-3.0, 2.0)	-0.1 (-3.2, 3.1)	0.5 (-2.8, 3.8)	
Air pollution*Black	4.0 (-0.3, 8.2)	6.1 (1.3, 10.8)	6.1 (1.3, 10.8)	2.4 (0.2, 4.6)	2.4 (0.2, 4.6)	3.2 (0.7, 5.7)	2.3 (-0.4, 4.9)	3.2 (0.2, 6.2)	
Air pollution*Hispanic	-0.3 (-2.3, 1.8)	0.1 (-2.1, 2.4)	0.1 (-2.1, 2.4)	-0.8 (-2.6, 1.1)	-0.8 (-2.6, 1.1)	0.3 (-1.6, 2.4)	-0.9 (-3.4, 1.5)	0.0 (-2.7, 2.8)	

Abbreviations: MD, mean difference; PM_{2.5}, particulate matter air pollution 2.5µm; NO_x, oxides of nitrogen; NO₂, nitrogen dioxide; SES, socioeconomic status

^aIn addition to the variables shown, all models were adjusted for: age, sex, study site, SES index, black census tract segregation, census tract poverty, and length of residence at address. Models 1b, 2b, and 3b include an interaction between race/ethnicity and air pollution. Models 1c, 2c, and 3c include additional adjustment for interactions between air pollution and both SES index and black census tract segregation. Air pollution measures were modeled as continuous and mean-centered before interactions. All estimates were modeled with clustered robust standard errors with respect to Census tract.

^bPM_{2.5} units are per 5µg/m³; NO_x units are per 40 ppb; NO₂ units are per 17 ppb

Table 3
Mean difference in left ventricular ejection fraction (LVEF) in % and 95% confidence intervals associated with year 2000 average air pollution exposure, race/ethnicity, and their additive interactions (n=4424), Multi-Ethnic Study of Atherosclerosis, 2000-2002^a

	--PM _{2.5} --			--NO _x --			--NO ₂ --		
	--1a-- MD (95%CI)	--1b-- MD (95%CI)	--1c-- MD (95%CI)	--2a-- MD (95%CI)	--2b-- MD (95%CI)	--2c-- MD (95%CI)	--3a-- MD (95%CI)	--3b-- MD (95%CI)	--3c-- MD (95%CI)
Air pollution ^b	-0.3 (-1.2, 0.6)	-0.3 (-1.4, 0.9)	0.6 (-1.1, 2.3)	-0.3 (-0.9, 0.4)	-0.4 (-1.3, 0.6)	-0.1 (-1.5, 1.3)	-0.5 (-1.7, 0.7)	-0.5 (-1.9, 0.9)	-0.5 (-2.4, 1.6)
Race/ethnicity									
White	ref	ref	ref	ref	ref	ref	ref	ref	ref
Chinese	2.7 (1.8, 3.5)	2.6 (1.6, 3.6)	2.6 (1.6, 3.6)	2.7 (1.8, 3.5)	2.7 (1.8, 3.6)	2.7 (1.8, 3.6)	2.7 (1.8, 3.5)	2.7 (1.8, 3.6)	2.7 (1.8, 3.6)
Black	-0.2 (-0.8, 0.5)	-0.3 (-1.0, 0.4)	-0.3 (-1.1, 0.4)	-0.2 (-0.9, 0.5)	-0.1 (-0.8, 0.6)	-0.2 (-0.9, 0.5)	-0.2 (-0.8, 0.5)	-0.2 (-0.9, 0.5)	-0.2 (-0.9, 0.6)
Hispanic	1.1 (0.4, 1.9)	1.2 (0.3, 2.0)	1.1 (0.3, 1.9)	1.2 (0.4, 1.9)	1.1 (0.2, 2.0)	1.1 (0.24, 2.0)	1.1 (0.4, 1.9)	1.2 (0.3, 2.1)	1.2 (0.3, 2.1)
Interactions									
Air pollution*White	ref	ref	ref	ref	ref	ref	ref	ref	ref
Air pollution*Chinese	0.3 (-1.1, 1.7)	0.3 (-1.1, 1.7)	0.0 (-1.5, 1.5)	0.2 (-1.1, 1.5)	0.2 (-1.1, 1.5)	0.1 (-1.2, 1.5)	0.1 (-1.2, 1.5)	0.0 (-1.7, 1.6)	0.0 (-1.7, 1.7)
Air pollution*Black	-0.9 (-2.8, 1.0)	-0.9 (-2.8, 1.0)	-1.2 (-3.2, 0.9)	0.0 (-3.2, 0.9)	0.0 (-1.0, 1.0)	0.0 (-1.1, 1.2)	0.2 (-1.1, 1.4)	0.2 (-1.1, 1.4)	0.0 (-1.3, 1.3)
Air pollution*Hispanic	0.3 (-0.8, 1.4)	0.3 (-0.8, 1.4)	0.0 (-1.3, 1.2)	0.1 (-1.3, 1.2)	0.3 (-0.7, 1.2)	0.1 (-1.0, 1.3)	0.1 (-1.2, 1.3)	0.0 (-1.2, 1.3)	0.0 (-1.5, 1.4)

Abbreviations: MD, mean difference; PM_{2.5}, particulate matter air pollution 2.5µm; NO_x, oxides of nitrogen; NO₂, nitrogen dioxide; SES, socioeconomic status

^aIn addition to the variables shown, all models were adjusted for: age, sex, study site, SES index, Black census tract segregation, census tract poverty, and length of residence at address. Models 1b, 2b, and 3b include interactions between race/ethnicity and air pollution. Models 1c, 2c, and 3c include additional adjustment for interactions between air pollution and both the SES index and Black census tract segregation. Air pollution measures were modeled continuous and mean-centered before interactions. All estimates were modeled with clustered robust standard errors with respect to Census tract.

^bPM_{2.5} units are per 5µg/m³; NO_x units are per 40 ppb; NO₂ units are per 17 ppb