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Assessing the spatial heterogeneity in black-white differences in optimal cardiovascular health and the impact of individual- and neighborhood-level risk factors: The Multi-Ethnic Study of Atherosclerosis (MESA)

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Abstract

Racial disparities in cardiovascular health (CVH) continue to remain a public health concern in the United States. We use unique population-based data from the Multi-Ethnic Study of Atherosclerosis cohort to explore the black-white differences in optimal CVH. Utilizing geographically weighted regression methods, we assess the spatial heterogeneity in black-white differences in optimal CVH and the impact of both individual- and neighborhood-level risk factors. We found evidence of significant spatial heterogeneity in black-white differences that varied within and between the five sites. Initial models showed decreased odds of optimal CVH for blacks that ranged from 60% to 70% reduced odds – with noticeable variation of these decreased odds within each site. Adjusting for risk factors resulted in reductions in the black-white differences in optimal CVH. Further understanding of the reasons for spatial heterogeneities in black-white differences in nationally representative cohorts may provide important clues regarding the drivers of these differences.

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CONTRIBUTIONS
LPT: study design, analyses, interpretation of results, and manuscript
LAM: study design, interpretation of results, manuscript
AO: analyses, manuscript
SM: maps, manuscript
MRJ: interpretation of results and manuscript
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ADR: study design, interpretation of results, manuscript

Keywords

Cardiovascular health; Disparities; Spatial heterogeneity

1. INTRODUCTION

Racial/ethnic disparities in cardiovascular disease (CVD), and ultimately in cardiovascular health (CVH), continue to remain a public health concern in the United States (US) [1-3]. While there has been overall progress in the narrowing of the black-white disparity in all-cause mortality for all ages from 33% in 1999 to 16% in 2015, disparities in CVH remain with some widening [4-6]. Over the past two decades, one of Healthy People's overarching goals has focused on disparities; for Healthy People 2020, the goal is to achieve health equity, eliminate disparities, and improve the health of all Americans.

Recently, the American Heart Association (AHA) has adopted the CVH framework for the prevention of CVD. The cardiovascular health approach is based on the following three concepts: (1) the power of primordial prevention; (2) the evidence that CVD and risk factors for it often develop early in life; and (3) the appropriate balance between population-level approaches for health promotion and disease prevention and individualized high-risk approaches [7]. An important component of the CVH approach is the measurement of ideal CVH. Ideal CVH is defined as the presence of both ideal health behaviors (nonsmoking, body mass index, BMI, <25 kg/m^2, physical activity at goal levels, and pursuit of a diet consistent with current guideline recommendations) and ideal health factors (untreated total cholesterol <200 mg/dL, untreated blood pressure $<120/<80$ mm Hg, and fasting blood glucose <100 mg/dL). Prior work has shown that ideal CVH is associated with lower risks of myocardial infarction, stroke, and vascular death [8], greater cognitive performance [9], and lower cancer incidence [10]. Ideal CVH has also been associated with many other major health outcomes, like lower healthcare costs [11], compression of morbidity [12], improved quality of life [13], and reduced depression [14].

Although some studies have shown similar relationships between ideal CVH and various health outcomes for both whites and blacks [8, 15-18], substantial racial/ethnic differences have been established for most indicators of ideal CVH. One recent study showed that black-white differences were significant for all ideal health factors, most behaviors, and all ideal CVH summary measures considered [19]. Additionally, racial differences in the incidence of cardiovascular risk factors have been found, such that blacks have a higher incidence of hypertension, diabetes mellitus, and dyslipidemia [20]. However, little work has examined the extent to which racial/ethnic differences vary spatially. While prior research examined the geographic variation in the prevalence of hypertension among blacks and whites [21, 22], little is known about the spatial patterning of black-white differences in ideal CVH across the US. Understanding the spatial heterogeneity – simply put, spatial patterning – in black-white differences in ideal CVH will allow for a deeper understanding of these differences, with an eye towards evidence-based solutions to eliminating these disparities. Furthermore, estimating the contributions of both individual- and neighborhood-level risk factors to these disparities will allow for a richer understanding of black-white differences in ideal CVH.

In this paper, we use unique population-based data from the Multi-Ethnic Study of Atherosclerosis (MESA) cohort to explore the black-white differences in optimal CVH, defined as a summary measure of ideal health factors and behaviors. The novelty in this approach lies in utilizing a diverse cohort found in MESA, that includes a rich amount of individual- and neighborhood-level measures, both objective and subjective, that have hypothesized associations with optimal CVH. Secondly, this research moves beyond the traditional assessment of the presence or absence of CVD, and, rather, explores the more comprehensive CVH framework, which has vast implications in preventing CVD events. Lastly, our research explores the spatial patterning in optimal CVH, with a specific emphasis on determining the spatial patterning in the racial differences in CVH between blacks and whites across several cities in the US. While the presence of racial disparities is widely reported for a host of cardiovascular outcomes, optimal CVH is an important under-studied indicator of CVD. Our specific aims include: (1) to assess the spatial heterogeneity in the black-white differences in optimal CVH, and (2) to examine the impact of both individual- and neighborhood-level risk factors on the spatial heterogeneity in the black-white differences in optimal CVH. The overarching goal of this work is to gauge the spatial heterogeneity that is present in these disparities, where both individual- and neighborhood-level risk factors collectively have the ability to potentially explain some of the geographic patterning in these disparities across several cities in the US.

2. MATERIALS AND METHODS

2.1. STUDY POPULATION

MESA is a longitudinal study of CVD among adults aged 45–84 years at six field sites (Forsyth County, NC; New York City, NY; Baltimore, MD; St Paul, MN; Chicago, IL; and Los Angeles, CA) in the US. Persons with a history of clinically overt CVD were excluded. The study recruited 6,814 participants at baseline. Whites were recruited at all six sites; blacks were recruited at all sites except the MN site; Hispanics were recruited at the NY, MN, and CA sites; and Asian Americans were recruited at the IL and CA sites. Baseline assessment was conducted from 2000 to 2002, with three follow-up exams occurring at approximately 1.5–2-year intervals and follow-up phone calls occurring every 18 months. The study was approved by the institutional review boards at each site and all participants provided written informed consent. Details of the study objectives and design are provided elsewhere [23].

We restricted our analyses to black and white MESA participants who participated in the MESA ancillary Neighborhood Study with baseline addresses (and geocoded locations) available from all sites except MN. The MESA Neighborhood Study included a questionnaire administered to both MESA participants and to other neighborhood residents sampled from MESA neighborhoods [24]. Our final analytic dataset included 3,154 participants with complete data on CVH, as well as individual- and neighborhood-level risk factors at baseline addresses. Figure 1 shows the location of each MESA site considered across the US, with the final number of study participants included as well. There were 826

MESA participants at the Forsyth County, NC site spanning 88 census tracts (CTs); 513 participants at the New York City, NY site spanning 206 CTs; 799 participants at the Baltimore, MD site spanning 145 CTs; 766 participants at the Chicago, IL site spanning 93 CTs; and 250 participants at the Los Angeles, CA site spanning 156 CTs.

2.2. STUDY VARIABLES

Cardiovascular Health—We utilized the AHA's definition of ideal CVH, which is defined as the presence of both ideal health behaviors (nonsmoking, BMI < 25 kg/m^2, physical activity at goal levels, and pursuit of a diet consistent with current guideline recommendations) and ideal health factors (untreated total cholesterol <200 mg/dL, untreated blood pressure <120/<80 mm Hg, and fasting blood glucose <100 mg/dL). Smoking status was self-reported by participants and characterized as never, former, or current smokers; BMI was computed via clinically measured height and weight. Physical activity was self-reported by participants and characterized as minutes of moderate and vigorous exercise per week, based on questions adapted from the Cross-Cultural Activity Participation Study [25]. Diet was measured using a 120-item food frequency questionnaire modified from the Insulin Resistance Atherosclerosis study [26]. Diet measures included high intake of fruit and vegetables, fish, whole grains, and low intake of sodium and sugar-sweetened beverages [7]. Cholesterol and fasting blood glucose were measured from a fasting blood sample. Blood pressure was assessed after resting for 5 minutes, and the average of the second and third readings was used. Self-reported medication was also considered for measures related to cholesterol, blood pressure, and diabetes.

Each health behavior and factor was assigned a score of 0, 1, or 2 to denote the factor as poor, intermediate, or ideal, respectively (see Table 1). The total CVH score was computed for each participant as the sum of all health behavior and factor scores, resulting in a total CVH score ranging from 0 to 14. Similar to previous studies, participants were then categorized to have either optimal (total CVH score 11-14), average (total CVH score 9-10), or inadequate (total CVH score 0-8) CVH [19, 27, 28]. Our outcome of interest was optimal CVH compared to average or inadequate CVH.

2.3. COVARIATES

Individual-level—Individual-level risk factors included self-reported race/ethnicity (non-Hispanic black; non-Hispanic white), age (years), and sex (male; female). Income ($/year) was operationalized as the midpoint of the following categories: $0-5,000 ($2,500 was used in this category); 5,000-7,999; 8,000-11,999; 12,000-15,999; 16,000-19,999; 20,000-24,999; 25,000-29,999; 30,000-34,999; 35,000-39,999; 40,000-49,999; 50,000-74,999; 75,000-99,999; > 100,000 ($112,500 was used in this category). Education (number of years) was operationalized as no schooling (0 years) and as the midpoint of the following categories: grades 1-8 (4 years), grades 9-11 (10 years); complete high school/GED (12 years); some college but no degree (13 years); technical school certificate (13 years); associate's degree (14 years); bachelor's degree (16 years); and graduate or professional school (18 years). For education and income, considering the midpoint of categories allowed for the use of continuous measures and an assessment of the possible gradient in the impact of these measures on optimal CVH. Marital status (married; not married) was also considered. All continuous individual-level measures were standardized relative to the overall MESA site's mean and standard deviation to create a z-score to ensure consistency and for ease of interpretation.

Neighborhood-level—Neighborhood-level risk factors included seven measures operationalized at the census tract (CT) level for each participant, and captured neighborhood socioeconomic status (SES) as well as the physical and social environments. The neighborhood SES measure, details provided elsewhere [29], combined six variables that describe wealth and income (log of median housing value, log of median household income, and percentage of households receiving interest/dividends/income), education (percentage of adults ≥ 25 years who completed high school and percentage of adults ≥ 25 years who completed college), and occupation (percentage of persons ≥ 16 years in executive, managerial, or professional specialty occupations); higher values indicate a better neighborhood SES. To create the neighborhood SES measure, we utilized 2000 Census data.

The physical and social environment measures included favorable food stores, physical activity resources, healthy food availability, the walking/physical activity environment, safety, and social cohesion. Previous MESA-focused studies [19, 28] have considered these measures and their relationship with CVH, which include a mix of both objective and self-report measures to completely characterize a given neighborhood. While objective measures of the physical and social environments are concrete approaches to characterizing a neighborhood, the self-report/survey measures of these environments are equally important to assess how these neighborhood characteristics are perceived in terms of quality, access, and ease. Favorable food stores were described as establishments likely to provide fresh fruits and vegetables, which included chain and non-chain supermarkets in addition to fruit and vegetable markets, as defined by the National Establishment Time Series data from Walls and Associate [30]. A density of favorable food stores was defined as the number of favorable food stores within a 1-mile radius of the participant's home address. Similarly, a density measure was created for physical activity resources, such that the density was defined as the number of physical activity facilities within a 1-mile radius of the participant's home address. Physical activity resources included facilities that provided indoor conditioning (health clubs/gyms, yoga, karate, etc.), dance, bowling, golf, team and racquet sports, and water activities. Measures of healthy food availability, the walking/physical activity environment, safety, and social cohesion were derived from surveys administered to participants, as well as to other residents sampled from MESA neighborhoods, [24] and responses were pooled to generate conditional empirical Bayes estimates for each participant's census tract. Details of the survey questions related to healthy food availability, the walking/physical activity environment, safety, and social cohesion are provided in Supplementary Material Table A1. Lastly, population density was considered as a way to capture how urban the participant's census tract is. All continuous neighborhood-level measures were standardized relative to the overall MESA site's mean and standard deviation to create a z-score to ensure consistency and for ease of interpretation.

2.4. STATISTICAL ANALYSES

Descriptive statistics of the CVH behaviors and health factors as well as individual- and neighborhood-level risk factors were examined for all MESA participants, and by race/ethnicity, via counts with percentages for categorical measures and means with standard deviations for continuous measures. To assess potential multicollinearity, we examined the variance inflation factor (VIF) for all individual- and neighborhood-level risk factors considered [31].

To address our study aims, we used a generalized geographically weighted regression approach, specifically geographically weighted logistic regression (GWLR) models [32, 33] for the odds of optimal CVH. GWLR was used because it allows spatial heterogeneity in regression coefficients, thus allowing the racial/ethnic differences to vary over space. This spatial heterogeneity is our main question of interest. For each participant i ($i = 1, \ldots, n$), we assumed the following model:

$$y_i \sim Bernoulli(p_i)$$

$$1 = Optimal\ CVH, 0 = Average\ or\ Inadequate\ CVH$$

$$logit(p_i) = \beta_{0i}(u_i, v_i) + \sum_{p=1}^{k} \beta_{pi}(u_i, v_i)X_{pi}$$

where (u_i, v_i) denotes the coordinates of participant i's home address, β_{0i} is the intercept, β_{pi} is the estimated effect of explanatory variable X_{pi}. To assess the spatial heterogeneity in the black-white differences in optimal CVH, the first GWLR model we examined included a main effect of race/ethnicity (Model 1). Our primary interest focused on the black-white difference in optimal CVH, where white, non-Hispanics served as the reference group, mainly because there are more white, non-Hispanics than blacks at each MESA site. To examine the impact of individual-level risk factors on the spatial heterogeneity in the black-white differences in optimal CVH, we then examined Model 2, which expanded Model 1 to also include the following individual-level risk measures: age, sex, income, education, and marital status. Lastly, to further examine the additional impact of neighborhood-level risk factors, we examined a fully adjusted model (Model 3), which expanded Model 2 to include the following: neighborhood SES, favorable food stores, physical activity resources, healthy food availability, the walking/physical activity environment, safety, social cohesion, and population density. To assess whether associations vary by MESA site, all models were fitted separately for each MESA site. Additionally, we conducted a sensitivity analysis that treated the CVH score as a continuous variable and used geographically weighted linear regression [32].

Because the GWLR approach results in local estimates of the racial/ethnic differences in optimal CVH, we examined the median odds ratios (ORs), range (maximum OR – minimum OR) as well as the percent change in these median ORs and in the spatial heterogeneity in the ORs as we iteratively assessed the impact of individual- and neighborhood-level risk factors. To obtain all model estimates, we utilized an adaptive bandwidth, since the locations of the MESA participants are not regularly spaced in a grid-like fashion in each of the five sites [34]. We assessed model fit via R^2 and Akaike Information Criterion (AIC) statistics [35]. All analyses were conducted in R [36].

To graphically display the spatial heterogeneity in the black-white differences in optimal CVH, after adjusting for the impact of individual- and neighborhood-level risk factors, we present maps of the estimated GWLR ORs from Model 3. These maps also display the statistical significance of the varying ORs, based on whether the corresponding *t* test statistics were less than −1.96 or larger than 1.96. The statistical significance presented in the maps highlight how significantly different the ORs are from 1, and does not speak to how different the ORs are from each other across each study region. Inverse distance weighted interpolation, a deterministic, local, exact interpolation technique, was used to convert the GWLR ORs to surfaces for each site. As an exact interpolator, this technique predicts a value identical to the estimated OR values at the point locations corresponding to participants' home addresses. Weights were assumed to be proportional to the inverse of the square of the distance (power = 2). As a local interpolation technique rather than a global technique, predictions were based on a subset of points within neighborhoods for each of the estimated OR values at each participant's location. Circular search neighborhoods were used with a minimum of 3 neighbors and a maximum of 15 neighbors [37]. The resulting surfaces were saved as 100m cell size rasters. The ArcGISPro Geostatistical Wizard tool was used to create surfaces from the points [38].

3. RESULTS

The CVH score components for all MESA participants and by race/ethnicity are presented in Table 1. Among the 3,154 MESA participants, most have an inadequate total CVH score (49.3%), followed by average (32.2%) and optimal (18.5%). For the health behaviors and factors, most MESA participants have ideal physical activity, cholesterol and blood sugar levels, and no smoking history or quit smoking more than a year ago. With the exception of cholesterol, the prevalence of ideal CVH behaviors and factors is higher in whites compared to blacks; additionally, there are greater proportions of white MESA participants with optimal total CVH scores (25.6%) compared to black MESA participants (9.7%).

Table 2 outlines the descriptive statistics for the individual- and neighborhood-level risk factors for all MESA participants and by race/ethnicity. The mean age was 62.2 years (SD = 9.9 years), the average annual income was $60,066.60 (SD = $34,694.40), and 59% of the sample was married. There are notable differences in the individual-level risk factors between black and white MESA participants, where the white MESA participants were significantly older, had a higher annual income, more years of education, and a higher proportion were married. For the neighborhood-level risk factors, higher values indicate better neighborhood environments, and a greater proportion of white MESA participants live in neighborhoods with better SES, physical activity resources, healthy food availability, walking/physical activity environment, safety and social cohesion. Greater proportions of black MESA participants live in neighborhoods that have higher densities of favorable food stores and are more densely populated. To assess multicollinearity between all individual- and neighborhood-level risk factors, we assessed the VIF of each and all resulted in values less than 10 (Supplementary Table A2) - indicating little to no evidence of significant multicollinearity.

Table 3 shows the local racial/ethnic differences in optimal CVH as well as fit statistics from the various GWLR models considered – where the local differences are estimated at each MESA participant's baseline address. The model estimates presented are odds ratios, and are mostly less than one at each MESA site – indicative of blacks consistently having reduced odds of ideal CVH compared to whites (the reference group). In assessing the spatial heterogeneity in the black-white differences in CVH, Model 1 results show noticeable variation in the odds of optimal CVH for blacks. The median ORs show that blacks are less likely to have optimal CVH compared to whites – with decreased odds of about 60% in CA (Med. OR = 0.36), but up to 70% at the other 4 sites. The range of these decreased odds vary across sites, where the range of values for the OR is as large as 1.15 in NC to as small as 0.18 in CA. The heterogeneity in the ORs is apparent within each site, such that, in NC, for instance, blacks have decreased odds of optimal CVH of 85% (Min. OR = 0.15), but a maximum OR as large as 1.30 – indicating that, in some regions of the NC site, blacks have increased odds of optimal CVH compared to whites. A similar pattern is noted in the IL site. The other three sites have ranges that all result in decreased odds of optimal CVH for blacks.

The impact of individual-level risk factors reduces the racial/ethnic differences in the odds of optimal CVH, as seen by the Model 2 results presented in Table 3, where, at each site, there are reductions in the estimated median ORs – with the exception of the IL site where the median OR slightly decreased from 0.30 (Model 1) to 0.29 (Model 2). In terms of the magnitude of the reductions in the estimated median ORs, the NC site resulted in a reduction of only about 7%. The CA site, though, resulted in a reduction in the median OR of 47%, which was the largest reduction seen across all five sites - indications of the individual-level risk factors explaining some (almost half) of the racial/ethnic differences in optimal CVH. Further reductions were noted when considering the additional impact of neighborhood-level risk factors (Model 3), although the reductions varied at each MESA site. While the CA site saw large percent change reductions in the median ORs when considering only individual-level risk factors (comparing Models 1 and 2), a 13% decrease in the odds of optimal CVH for blacks compared to whites was evident when considering both individual- and neighborhood-level risk factors – resulting in a decreased odds of approximately 60% (Med. OR = 0.41). The MD, NC, and IL sites also saw reductions in the median ORs of 22%, 25%, and 39%, respectively. The largest percent change in median ORs was apparent at the NY site, where there was a 77% change from Model 1 to Model 3; furthermore, even after adjusting for individual- and neighborhood-level risk factors, blacks were still less likely to have optimal CVH (Med. OR = 0.46).

To assess whether spatial heterogeneity in optimal CVH is explained by individual- and neighborhood-level risk factors, the range in the ORs is explored in more detail. Specifically, for the NC and NY sites, the range noticeably reduces in an almost linear fashion once individual- and then both individual- and neighborhood-level risk factors are considered, respectively; such that, most of the variability in optimal CVH is being explained by these factors. For the MD and IL sites, the individual-level risk factors appear to explain most of the spatial heterogeneity in optimal CVH, compared to the additional adjustment of the

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neighborhood-level risk factors. The spatial heterogeneity in optimal CVH at the CA site actually increased when individual-level risk factors were considered, but noticeably decreased when both individual- and neighborhood-level risk factors were considered. Additionally, while the range in the ORs across each site decreased when comparing Model 1 to Models 2 and 3, there still remained some variation in the estimated ORs at each site, with noticeable variation in some sites but not in others; nonetheless, blacks consistently have reduced odds of optimal CVH.

The fit statistics presented in Table 3 show evidence of the performance of our models. The R^2 values show consistent improvements of Models 2 and 3, compared to Model 1, where the proportion of the variation in optimal CVH within each site is increasingly being explained by the risk factors considered. At all sites, except NY, the AIC values for Models 2 and 3 show improvements over Model 1, when considering individual- and then individual- and neighborhood-level risk factors. In terms of comparisons between the GWLR and the global logistic regression models, the AIC fit statistics show improvements of the GWLR approach that are of modest to significant gains in model fit and improvement at the NC, NY (except for Model 3), and MD sites. The IL models, with the exception of Model 1, and the CA models resulted in AIC values that are similar between the GWLR and the global logistic regression models.

We also present the results from the geographically weighted linear regression models focusing on the total CVH score (as opposed to the odds of optimal CVH) in Table 4. The AIC statistics for each model at each MESA site shows significant improvements over the global AIC statistics – indicative of spatial patterning apparent in overall CVH. At each site, the estimated racial/ethnic differences were negative, demonstrating that blacks, compared to whites, have lower total CVH scores. For instance, blacks have an average decrease in their total CVH score of approximately 0.5 points in NC and NY, even after adjusting for individual- and neighborhood-level risk factors (Model 3). Similar to the GWLR results, the range in the estimates within each site is reduced once both individual- and neighborhood-level risk factors are considered. The Model 3 ranges at each site show very little remaining spatial heterogeneity, where the MD site had the largest range of 0.18 for Model 3.

To further characterize the black-white differences in the odds of optimal CVH and the spatial heterogeneity in these differences, Figure 2 shows maps of the five MESA sites and the corresponding estimated ORs from the fully adjusted GWLR models (Model 3) – where these maps are a direct result of using inverse distance weighted interpolation. Each map has a black border around the city or county limits to aid in interpretability of the catchment area of each MESA site. Additionally, each map shows grey census tract boundaries within the city or county limits. All sites show noticeable variation in the black-white differences in optimal CVH, even after adjusting for both individual- and neighborhood-level risk factors. For the NC site, there are significantly decreased odds (60%) of optimal CVH in the northwest regions of Forsyth County; however, there is a noticeable gradient in these odds that decrease to 50% towards the central and eastern regions. While the majority of the NC study region resulted in statistically significant ORs, there is a small portion in the eastern region that is not statistically significant. In the New York map, variation in the black-white disparities is present, although not statistically significant, throughout the entire region –

with decreased odds of up to 50% in the central region, but 40% decreased odds in the northeast region. For the MD site, all GWLR ORs were statistically significant, with decreased odds (70%) of optimal CVH apparent in the northeastern region of Baltimore, whereas there are decreased odds of 60% as you move more southwest of the city. For the IL site, the central east coast region of Chicago resulted in significantly decreased odds (60%) of optimal CVH – with noticeable variation as you move more north and south. Lastly, in Los Angeles, CA, while the decreased odds of optimal CVH for blacks was not statistically significant across the entire region, the variation in the ORs is apparent with decreased odds of 60% in the northeast region of the city, but decreased odds of 50% in the western region.

4. CONCLUSIONS

Our study focused on assessing the spatial heterogeneity in the black-white differences in optimal CVH and examined the impact of individual- and neighborhood-level risk factors to this heterogeneity. Using the MESA cohort, we found evidence of significant spatial heterogeneity in black-white differences that varied within and between the five MESA sites. Initial models, which assessed the spatial heterogeneity in the black-white differences in optimal CVH, showed decreased odds of optimal CVH for blacks that ranged from 60% reduced odds in CA up to 70% reduced odds in all other sites – with noticeable variation of these decreased odds of optimal CVH for blacks. Adjusting for individual-level risk factors resulted in reductions in the black-white differences in optimal CVH, but the additional consideration of neighborhood-level risk factors resulted in even more reductions in the spatial heterogeneity within each site. The maps presented highlight the varying nature of the black-white differences in optimal CVH. We compared each geographically weighted logistic regression model with its corresponding logistic regression model to formally test if spatial heterogeneity was present, and found modest gains in model fit in. While we were not specifically focused on the varying black-white differences across each of the five MESA sites, we were still able to draw inference on the noticeable patterns of these differences within each site.

For our secondary analysis, we also looked at the black-white difference in overall CVH score. Once individual-level risk factors were considered, the spatial heterogeneity in the racial differences in Forsyth County, NC and Los Angeles, CA ultimately reduced to none – whereas, at the other 3 sites, there still remained some spatial patterning in these racial differences, as seen by the significant drop in the range of the GWR differences. When additionally considering neighborhood level risk factors, all sites, with the exception of Baltimore, MD resulted in negligible spatial patterning in the racial differences between blacks and whites. The drivers of spatial heterogeneity in the racial difference of CVH, as evidenced by examining the total CVH score for each MESA participant, seems to be a direct function of those individual- and neighborhood-level risk factors we considered. For Baltimore, MD, though, there is likely residual confounding that exists, and whether that is at the individual- or neighborhood level is to be further examined.

Other studies have also reported black–white differences in ideal CVH Racial differences in CVH behaviors were found in examining the Coronary Artery Risk Development in Young Adults Study; such that, blacks had significantly lower health behavior scores than whites across 30 years of follow-up [39]. Another study found racial differences in ideal CVH among adults living in Mississippi using the 2009 Mississippi Behavioral Risk Factor Surveillance System [40]. The prevalence of four of the seven ideal CVH health behaviors and factors was significantly lower among the total population of blacks than among whites, including BMI, diabetes, hypertension, and physical activity. Some studies have also reported that individual-level SES and neighborhood factors are related to CVH [19, 28] – some of which we have considered in our current research, including income and neighborhood SES (results not shown). Our results show the importance of both individual- and neighborhood-level risk factors on the varying degree of black-white differences in optimal CVH. For example, we found that individual income was significantly associated with optimal CVH, where, at every MESA site, as income increased, the odds of optimal CVH also increased. Additionally, at the neighborhood level, we found that, in the New York City, NY and Chicago, IL sites, as neighborhood SES improved, so did the odds of optimal CVH.

To our knowledge, spatial variations in optimal CVH or in the black-white differences in optimal CVH have not been examined. Black-white differences have been found for hypertension, systolic blood pressure, diabetes, and smoking, and geographic differences have been described for diabetes and hypertension using the Reasons for Geographic and Racial Differences in Stroke (REGARDS) study [41]. Additionally, and most recently, the geographic variation in the prevalence of hypertension, diabetes mellitus, and smoking within and across US counties was described in the REGARDS study [22]. While these previous studies are not directly comparable to our study, our findings of black-white differences in optimal CVH and the spatial heterogeneity in these differences should continue to provide the evidence necessary to tailor more community-based informed interventions towards improving CVH for blacks.

Our study is the first to assess the spatial heterogeneity in the black-white differences in optimal CVH, while also considering the impact of both individual- and neighborhood-level risk factors on these differences across the US. Spatial heterogeneity in this context allows for a more thorough examination of the impact of individual- and neighborhood-level risk factors. The strengths of our study include the use of a sample of individuals from five cities across the US found in the MESA cohort, which provides information about specific racial/ethnic groups and allow comparisons among groups at different levels of risk. The MESA cohort allows for the assessment of not only traditional individual-level risk factors, such as age, sex, income, education, and, most importantly in this study, race/ethnicity, but it also includes a wealth of neighborhood-level risk factors. Moreover, the MESA cohort and the five sites considered allow for an assessment of the spatial heterogeneity in the black-white differences in optimal CVH within each site and across sites. Our use of spatial methods, specifically, GWLR models, allow for a flexible approach to estimating the spatially varying black-white differences in optimal CVH, while considering both individual- and neighborhood-level risk factors. This spatially varying model provides both the magnitude of the relationships between optimal CVH, race/ethnicity, and other risk factors, in addition to the direction of these varying associations. Additionally, using GWLR models allow for a visual assessment of the geographic variations in these differences between blacks and whites – found in our maps. While this approach is powerful in exploring spatial patterning and non-stationarity [32], there are some challenges, including that this method is highly susceptible to the effects of multicollinearity [42]. Though all of the VIFs within each analysis was less than 10, the analyses in IL resulted in VIFs approaching 10 – indicating potential multicollinearity. More recently, though, the GWR approach has actually been found to be robust to multicollinearity among explanatory variables except in the most extreme settings [43].

Our findings highlight not only the usefulness of spatially focused statistical methods, found in geographically weighted regression approaches, in exploring the geographic patterning in black-white differences in optimal CVH, but also provides further understanding of the spatial patterning in the relationship between CVH and the individual and neighborhood-level risk factors – both equally contributing insight into the health equity and CVH literature. Spatial heterogeneity in optimal CVH speaks broadly to the concept of how this health outcome may vary from region to region, where a global understanding of this health outcome could likely lead to misrepresentation. Spatial heterogeneity found in the individual- and neighborhood-level risk factors, and how they actually impact optimal CVH, speaks to the multilevel and varying nature of these factors; however, this also sheds light on the possible unmeasured individual- and neighborhood-level risk factors not considered or even measured in this setting.

Some limitations of our study include the exclusion of the St. Paul, MN site due to blacks not being recruited from this site; which speaks to the generalizability of our findings in that region of the US. While the CA site was considered in evaluating the spatially varying differences between blacks and whites and showed decreased odds of optimal CVH, the sample size at this site was much smaller (n=250) than the other four sites. Another limitation to consider is that MESA participants were free of clinical CVD at baseline, so the black-white differences in overall CVH as well as the components of CVH in our study may be less than what we would expect in the general population. The cross-sectional study design also does not allow for an examination of temporal trends in these differences in optimal CVH between blacks and whites. Additionally, as with many other studies that utilize data from observational cohorts, many measures considered rely on self-report, which is subject to recall bias and possible misclassification. Lastly, unmeasured confounding is a limitation in almost any study, and our study is no exception. When considering disparities in general, there are numerous factors that contribute to a wide variety of health outcomes and how they impact different subpopulations. When considering, specifically, black-white differences in health outcomes, measures like discrimination, unfair treatment, and racism often play key roles in explaining the differences that exist – beyond socioeconomic factors alone. For example, discrimination has been shown to be significantly associated with worse physical and mental health in both men and women [44]. When focusing on CVD, a MESA based study has found that perceived discrimination is adversely related to CVD risk in middle-aged and older adults [45]. While our study did not consider these measures, these factors might play a role in fully explaining this complex relationship between optimal CVH and race/ethnicity. In the Baltimore, MD MESA site, for instance, even after controlling for individual- and neighborhood-level risk factors, spatial patterning in the racial differences between blacks and whites persisted – it’s possible unmeasured confounders could explain the remaining variability in these differences.

An additional limitation with our study, and similar to many other cohort, population-based studies utilizing spatial data analytic methods, involves the modifiable areal unit problem [46]. With census tracts as our spatial unit of analysis, which had direct implications on how many of the objective neighborhood measures were operationalized, we acknowledge the varying sprawl and population density within each MESA site. Knowing this, all models considered adjusted for population density, to ensure that we recognize the varying nature of how densely populated each census tract is. However, we also realize that classifying one's neighborhood based on census tract boundaries will have potentially different estimated relationships between CVH, race/ethnicity, and individual- and neighborhood-level risk factors versus any other spatial unit of analysis, like a census block group or even at the county level.

CVH is a critical component of not only Healthy People 2020, but also the AHA's 2020 Strategic Goals of improving CVH of all Americans by 20% while reducing deaths from CVD and stroke by 20%. Our study findings suggest racial/ethnic differences in optimal CVH as well as spatial heterogeneity in these differences. Additionally, we found that both individual- and neighborhood-level risk factors contributed to a noteworthy portion of the spatial patterning in the black-white differences in optimal CVH, which underscores the need for future research that captures risk factors at both levels. It was also true, however, that some spatial heterogeneity in ORs persisted even after available individual- and neighborhood-level risk factors were taken into consideration. Further understanding of the reasons for spatial heterogeneities in black-white differences in nationally representative cohorts across the US may provide important clues regarding the drivers of these differences.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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HIGHLIGHTS

- Cardiovascular health (CVH) is examined, which focuses on health behaviors and factors
- Spatial variation in CVH was explored using a unique, diverse population-based cohort study
- Black-white disparities in CVH vary within and across 5 US cities
- Blacks have decreased odds of optimal and overall cardiovascular health
- Individual- and neighborhood-level risk factors, both subjective and objective measures, reduced varying disparities

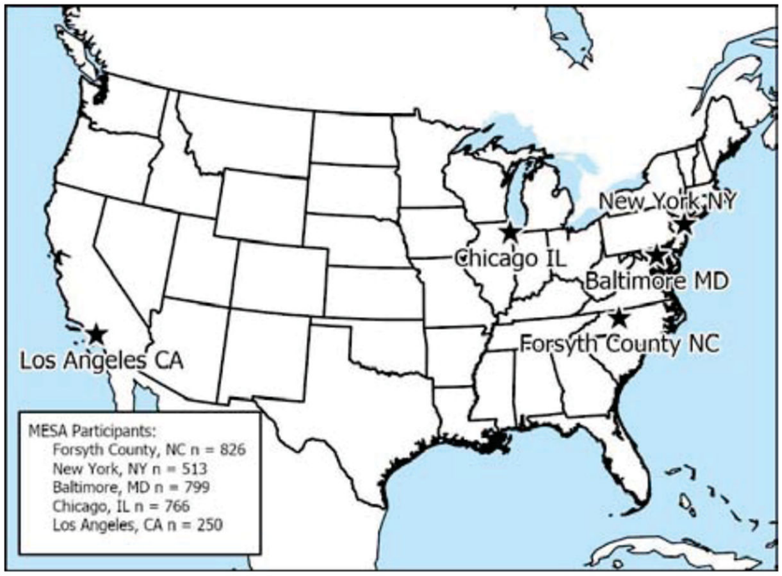

Figure 1.
Map of MESA sites considered for the final analytic dataset, including a total of 3,154 participants across 5 cities.*
*MESA, Multi-Ethnic Study of Atherosclerosis

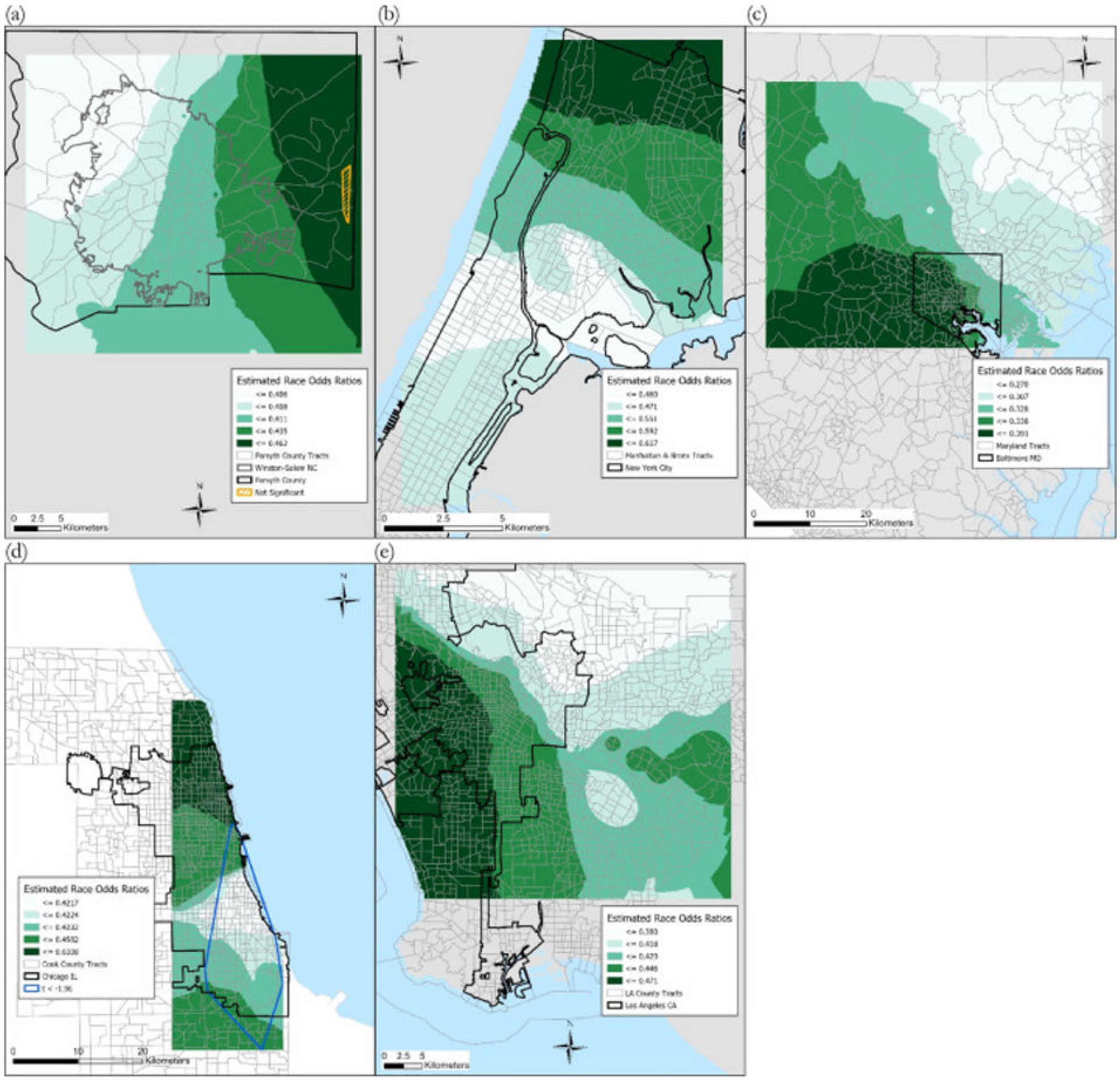

Figure 2.

GWLR spatial associations between race (blacks vs. whites) and ideal CVH by MESA site, assuming Model 3 for: (a) Forsyth County, NC; (b) New York City, NY; (c) Baltimore, MD; (d) Chicago, IL; and (e) Los Angeles, CA. *

* Model 3 is adjusted for race/ethnicity, age, sex, income, education, marital status, neighborhood socioeconomic status, favorable food stores, physical activity resources, healthy food availability, the walking/physical activity environment, safety, social cohesion, and population density.

Table 1.

Cardiovascular health score components for all MESA participants and by race/ethnicity.*

Component	Score	Definition	Black and White MESA Population (n = 3154)	Black MESA Population (n = 1409)	White MESA Population (n = 1745)
Smoking	0	Current smoker	13.1	17.7	9.3
	1	Former smoker, quit ≤ 12 mo ago	0.5	0.4	0.6
	2	Never smoker or quit > 12 mo ago	86.4	81.9	90
BMI	0	≥30 kg/m^2	33.5	44.2	24.9
	1	25.0-29.99 kg/m^2	47	43.5	49.8
	2	<25.0 kg/m^2	19.5	12.3	25.3
Physical Activity	0	No exercise	18.8	22.6	15.8
	1	1-149 min of moderate exercise or 1-74 min of vigorous exercise/week	16.9	16.9	16.8
	2	150+ min of moderate exercise or 75+ min of vigorous exercise/week	64.3	60.5	67.4
Diet	0	0-1 components of healthy diet	48.3	56.6	41.6
	1	2-3 components of healthy diet	50.3	42.5	56.6
	2	4-5 components of healthy diet	1.4	0.9	1.8
Cholesterol	0	≥ 240 mg/dL	12.5	11.3	13.5
	1	200-239 mg/dL or treated to <200 mg/dL	39.9	37.6	41.7
	2	<200 mg/dL, unmedicated	47.6	51.1	44.8
Blood Pressure	0	SBP ≥140 mm Hg or DBP ≥ mm Hg	46.1	55.4	38.7
	1	SBP 120-139 mm Hg or DBP 80-89 mm Hg or treated to <120/80 mm Hg	22.3	21.1	23.3
	2	<120/80 mm Hg, unmedicated	31.5	23.5	38.1
Blood Sugar	0	≥ 126 mg/dL fasting	8.9	14	4.9
	1	100-125 mg/dL fasting or treated to <100 mg/dL	13.4	16.2	11.2
	2	<100 mg/dL fasting, unmedicated	77.6	69.8	84
Total Cardiovascular Health Score		Inadequate (0-8)	49.3	63.4	37.9
		Average (9-10)	32.2	26.9	36.4
		Optimal (11-14)	18.5	9.7	25.6

*MESA, Multi-Ethnic Study of Atherosclerosis; BMI, body mass index; DBP, diastolic blood pressure; SBP, systolic blood pressure. Both races are non-Hispanic.

Table 2.

Individual- and neighborhood-level risk factors for all MESA participants and by race/ethnicity*

Risk Factors	Black and White MESA Population (n = 3154)	Black MESA Population (n = 1409)	White MESA Population (n = 1745)
Individual			
Age, y, mean (SD)	62.2 (9.9)	61.5 (9.8)	62.7 (9.9)
Men, n (%)	1480 (46.9)	634 (45.0)	846 (48.5)
Income, mean (SD)	60066.6 (34694.4)	47787.4 (30616.6)	69981.4 (34630.0)
Education, mean (SD)	14.5 (2.9)	13.8 (3.0)	15.1 (2.8)
Married, n (%)	1870 (59.3)	664 (47.1)	1206 (69.1)
Neighborhood			
Socioeconomic status, mean (SD)	1.5 (6.3)	−2.1 (5.4)	4.3 (5.3)
Favorable Food Stores/mile^2, mean (SD)	2.8 (4.5)	3.1 (4.5)	2.6 (4.5)
Physical Activity Resources/mile^2, mean (SD)	6 (10.1)	3.7 (6.4)	7.9 (12.0)
Healthy Food Availability**, mean(SD)	3.5 (0.6)	3.4 (0.5)	3.6 (0.6)
Walking/Physical Activity Environment**, mean (SD)	4.0 (0.4)	3.9 (0.3)	4.1 (0.4)
Safety Condition**, mean (SD)	3.7 (0.4)	3.5 (0.4)	3.8 (0.4)
Social Cohesion**, mean (SD)	3.6 (0.2)	3.5 (0.3)	3.7 (0.2)
Population Density/mile^2, mean (SD)	15668.0 (19436.9)	18891.2 (22068.3)	13065.4 (16572.9)

*MESA, Multi-Ethnic Study of Atherosclerosis; SD, standard deviation. Both races are non-Hispanic.

**Conditional empirical Bayes estimate for census tract.

Table 3.

Summaries of the local black vs. white odds ratio estimates (minimum, median, maximum, and range = max. – min.) from geographically weighted logistic regression Models 1, 2, and 3 of optimal cardiovascular health by MESA site, with model fit statistics. Local estimates are based on MESA participants' baseline addresses.*

Forsyth County, NC (n = 826)	Min.	Med.	Max.	Range	R^2	AIC	Global AIC
Model 1 [a]	0.15	0.33	1.30	1.15	0.07	631.09	635.09
Model 2 [b]	0.30	0.35	0.55	0.25	0.10	616.15	616.18
Model 3 [c]	0.40	0.41	0.49	0.08	0.10	622.14	623.49
New York City, NY (n = 513)	**Min.**	**Med.**	**Max.**	**Range**	R^2	**AIC**	**Global AIC**
Model 1 [a]	0.17	0.26	0.78	0.61	0.09	500.92	511.68
Model 2 [b]	0.30	0.33	.80	0.50	0.10	506.95	509.63
Model 3 [c]	0.44	0.46	0.62	0.17	0.13	518.08	510.33
Baltimore, MD (n = 799)	**Min.**	**Med.**	**Max.**	**Range**	R^2	**AIC**	**Global AIC**
Model 1 [a]	0.10	0.28	0.99	0.89	0.09	623.95	631.96
Model 2 [b]	0.24	0.30	0.36	0.12	0.12	609.15	610.78
Model 3 [c]	0.22	0.34	0.39	0.17	0.15	608.62	612.92
Chicago, IL (n = 766)	**Min.**	**Med.**	**Max.**	**Range**	R^2	**AIC**	**Global AIC**
Model 1 [a]	0.26	0.30	1.09	0.83	0.07	836.58	838.05
Model 2 [b]	0.29	0.29	0.42	0.13	0.09	825.51	824.71
Model 3 [c]	0.42	0.42	0.71	0.29	0.11	828.55	825.40
Los Angeles, CA (n = 250)	**Min.**	**Med.**	**Max.**	**Range**	R^2	**AIC**	**Global AIC**
Model 1 [a]	0.25	0.36	0.43	0.18	0.05	223.43	222.28
Model 2 [b]	0.39	0.53	0.72	0.33	0.15	216.99	215.71
Model 3 [c]	0.32	0.41	0.47	0.15	0.25	223.18	219.51

*MESA, Multi-Ethnic Study of Atherosclerosis; AIC = Akaike information criterion

[a] Model 1 is adjusted for race/ethnicity.

[b] Model 2 is adjusted for race/ethnicity, age, sex, income, education, and marital status.

[c] Model 3 is adjusted for race/ethnicity, age, sex, income, education, marital status, neighborhood socioeconomic status, favorable food stores, physical activity resources, healthy food availability, the walking/physical activity environment, safety, social cohesion, and population density.

Table 4.

Summaries of the local racial/ethnic differences (minimum, median, maximum, and range = max. – min.) from geographically weighted linear regression Models 1, 2, and 3 of total cardiovascular health score by MESA site. Local estimates are based on MESA participants' baseline addresses.[*]

Forsyth County, NC (n = 826)	**Min.**	**Med.**	**Max.**	**Range**	**R^2**	**AIC**	**Global AIC**
Model 1 [a]	−0.88	−0.48	0.76	1.64	0.10	2281.27	2308.38
Model 2 [b]	−0.40	−0.39	−0.39	0.01	0.11	2252.60	2261.68
Model 3 [c]	−0.46	−0.45	−0.45	0.01	0.12	2252.30	2269.34
New York City, NY (n = 513)	**Min.**	**Med.**	**Max.**	**Range**	**R^2**	**AIC**	**Global AIC**
Model 1 [a]	−0.88	−0.75	1.36	2.24	0.14	1384.68	1399.93
Model 2 [b]	−0.69	−0.58	−0.25	0.44	0.16	1374.83	1392.05
Model 3 [c]	−0.48	−0.47	−0.47	0.00	0.17	426.98	1393.81
Baltimore, MD (n = 799)	**Min.**	**Med.**	**Max.**	**Range**	**R^2**	**AIC**	**Global AIC**
Model 1 [a]	−1.07	−0.51	0.93	2.00	0.13	2176.88	2211.14
Model 2 [b]	−0.58	−0.47	−0.27	0.31	0.15	2154.46	2172.73
Model 3 [c]	−0.54	−0.38	−0.36	0.18	0.16	2147.13	2173.02
Chicago, IL (n = 766)	**Min.**	**Med.**	**Max.**	**Range**	**R^2**	**AIC**	**Global AIC**
Model 1 [a]	−0.79	−0.65	1.02	1.81	0.12	2079.49	2092.43
Model 2 [b]	−0.68	−0.45	0.65	1.33	0.20	2024.10	2050.84
Model 3 [c]	−0.35	−0.35	−0.35	0.01	0.18	2037.08	2054.11
Los Angeles, CA (n = 250)	**Min.**	**Med.**	**Max.**	**Range**	**R^2**	**AIC**	**Global AIC**
Model 1 [a]	−0.90	−0.60	−0.22	0.67	0.15	677.77	692.45
Model 2 [b]	−0.34	−0.33	−0.33	0.01	0.20	661.67	670.87
Model 3 [c]	−0.34	−0.34	−0.33	0.01	0.23	660.22	677.83

[*] MESA, Multi-Ethnic Study of Atherosclerosis; AIC = Akaike information criterion

[a] Model 1 is adjusted for race/ethnicity.

[b] Model 2 is adjusted for race/ethnicity, age, sex, income, education, and marital status.

[c] Model 3 is adjusted for race/ethnicity, age, sex, income, education, marital status, neighborhood socioeconomic status, favorable food stores, physical activity resources, healthy food availability, the walking/physical activity environment, safety, social cohesion, and population density.