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Relationship between Neighborhood-Level Social Risk Factor Measures and Presenting Glaucoma Severity Utilizing Multilevel Modeling

Patrice M. Hicks, PhD, MPH,[1] *Ming-Chen Lu, MS,*[1] *Maria A. Woodward, MD, MS,*[1,2] *Leslie M. Niziol, MS,*[1] *Deborah Darnley-Fisch, MD,*[3] *Michele Heisler, MD,*[4,5] *Kenneth Resnicow, PhD,*[5] *David C. Musch, PhD, MPH,*[1,6] *Jamie Mitchell, PhD, MSW,*[7] *Roshanak Mehdipanah, PhD, MS,*[5] *Nauman R. Imami, MD,*[3] *Paula Anne Newman-Casey, MD MS*[1,2]

Purpose: The neighborhood and built environment social determinant of health domain has several social risk factors (SRFs) that are modifiable through policy efforts. We investigated the impact of neighborhood-level SRFs on presenting glaucoma severity at a tertiary eye care center.

Design: A cross-sectional study from August 2012 to May 2022 in the University of Michigan electronic health record (EHR).

Participants: Patients with a diagnosis of any open-angle glaucoma with ≥1 eye care visit at the University of Michigan Kellogg Eye Center and ≥1 reliable visual field (VF).

Methods: Participants who met inclusion criteria were identified by International Classification of Diseases ninth and tenth revision codes (365.x/H40.x). Data extracted from the EHR included patient demographics, address, presenting mean deviation (MD), and VF reliability. Addresses were mapped to SRF measures at the census tract, block group, and county levels. Multilevel linear regression models were used to estimate the fixed effects of each SRF on MD, after adjusting for patient-level demographic factors and a random effect for neighborhood. Interactions between each SRF measure with patient-level race and Medicaid status were tested for an additive effect on MD.

Main Outcome Measures: The main outcome measure was the effect of SRF on presenting MD.

Results: In total, 4428 patients were included in the analysis who were, on average, 70.3 years old (standard deviation = 11.9), 52.6% self-identified as female, 75.8% self-identified as White race, and 8.9% had Medicaid. The median value of presenting MD was −4.94 decibels (dB) (interquartile range = −11.45 to −2.07 dB). Neighborhood differences accounted for 4.4% of the variability in presenting MD. Neighborhood-level measures, including worse area deprivation (estimate, $\beta = -0.31$ per 1-unit increase; $P < 0.001$), increased segregation ($\beta = -0.92$ per 0.1-unit increase in Theil's H index; $P < 0.001$), and increased neighborhood Medicaid ($\beta = -0.68$; $P < 0.001$) were associated with worse presenting MD. Significant interaction effects with race and Medicaid status were found in several neighborhood-level SRF measures.

Conclusions: Although patients' neighborhood SRF measures accounted for a minority of the variability in presenting MD, most neighborhood-level SRFs are modifiable and were associated with clinically meaningful differences in presenting MD. Policies that aim to reduce neighborhood inequities by addressing allocation of resources could have lasting impacts on vision outcomes.

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In recent years, there has been an interest in exploring the relationship between social risk factors (SRFs) and health outcomes.[1,2] Social risk factors are individual-level adverse social conditions that are associated with poor health outcomes.[3,4] Social risk factors can occur in any of the 5 domains of social determinants of health. Examples of SRFs include having low income (economic stability domain), having low education (education access and quality domain), not having health insurance (health care access and quality domain), experiencing discrimination

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(social and community context domain), or having high exposure to environmental pollutants (neighborhood and built environment domain). Social risk factors have been associated with several negative health outcomes. For example, cancer risk and decreased survivorship have been associated with poor access to quality education, greater exposure to psychosocial stressors, and segregated residential environments.[5]

Social risk factors have also been shown to be associated with eye health outcomes, including an increased prevalence of visual impairment and blindness, more severe presentation of microbial keratitis, and an increased prevalence and worse outcomes for glaucoma.[6–8] Understanding the relationship between SRFs and individual eye conditions can inform screening and policy interventions to improve public health. There is very little literature exploring how neighborhood-level SRFs impact eye health. Specifically, how one's neighborhood impacts glaucoma severity remains understudied.

In this study we aimed to investigate the association between neighborhood-level SRFs and glaucoma severity at presentation to a tertiary eye care center and to determine how much neighborhood factors account for glaucoma severity at presentation compared to individual demographic factors. By understanding the unique contributions of neighborhood-level SRFs and patient-level demographics, we can start to assess the possible impacts of where a patient lives on their glaucoma outcomes.

Methods

This study was approved by The University of Michigan Medical School Institutional Review Board (HUM#00209676). All research adhered to the tenets of the Declaration of Helsinki. Patients who were ≥18 years of age and had a diagnosis of any primary or secondary open-angle glaucoma between August 2012 and May 2022 were identified in the electronic health record (EHR) at the University of Michigan (Epic System). Both International Classification of Diseases nine (365.x) and ten (H40.1x) codes that originated in the ophthalmology department at an in-person office visit were used (Supplemental Table 1, available at www.ophthalmologyscience.org). Of these patients with glaucoma, those who lived in Michigan (95%) and had a reliable or borderline reliable Humphrey 24-2 visual field (VF) within 2 years of their first diagnosis were included. We utilized subsequent reliable VFs if available for patients with initial "not reliable" VFs, up to 2 years after the initial diagnosis. If a patient did not have a reliable or borderline reliable Humphrey VF 24-2 within 2 years of the diagnosis, the patient was excluded. The assessment of reliability was based on physician impression. Physicians grade each field as reliable, borderline, or not reliable. All "not reliable" fields were excluded. Further, since open-angle glaucoma is typically a slowly progressing disease, we allowed for the first measure of mean deviation (MD) to be up to 2 years after initial diagnosis. While 44% of our sample had a reliable VF at diagnosis (n = 1952 out of 4428), for those who did not, the first reliable VF was on average 297 days after diagnosis (median = 266, interquartile range [IQR] = 133−428). Presenting MD was defined as the MD for each participant at the date the first reliable VF was obtained. Since glaucoma is typically a binocular but asymmetric disease, the worse eye was selected for inclusion based on MD, and the best-corrected visual acuity was obtained for that same eye. Patient demographics (age, self-reported gender, self-reported race, and self-reported ethnicity) and addresses were extracted from the EHR. Race included White, Black/African American, Asian, and other (American Indian/Alaskan Native, ≥2 races, and any other race not previously listed). Ethnicity was reported as either Hispanic or non-Hispanic. Patient insurance status was obtained from DataDirect (a tool to query the EHR at the University of Michigan) and those who had any type of insurance were coded as either Medicaid insured or non-Medicaid insured.

Neighborhood-Level SRF Measures

Patient addresses at the date of the first reliable VF measured were mapped to the 2010 or 2020 12-digit Federal Information Processing Standards codes, whichever date was closest to the date of the reliable field. The Federal Information Processing Standard codes contain census block group, census tract, and county numbers and were used to map individuals to neighborhood-level measures. Neighborhood-level measures were obtained from the University of Wisconsin's Neighborhood Atlas, the Department of Energy's Low-income Energy Affordability Data tool, and the American Community Survey data from PolicyMap.[9–11] Full descriptions of each neighborhood-level SRF are listed in Supplemental Table 2 (available at www.ophthalmologyscience.org). Briefly, food insecurity was assessed by the percent of Supplemental Nutrition Assistance Program recipients in the county.[12] Housing insecurity measures included average percentage of income spent on energy costs in a census tract, percentage of renters burdened by rental costs, and percentage of homeowners burdened by owner costs in a census block group.[9,13,14] Neighborhood safety was assessed by violent and property crime rates per 100 000 people in the county.[15] Neighborhood residential inequity was assessed by the state area deprivation index (ADI) in a census block group, average historical redlining score (historical systematic denial of mortgages to Black individuals) in a census tract, Gini index (a measure of neighborhood income inequality) in a census tract, and Theil's H index (a measure of neighborhood segregation) in a census block group.[10,16–19] Neighborhood transportation accessibility was assessed by the average number of vehicles per household in a census tract.[20] Health care accessibility measures included percentage of individuals with no insurance and percentage of individuals with Medicaid in a census tract.[21,22] Neighborhood-level demographic factors were also assessed by percentage of persons of color in a census block group, per capita income in a census block group, and urban status of a census tract per the United States (US) Department of Agriculture.[23–25]

Statistical Methods

Patient-level characteristics and neighborhood-level SRF measures for the glaucoma sample were summarized with descriptive statistics including frequency, percentage, mean, standard deviation, median, and IQR. Univariate associations of patient-level characteristics and neighborhood-level SRFs with presenting MD were investigated with Kendall correlation for continuous variables, and Wilcoxon or Kruskal−Wallis tests for categorical variables. Significant Kruskal−Wallis tests were followed by post hoc Dunn's multiple comparisons with Holm adjustment. Differences in patient characteristics between those with reliable or borderline Humphrey 24-2 VF (the study sample) and those with unreliable Humphrey 24-2 VF (the excluded sample) were tested using *t* tests for continuous variables and chi-square or Fisher exact tests for categorical variables.

To account for the fact that patients residing in the same neighborhood may be more alike than patients from different neighborhoods, therefore making these observations less independent, multilevel linear regression models were used to understand

the impact of neighborhood and SRF measures on presenting MD. First, an unconditional means model was fit with the census block group as a random intercept; the intraclass correlation coefficient was reported to assess the proportion of the total variance in the presenting MD that is attributable to the neighborhood. Second, a model adjusted for patient-level characteristics (age, gender, race, ethnicity, and Medicaid status) with the census block group as a random intercept was fit to investigate the change in intraclass correlation coefficient. Third, separate models were fit to estimate the fixed effects of each SRF measure on presenting MD, after adjusting for patient-level characteristics and a random effect for the census block group. Interactions between each SRF measure with patient-level race and Medicaid status, respectively, were tested for an additive effect on presenting MD. These interactions were tested because of the established association between neighborhood-level resources, race, and poverty, where Medicaid status was used as a proxy for socioeconomic status. Other race was excluded from the interaction analysis with each SRF measure due to its small sample size. Presenting visual acuity was not included in the main models to avoid multicollinearity. Model estimates (β) are reported with 95% confidence intervals (CIs). Holm's procedure was used to adjust for multiple comparisons. Statistical analysis was performed in R statistical software version 4.4.0 (R Foundation for Statistical Computing).

Results

A total of 9887 patients with a diagnosis of a primary or secondary open-angle glaucoma were identified. Of these, 4605 (46.6%) had a reliable or borderline reliable Humphrey 24-2 VF within 2 years of presentation with glaucoma. After excluding patients residing in other states or with missing addresses, 4428 patients were included in the analysis (Fig 1). These 4428 patients were on average 70.3 years old (standard deviation = 11.9), 52.6% identified as female, 75.8% identified as White, 16.2% identified as Black or African American, 5.2% identified as Asian, 2.8% identified as other race, 2.2% identified as Hispanic, and 8.9% had Medicaid insurance (Table 1). Patients' best-corrected visual acuity was a median of 0.1 logarithm of the minimum angle of resolution units (Snellen equivalent = 20/25, IQR = 20/20 to 20/40). Presenting MD was a median of −4.9 decibels (dB) (IQR = −11.5 to −2.1). Presenting MD was significantly associated with patient-level characteristics. Specifically, patients who were older compared with younger ($P < 0.001$), identified as male compared with female ($P < 0.001$), identified as Black or African American compared with those who identified as White or other ($P < 0.001$), and those who had Medicaid compared with non-Medicaid insurance ($P < 0.001$) presented with significantly worse MD (Table 1). Patient characteristics of our study sample were different from the excluded sample (those with unreliable Humphrey 24-2 VF) such that our study sample was younger (70.3 ± 11.9 years vs. 74.0 ± 13.0, $P < 0.0001$) and had a lower percentage of patients who identified as Black or African American (16.2% vs. 22.1%, Holm-adjusted $P = 0.0158$). No other significant differences in gender, ethnicity, or Medicaid status were observed between our study sample and the excluded sample (all $P > 0.05$) (Supplemental Table 4, available at www.ophthalmologyscience.org).

Most patients with a reliable VF had Michigan residential address information that could be mapped to a census block group (4319 of 4428; 97.5%) for evaluation of neighborhood-level SRFs. Figure 1 provides the number of patients that had data available for each of the neighborhood-level SRFs of interest. Table 2 provides descriptive statistics of neighborhood-level SRFs for the sample. Many neighborhood-level SRF measures were significantly associated with presenting MD. Specifically, patients presented with significantly worse MD if they lived in a neighborhood with a higher percent of Supplemental Nutrition Assistance Program recipients ($P = 0.005$), higher percent of people who were energy burdened ($P < 0.001$), higher percent of renters that were cost burdened ($P = 0.001$), worse ADI rank ($P < 0.001$), worse historical redlining score ($P = 0.013$), worse Theil's H index ($P < 0.001$), lower average number of cars per household ($P = 0.002$), higher percent of individuals with no insurance ($P < 0.001$), higher percent of individuals with Medicaid ($P < 0.001$), higher percent of racial and ethnic minorities ($P = 0.001$), and lower income per capita ($P < 0.001$). Worse ADI rank was positively correlated with a higher percent of Supplemental Nutrition Assistance Program recipients, higher percent of people who were energy burdened, higher percent of renters that were cost burdened, and higher percent of owners that were cost burdened (all $P < 0.0001$).

The unconditional means model demonstrates that neighborhood differences accounted for 4.1% of the variability (variance = 2.35) in presenting MD, whereas patient differences accounted for 95.9% of the variability (variance = 54.87). After adjusting for patient age, gender, race, ethnicity, and Medicaid status, the neighborhood differences accounted for 4.4% of the variability (variance = 2.35) in presenting MD, whereas patient differences accounted for 95.6% (variance = 51.44). Several neighborhood-level SRF factors were independently associated with worse presenting MD after adjusting for patient-level characteristics (age, gender, race, ethnicity, and Medicaid status) (Table 3). Three neighborhood-level SRF measures showed a main effect on presenting MD (not modified by race or Medicaid status). Specifically, a 1-unit increase in state ADI rank (worse deprivation) was associated with a 0.31 dB decrease (worsening) in presenting MD ($\beta = -0.31$, 95% CI = −0.41 to −0.22, $P < 0.001$). A 0.1-unit increase in Theil's H index (more segregation) was associated with 0.92 dB decrease in presenting MD ($\beta = -0.92$, 95% CI = −1.25 to −0.59, $P < 0.001$). Lastly, a 10% point increase in the proportion of individuals with Medicaid in a neighborhood was associated with 0.68 dB decrease in presenting MD ($\beta = -0.68$, 95% CI = −0.91 to −0.45, $P < 0.001$). Similar results were found in models that adjusted for patient-level characteristics and presenting visual acuity (Supplemental Table 3, available at www.ophthalmologyscience.org).

After adjusting for patient-level characteristics in the multilevel models of presenting MD, significant interaction effects were found between race and 2 neighborhood-level SRF measures including average number of cars per household ($P = 0.002$) and income per capita ($P = 0.002$).

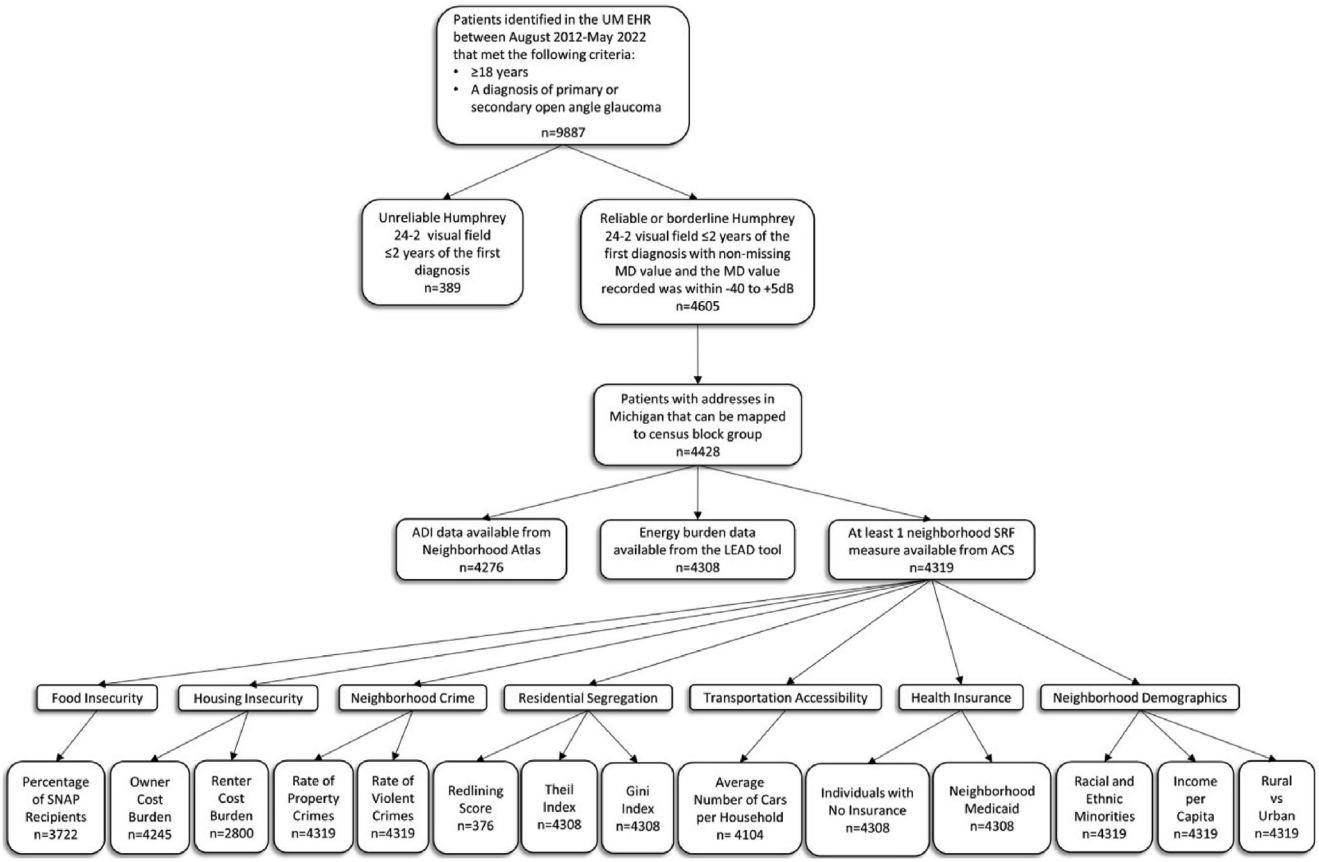

Figure 1. Flow chart of patient with glaucoma cohort including both selection criteria and neighborhood social risk factors. ACS = American Community Survey; ADI = area deprivation index; dB = decibels; EHR = electronic health record; LEAD = Low-Income Energy Affordability Data; MD = mean deviation; SNAP = Supplemental Nutrition Assistance Program; SRF = social risk factor; UM = University of Michigan.

Table 1. Comparison between Patient-Level Characteristics and Presenting MD in Patients with Glaucoma (n = 4428)

Continuous Variable	n	Mean (SD)	Median (IQR)	Kendall's Correlation with MD	*P* Value*
Age (yrs)	4426	70.3 (11.9)	71.1 (63.2-78.8)	−0.10	<0.001
logMAR BCVA	4380	0.2 (0.3)	0.1 (0.0-0.3)	−0.26	<0.001

Categorical variable	n	Frequency (%)	Median MD in dB (IQR)	*P* value*
Gender				
Female	4426	2326 (52.6)	−4.6 (−10.4, −2.0)	<0.001
Male		2100 (47.4)	−5.4 (−13.0, −2.2)	
Race				
White	4336	3286 (75.8)	−4.7 (−10.6, −1.9)	<0.001
Black/African American		703 (16.2)	−6.4 (−15.9, −2.9)	
Asian		226 (5.2)	−5.5 (−12.2, −2.4)	
Other		121 (2.8)	−4.6 (−11.2, −1.5)	
Ethnicity				
Hispanic	4156	91 (2.2)	−5.4 (−14.7, −1.4)	0.737
Non-Hispanic		4065 (97.8)	−4.9 (−11.5, −2.1)	
Insurance status				
Medicaid	4251	377 (8.9)	−6.5 (−14.9, −3.0)	<0.001
Non-Medicaid		3874 (91.1)	−4.9 (−11.1, −2.0)	

BCVA = best-corrected visual acuity; dB = decibels; IQR = interquartile range; logMAR = logarithm of the minimum angle of resolution; MD = mean deviation; SD = standard deviation.
Post hoc pairwise comparison showed significant differences in presenting MD between Black or African American vs. White (Holm-adjusted $P < 0.0001$) and Black or African American vs. other (Holm-adjusted $P = 0.0123$).
*Kendall correlation test for continuous variables and Wilcoxon or Kruskal–Wallis tests for categorical variables.

Table 2. Descriptive Statistics of Neighborhood-Level Variables and Univariate Associations with Presenting MD in Patients with Glaucoma (n = 4428)

Continuous Neighborhood-Level Variable	n	Mean (SD)	Kendall's Correlation with MD	*P* Value*
Food Insecurity				
SNAP recipients (%)	3722	12.6 (7.7)	−0.031	0.005
Housing insecurity				
Energy burden (%)	4308	2.8 (1.5)	−0.085	<0.001
Owner cost burden (%)	4245	17.6 (4.1)	−0.005	0.601
Renter cost burden (%)	2800	30.4 (10.6)	−0.041	0.001
Neighborhood crime				
Rate of property crimes (per 100 000 inhabitants)	4319	1752.6 (792.6)	−0.016	0.130
Rate of violent crimes (per 100 000 inhabitants)	4319	463.9 (333.0)	−0.009	0.359
Residential segregation				
State area deprivation index rank	4276	3.5 (2.7)	−0.090	<0.001
Historical redlining score	376	2.9 (0.8)	−0.089	0.013
Theil's H index	4308	0.2 (0.1)	−0.040	<0.001
Gini index	4308	0.4 (0.1)	−0.017	0.097
Transportation accessibility				
Average number of cars per household	4104	1.9 (0.4)	0.034	0.002
Health insurance				
No insurance (%)	4308	4.6 (3.6)	−0.037	<0.001
Neighborhood Medicaid (%)	4308	14.2 (11.8)	−0.080	<0.001
Neighborhood demographics				
Racial and ethnic minorities (%)	4319	22.3 (22.5)	−0.035	0.001
Income per capita (USD)	4319	36 382.6 (15 878.5)	0.079	<0.001

Categorical neighborhood-level variable	n	Frequency (%)	Median MD in dB (IQR)	*P* value*
Rural:urban	4319	875 (20.3): 3444 (79.4)	−5.4 (−12.0 to −2.2): −4.9 (−11.3 to −2.0)	0.0592

dB = decibels; IQR = interquartile range; MD = mean deviation; SD = standard deviation; SNAP = Supplemental Nutrition Assistance Program; USD = United States Dollar.
*Kendall correlation test for continuous variables and Wilcoxon test for categorical variables.

Specifically, a 1-car decrease in the average number of cars per household in a neighborhood was associated with 2.22 dB decrease (worsening) in presenting MD for patients who identified as Black or African American (95% CI = −3.75 to −0.68), whereas the same decrease in the average number of cars per household was associated with a 0.54 dB increase (improvement) in presenting MD for those who identified as White (95% CI = −0.26 to 1.34 dB) and a 2.11 dB increase in presenting MD for those who identified as Asian (95% CI = −0.42 to −4.63 dB). For example, when the average number of cars per household in a neighborhood was 1, the predicted presenting MD for Black or African Americans glaucoma patients was −12.62 dB, compared with −7.77 dB for White patients and −8.14 dB for Asian patients. However, when the average number of cars per household in a neighborhood was 2, the predicted presenting MD was −10.41 dB for Black or African Americans patients, −8.31 dB for White patients, and −10.25 dB for Asian patients. The interaction slope for Black or African American patients was significantly different from the slope for White patients (P = 0.014). A $10 000 US dollar decrease in income per capita in a neighborhood was associated with a 1.21 dB decrease (worsening) in presenting MD for patients who identified as Black or African American (95% CI = −1.65 to −0.77), whereas the same decrease in income per capita was associated with a 0.40 dB decrease in presenting MD for patients who identified as White (95% CI = −0.58 to −0.23) and a 0.25 dB decrease in presenting MD for those identified as Asian (95% CI = −0.85 to 0.34, Fig 2). The interaction slope for Black or African American patients was significantly different from the slope for White patients (P = 0.005).

After adjusting for patient-level characteristics in the multilevel models of presenting MD, significant interaction effects were found between patients' Medicaid status and 2 neighborhood-level SRFs measures including energy burden (P = 0.018) and urban or rural status (P = 0.010). Specifically, a 1% point increase in energy burden was associated with a 0.24 dB decrease (worsening) in presenting MD for patients who had Medicaid (95% CI = −0.57 to 0.10), whereas the same increase in energy burden was associated with a 0.69 dB decrease in presenting MD for those who were non-Medicaid insured (95% CI = −0.87 to −0.50, slope comparison P = 0.018, Fig 3). No significant interaction effects were observed between patient's Medicaid status and the energy burden when

Table 3. Effect of Each Neighborhood-Level Social Risk Factor Measure on Presenting Mean Deviation, after Adjusting for Patient-Level Characteristics (Sex, Age, Race, Ethnicity, Medicaid Status) and a Random Effect for Neighborhood

Neighborhood-Level Variable	Estimate	95% CI	*P* Value*
Food insecurity			
SNAP recipients (per 10%)	−0.29	−0.63, 0.06	0.916
Housing insecurity			
Energy burden (per 1%)			
With Medicaid	−0.24	−0.57, 0.10	0.018
Without Medicaid	−0.69	−0.87, −0.50	
Owner cost burden (per 10%)	−0.15	−0.38, 0.07	1.000
Renter cost burden (per 10%)	−0.02	−0.11, 0.07	1.000
Neighborhood crime			
Rate of property crimes (per 1 SD)	0.06	−0.18, 0.31	1.000
Rate of violent crimes (per 1 SD)	0.01	−0.23, 0.26	1.000
Residential segregation			
State area deprivation index rank (per 1 decile)	−0.31	−0.41, −0.22	<0.001
Redlining score (per 1 unit)	−0.61	−1.81, 0.58	1.000
Theil's H index (per 0.1 unit)	−0.92	−1.25, −0.59	<0.001
Gini index (per 0.1 unit)	0.003	−0.39, 0.39	1.000
Transportation accessibility			
Average number of cars per household (per 1 car)			
White	−0.54	−1.34, 0.26	0.002
Black	2.22	0.68, 3.75	
Asian	−2.11	−4.63, 0.42	
Health insurance			
No insurance (per 1%)	−0.08	−0.15, −0.01	0.264
Neighborhood Medicaid (per 10%)	−0.68	−0.91, −0.45	<0.001
Neighborhood demographics			
Racial and ethnic minorities (per 1 SD)	−0.002	−0.30, 0.29	1.000
Income per capita (per $10 000 USD)			
White	0.40	0.23, 0.58	0.002
Black	1.21	0.77, 1.65	
Asian	0.25	−0.34, 0.85	
Rural or urban x patient Medicaid Status			
Urban with Medicaid	−11.28	−12.41, −10.16	0.010
Urban without Medicaid	−8.60	−9.46, −7.74	
Rural with Medicaid	−9.03	−11.69, −6.36	
Rural without Medicaid	−9.92	−10.92, −8.93	

CI = confidence interval; SD = standard deviation; SNAP = Supplemental Nutrition Assistance Program; USD = United States Dollar.
Each social determinants of health (SDoH) measure was included in a separate model. Interactions between each SDoH measure with race and Medicaid status, respectively, were tested for an additive effect on presenting mean deviation.
The estimates for interactions between rural or urban areas and patient Medicaid status were predicted marginal means of presenting mean deviation, while the estimates for the rest of neighborhood-level variables were predicted slopes of presenting mean deviation.
*If the interaction with race or Medicaid status is presented, *P* value from Wald test for testing the overall interaction effect was reported; otherwise, *P* value for testing the main effect was reported.

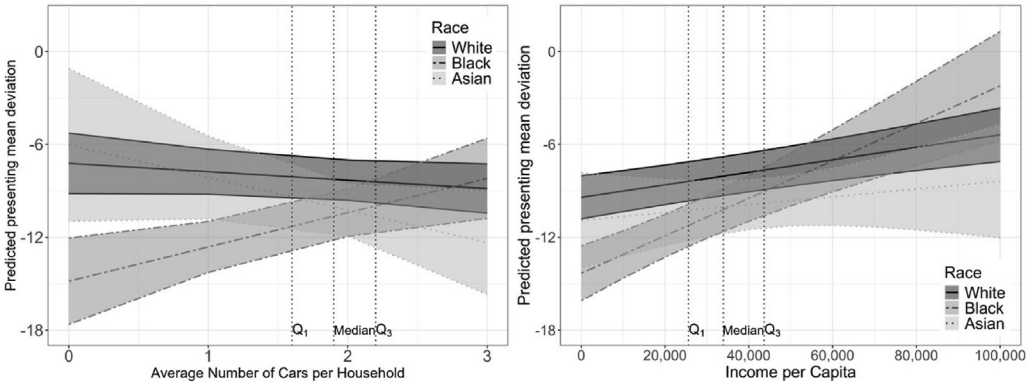

Figure 2. Panel plot of the interaction effects of patient race with average number of cars per household and income per capita.

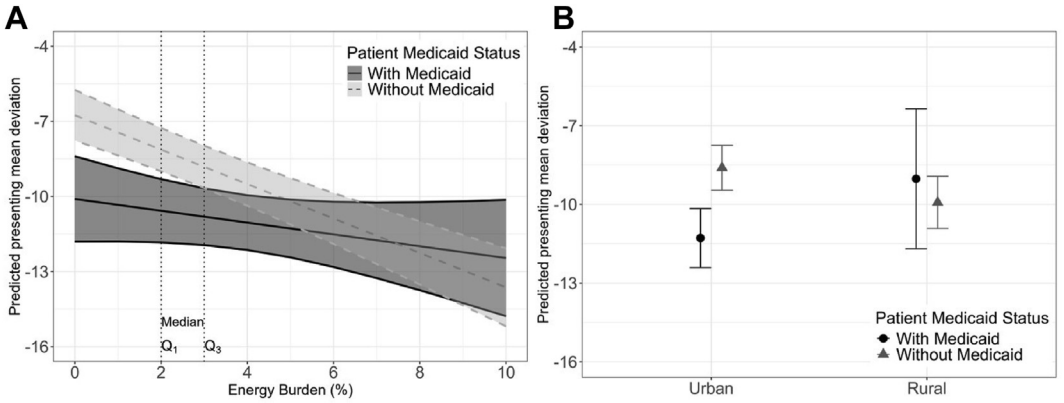

Figure 3. Panel plot of the interaction effects of Medicaid status with energy burden and urban vs. rural status.

adjusted for presenting visual acuity (Supplemental Table 3, available at www.ophthalmologyscience.org). When patients resided in an urban area, the predicted presenting MDs were −11.28 dB for patients who had Medicaid (95% CI = −12.41, −10.16) and −8.60 dB for those who did not have Medicaid (95% CI = −9.46, −7.74). However, when patients resided in a rural area, the predicted presenting MDs were −9.03 dB for patients who had Medicaid (95% CI = −11.69, −6.36) and −9.92 dB for those who did not have Medicaid (95% CI = −10.92, −8.93).

Discussion

In this cross-sectional study examining presenting glaucoma severity among patients from a tertiary eye care center, we found an association between presenting MD and neighborhood-level SRFs. Specifically, worse neighborhood measures of housing security, neighborhood inequity, insurance, income, and living in a rural area were associated with increased severity of glaucoma at presentation after adjusting for significant patient-level factors. This demonstrates that where a patient lives impacts the severity of their glaucoma at presentation beyond their individual level risk factors. Though the magnitude of the variability accounted for by neighborhood-level risk factors was much smaller than that accounted for by individual level variance (4.4% vs. 95.6%, respectively), the neighborhood-level risk factors may be mitigated through policy change focused on decreasing poverty and increasing access to resources, while the only individual level variable that can be changed is access to insurance, as race, gender, and age cannot be changed.

Additional studies have also demonstrated associations between where people live and eye care utilization and outcomes. Ocansey et al found that those living in a rural area in Ghana were less likely to perceive that they needed screening for glaucoma compared with people living in an urban area (odds ratio [OR] = 0.34, 95% CI: 0.21−0.57).[26] Xai et al reported an association between the neighborhood, physical environment, and social cohesion and the underutilization of eye care in a national sample of individuals with diabetes. Specifically, renters with self-reported diabetes were less likely to report eye care use than owners (OR: 0.72; 95% CI: 0.66−0.79); $P < 0.001$) after adjusting for age, sex, race/ethnicity, geographic region, Charlson Comorbidity Index, year of the survey, and vision impairment.[27] Yusuf et al found that living in the most disadvantaged neighborhoods (based on the National ADI) was associated with poor attendance at recommended ophthalmology appointments for diabetic retinopathy screening compared with living in the least disadvantaged neighborhoods (OR: 0.65; 95% CI: 0.44−0.97; P-value = 0.035).[28] Buys et al found that individuals from the wealthiest neighborhoods in Canada had a decreased risk for presenting with moderate or advanced glaucoma compared with individuals from the poorest neighborhoods (prevalence risk: 0.66, 95% CI: 0.43−1.02, P=0.06).[29] Similarly, in the United Kingdom, those presenting with worse glaucoma severity had more deprivation based on the Scottish Index of Multiple Deprivation Rank (P = 0.026).[30] In the US, Swaminathan et al reported that amongst patients with primary open-angle glaucoma, higher social vulnerability index scores were associated with worse initial disease severity (OR: 1.25, 95% CI: 1.22−1.28, P =< 0.001).[31] We previously reported that for every 1 percentage point increase of households with no car there was a higher odds for patients with microbial keratitis to present with a visual acuity <20/40 (OR, 1.25; 95% CI, 1.12−1.40; P = 0.001) and that for every 10 percent increase in neighborhood segregation (measured as the even distribution of ethnic and racial group across a region, as measured by the Theil's H index), there was a 44% higher odds for patients with microbial keratitis to present with visual impairment.[8] We have also previously reported on the association between housing insecurity and screening positive for uncorrected refractive error (OR = 3.74; 95% CI: 1.61−7.90; P = 0.006) and visual impairment (OR: 3.53; 95% CI: 1.59−7.31; P = 0.006) in the Michigan Screening and Intervention for Glaucoma

and Eye Health through Telemedicine program. Historically, highly segregated neighborhoods have sustained higher rates of disinvestment and are often lacking in resources that could impact eye health outcomes, such as easy access to trusted eye care providers who accept all forms of insurance, both public and private. In addition, these studies highlight that the severity of disease at presentation for both chronic conditions, such as glaucoma, and acute conditions, such as microbial keratitis, may be impacted by the neighborhood in which people live.

One significant factor for presenting with more severe glaucoma was living in a rural area, echoing the findings from a cross-sectional study by Onyia et al who found that patients who lived in an urban area had an adjusted decreased odds (OR: 0.55; 95% CI: 0.34−0.89; $P = 0.02$) of late glaucoma presentation compared with those living in a rural area.[32] Kilmer et al reported a decrease in eye examinations within the last year for participants living in a rural compared with an urban area, after adjusting for age (OR: 1.29; 95% CI: 1.11−1.50; $P < 0.001$).[33] Many factors may impact low utilization of eye care in rural areas; long distances to quality eye care providers may be one prominent factor. Another could be a decreased perceived risk of glaucoma among those living in rural areas, as Ocansey et al found (adjusted OR: 0.344; 95% CI = 0.21−0.57).[26] These studies highlight the need for initiatives to expand eye care services to rural geographic areas. Salient public health messaging at appropriate health literacy levels about the importance of eye disease screening and regular referrals from primary care providers for high-risk patients to eye care providers could assist in making patients' personal glaucoma risk assessment more realistic. One method to expand eye care to this population is through the addition of expanded eye care services at Federally Qualified Health Centers that serve rural populations. For areas with high rates of disinvestment in either rural or urban areas, improving access to eye care could help mitigate preventable vision loss.[34]

Multiple significant interaction effects between race, Medicaid status, and neighborhood-level SRFs were identified. For example, when the per capita income in a block group was lower, Black patients presented with worse MD compared with White or Asian patients and this racial difference went away when the per capita income in the block group was higher. When the percent of individuals in a block group that identified as persons of color increased, Black patients presented with worse MD compared with Asian or White patients. When the average number of cars per household in a census tract went from 2 to 1, Black patients presented with worse MD, but glaucoma severity at presentation did not change for White or Asian patients. In terms of race, Black patients living in block groups with more deprivation had more severe glaucoma at presentation than White or Asian patients living in those same block groups and the effect of race went away in less deprived block groups.

In terms of insurance status, those without Medicaid, compared with those with Medicaid, presented with more severe glaucoma when they lived in a census tract with a higher neighborhood energy burden or more people insured by Medicaid. This could be because those living in a census track with more poverty but who do not meet criteria for Medicaid could be living with lower income that is just above the cut off to be insured by Medicaid. Surprisingly, in census tracks with more segregation—denoted by a worse redlining score—patients with Medicaid had better presenting MD compared with patients not insured by Medicaid. This could be for similar reasons that those without Medicaid who lived in neighborhoods with more poverty had worse glaucoma at presentation than those with Medicaid, as more people could be living right above the Medicaid cut-off and still lack the resources to fully take care of their health. Taken together, these findings demonstrate that where people live impacts the severity of their presenting glaucoma.

This study found that differences in neighborhood-level resources accounted for 4.3% of the variability in presenting MD. The magnitude of this finding is similar to the variance in prevalent glaucoma due to genetics. In the Genetic Epidemiology Research in Adult Health and Aging cohort, researchers found that the variance in risk for primary open-angle glaucoma explained by genetics was 3.1% among African Americans, 3.0% in non-Hispanic Whites, 0.5% among East Asians, and 3.3% among Latinos.[35] Research into the impact of social and neighborhood-level risk factors on disease prevalence and severity is as important as research into the genetic underpinnings of disease prevalence and severity; both may lead to interventions to improve outcomes for glaucoma. In comparing our findings to other work, a study from Sweden found that the proportion of variance in glaucoma prevalence explained by a person's neighborhood (neighborhood deprivation) was 3%, which is slightly less than what we found in the US.[36] Sweden has significantly less poverty than the US, in part due to a more robust financial assistance program for people with limited means, with 6% of people living below the poverty limit compared with 10.5% of people in the US in 2019.[37,38]

This study has several strengths including a large sample size and the use of multilevel modeling to understand the impact of neighborhood on presenting glaucoma severity above and beyond individual patient-level factors. There are several limitations to this study. First, the study was conducted at one tertiary eye care center so the generalizability to other eye care centers may be limited. Second, several variables from PolicyMap come from the American Community Survey data. Self-report can lead to social desirability bias and reporting bias. Third, due to the limited sample size of individuals who identified their race as American Indian/Alaskan Native and ≥2 races, we were unable to analyze their data in separate race categories. Fourth, though we were able to obtain place-based measurements for most patients, some did not have an address

that could be mapped to neighborhood-level SRFs. Fifth, the US Census, and associated surveys, suppress or withhold some data in order to ensure confidentiality in certain neighborhood-level measures where responses are low. Sixth, we utilized physician impression of VF reliability, a structured data element in the EHR, rather than VF reliability indices as these are not input as structured data elements in the EHR. Thus, there is the possibility that fields that would have met objective reliability criteria were excluded and those who that would not have met objective reliability criteria were included. Seventh, we did find demographic differences between those that were included and had a reliable VF versus those that did not have a reliable VF and were excluded (more individuals who were younger and identified as Black); we adjusted for these demographic factors in our models. Eighth, we analyzed only the first VF, thus biasing our MD at initial presentation to more negative values due to the learner's effect, though we do not think this effect should differ by socioeconomic status or race. Finally, there were limited numbers of participants in this sample living in neighborhoods that were previously redlined so the results may have differed if there had been more participants from previously redlined neighborhoods. In addition, we did not assess distance to the provider or patients' experience with racism and discrimination, as we did not have access to those patient-level variables, and both could impact glaucoma severity at presentation.

In conclusion, those who lived in a neighborhood with higher levels of poverty presented with more severe glaucoma after accounting for individual level variance. Addressing poverty and income inequality through policy change, such as having a living minimum wage, expanding access to Medicaid, and increasing funding for safe affordable housing may all help address barriers to eye care utilization in the US so that eye disease can be identified and treated earlier. Living in a rural area was another risk factor for presenting with more severe glaucoma and speaks to the need for improved access to specialty care in more sparsely populated areas in the US. Future research is needed to explore the potential interplay between nature—a person's genetic makeup and susceptibilities—and nurture—a person's neighborhood and environmental exposures—in the epidemiology and pathogenesis of glaucoma.

Footnotes and Disclosures

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[1] Department of Ophthalmology and Visual Sciences, School of Medicine, University of Michigan, Ann Arbor, Michigan.

[2] Institute for Healthcare Policy and Innovation, University of Michigan, Ann Arbor, Michigan.

[3] Department of Ophthalmology, Henry Ford Health System, Detroit, Michigan.

[4] Department of Internal Medicine, School of Medicine, University of Michigan, Ann Arbor, Michigan.

[5] Department of Health Behavior and Health Education, School of Public Health, University of Michigan, Ann Arbor, Michigan.

[6] Department of Epidemiology, School of Public Health, University of Michigan, Ann Arbor, Michigan.

[7] School of Social Work, University of Michigan, Ann Arbor, Michigan.

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Author Contributions:

Conception and design: Hicks, Lu, Niziol, Newman-Casey

Data collection: Hicks, Lu, Newman-Casey

Analysis and interpretation: Hicks, Lu, Newman-Casey

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Abbreviations and Acronyms:
ADI = area deprivation index; **CI** = confidence interval; **dB** = decibels; **EHR** = electronic health record; **IQR** = interquartile range; **MD** = mean deviation; **OR** = odds ratio; **SRF** = social risk factor; **US** = United States; **VF** = visual field.

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Correspondence:
Paula Anne Newman-Casey, MD, MS, Kellogg Eye Center, Department of Ophthalmology and Visual Sciences, University of Michigan, 1000 Wall Street, Ann Arbor, MI, 48105. E-mail: panewman@med.umich.edu.

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