

Neighborhood Segregation and Access to Live Donor Kidney Transplantation

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[+ Supplemental content](#)

IMPORTANCE Identifying the mechanisms of structural racism, such as racial and ethnic segregation, is a crucial first step in addressing the persistent disparities in access to live donor kidney transplantation (LDKT).

OBJECTIVE To assess whether segregation at the candidate's residential neighborhood and transplant center neighborhood is associated with access to LDKT.

DESIGN, SETTING, AND PARTICIPANTS In this cohort study spanning January 1995 to December 2021, participants included non-Hispanic Black or White adult candidates for first-time LDKT reported in the US national transplant registry. The median (IQR) follow-up time for each participant was 1.9 (0.6-3.0) years.

MAIN OUTCOME AND MEASURES Segregation, measured using the Theil H method to calculate segregation tertiles in zip code tabulation areas based on the American Community Survey 5-year estimates, reflects the heterogeneity in neighborhood racial and ethnic composition. To quantify the likelihood of LDKT by neighborhood segregation, cause-specific hazard models were adjusted for individual-level and neighborhood-level factors and included an interaction between segregation tertiles and race.

RESULTS Among 162 587 candidates for kidney transplant, the mean (SD) age was 51.6 (13.2) years, 65 141 (40.1%) were female, 80 023 (49.2%) were Black, and 82 564 (50.8%) were White. Among Black candidates, living in a high-segregation neighborhood was associated with 10% (adjusted hazard ratio [AHR], 0.90 [95% CI, 0.84-0.97]) lower access to LDKT relative to residence in low-segregation neighborhoods; no such association was observed among White candidates (*P* for interaction = .01). Both Black candidates (AHR, 0.94 [95% CI, 0.89-1.00]) and White candidates (AHR, 0.92 [95% CI, 0.88-0.97]) listed at transplant centers in high-segregation neighborhoods had lower access to LDKT relative to their counterparts listed at centers in low-segregation neighborhoods (*P* for interaction = .64). Within high-segregation transplant center neighborhoods, candidates listed at predominantly minority neighborhoods had 17% lower access to LDKT relative to candidates listed at predominantly White neighborhoods (AHR, 0.83 [95% CI, 0.75-0.92]). Black candidates residing in or listed at transplant centers in predominantly minority neighborhoods had significantly lower likelihood of LDKT relative to White candidates residing in or listed at transplant centers located in predominantly White neighborhoods (65% and 64%, respectively).

CONCLUSIONS Segregated residential and transplant center neighborhoods likely serve as a mechanism of structural racism, contributing to persistent racial disparities in access to LDKT. To promote equitable access, studies should assess targeted interventions (eg, community outreach clinics) to improve support for potential candidates and donors and ultimately mitigate the effects of segregation.

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Live donor kidney transplantation (LDKT) remains the preferred method of kidney replacement therapy, offering improved survival and quality of life compared with dialysis and deceased donor kidney transplantation (DDKT).¹⁻³ There are distinct advantages of LDKT, including shorter waitlist time for recipients, and improved patient/graft survival compared with DDKT. Black individuals have a 3.8-fold higher rate of end-stage kidney disease (ESKD), yet their rate of LDKT is 4.3-fold lower than their White counterparts.³⁻⁵ Despite 2 decades of extensive efforts,⁵⁻¹⁰ substantial racial disparities in accessing LDKT persist. Although the detrimental effects of structural racism on health and the role of social determinants of health on access to LDKT are well documented,¹¹⁻¹⁸ the specific mechanisms that contribute to these disparities remain underexplored.

One such understudied mechanism is racial and ethnic segregation (referred to as segregation hereafter), the spatial separation of individuals or groups based on race or ethnicity. Historically, segregation has been used as a tool to enforce racial hierarchies and exclusion within societies.^{14,19,20} As a form of institutionalized structural racism,¹⁵ segregation likely limits access to LDKT through 2 distinct pathways: candidates' residential neighborhood segregation and their transplant center neighborhood segregation. Segregation on both levels likely is associated with disparities in access to LDKT because potential donors often come from the same residential neighborhoods or social networks as candidates,^{5,21,22} and both donors and candidates must be evaluated by the transplant center. In this national cohort study, we examined the association of the candidate's residential neighborhood segregation and their transplant center's neighborhood segregation with access to LDKT.

Methods

The study population included adult candidates for first-time kidney transplant (KT), including nonlisted patients who underwent LDKT (January 1, 1995, to December 31, 2021). The race and ethnicity of the individuals were designated as one of the following fixed categories: non-Hispanic/Latino Black or non-Hispanic White (hereafter referred to as Black and White, respectively) based on the variables provided in the Organ Procurement and Transplantation Network (OPTN) forms. If a recipient had multiple kidney-only transplants, only the first one was considered. Candidates with missing clinical and/or demographic data, patients who were listed and underwent KT on the same day, or those who were listed and died on the same day were excluded (eFigure 1 in Supplement 1).

This study used data from the Scientific Registry of Transplant Recipients (SRTR). The SRTR data system includes data on all donors, wait-listed candidates, and patients who underwent transplants in the US, submitted by the members of the OPTN. The Health Resources and Services Administration within the US Department of Health and Human Services provides oversight of the activities of the OPTN and SRTR contractors.²³ SRTR data were linked to the American Community Survey (ACS) 5-year estimates from the US Census

Key Points

Question Is racial and ethnic segregation in the residential and transplant center neighborhood associated with access to live donor kidney transplantation (LDKT) for candidates?

Findings In this national cohort study of 162 587 candidates, Black candidates who resided in or were listed at a transplant center located in a high-segregation neighborhood had 10% and 6% lower access to LDKT, respectively, compared with Black candidates in low-segregation neighborhoods.

Meaning Segregation at the residential and transplant center neighborhoods may be a key mechanism driving racial inequalities; to address racial disparities in LDKT access, it is crucial to identify interventions that can be targeted at the community and health care levels.

Bureau by the candidate's residential and transplant center's 5-digit zip code.²⁴

The institutional review board at the New York University Grossman School of Medicine reviewed this study and granted it an exemption under i22-00146, waiving the need for informed consent. The analyses presented were based on a complete case analysis and followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline.

Racial and Ethnic Segregation

We obtained race-specific population counts at the Zip Code Tabulation Area (ZCTA) level from the ACS 5-year estimates. We used ZCTA/zip codes as proxies for neighborhoods. To determine segregation scores, we used the Multigroup Entropy Index, also known as the Theil H method,²⁵ a robust method allowing for simultaneous measurement of segregation among multiple groups. The calculation involved measuring the level of diversity within a ZCTA and assessing the distribution of racial and ethnic groups across neighborhoods of the respective city (see the eMethods in Supplement 1 for the calculation),^{25,26} including the following categories: non-Hispanic Asian, non-Hispanic Black, Hispanic/Latino, non-Hispanic White, and non-Hispanic other (American Indian was combined with Alaska Native, a listed nationality [eg, Brazilian], and multiracial). The analytic population consisted of only Black and White candidates.

We used candidates' residential neighborhood (based on residential 5-digit zip code) and center neighborhood (based on the transplant center's 5-digit zip code) segregation scores and organized the scores into tertiles, consistent with previous research²⁷⁻³²; residential neighborhood segregation: low (≤ 4.2), medium (> 4.2 and ≤ 12.4), and high (> 12.4); center neighborhood segregation: low (≤ 11.6), medium (> 11.6 and ≤ 18.5), and high (> 18.5).

Candidate and Center Characteristics

Candidate characteristics included age, sex, race, body mass index (calculated as weight in kilograms divided by height in meters squared), era of waitlisting (1995-1999, 2000-2004,

2005-2009, 2010-2014, and 2015-2021), primary health insurance, blood group, cause of ESKD, and education level. Center characteristics included mean annual KT volume, percentage of Black recipients of KT, mean annual LDKT volume, and percentage of centers with a median time to DDKT of more than 3 years. We identified 214 US transplant centers that were dedicated to performing organ transplants, according to OPTN, and these health care facilities were included in the analytical cohort.^{33,34}

Access to LDKT

Candidates undergoing LDKT without being on the waitlist were given 1 day on the waitlist prior to LDKT, while those who were on the waitlist were followed up from their first listing date until the date at which any of the following occurred: end of follow-up (December 31, 2021), 3 years from their first listing date (based on a previous study suggesting most LDKT occur <6 months after listing),^{5,35} waitlist removal, LDKT, DDKT, preemptive KT, or death.

Statistical Analysis

Using the Kaplan-Meier method, we estimated the unadjusted cumulative incidence of the first LDKT, by candidate race and tertiles of the candidate's residential neighborhood and the transplant center's neighborhood segregation.

We then used the cause-specific hazards models to determine the likelihood of LDKT by tertiles of residential neighborhood and transplant center neighborhood segregation. Models were adjusted for candidate and neighborhood factors based on the conceptual model used for this study (eFigure 2 in Supplement 1). We quantified the association of the residential neighborhoods' and transplant centers' neighborhood segregation by race and tested for temporal trends. We confirmed the proportional hazards assumption using complementary log-log plots and Schoenfeld residuals.

We then examined within-group differences in high-segregation neighborhoods, comparing predominantly White neighborhoods (defined as neighborhoods for whom ≥70% of residents are White) to multiracial neighborhoods (31%-69% White residents) and predominantly minority neighborhoods (≤30% White residents), testing whether these associations varied by candidate race.

Sensitivity Analysis

To validate the findings, we used the Index of Concentration at Extremes-Race-Income measure,^{36,37} which identifies racialized economic segregation in a geographical area, as a proxy for segregation.³⁶⁻³⁸

We evaluated the robustness of the estimates through the following sensitivity analyses: (1) Fine and Gray subdistribution hazards models with DDKT, preemptive KT, and death as competing risks; (2) alternative modeling approach for handling missing data (creating separate categories for missing values)⁵; (3) multiple imputation using chained equations (MICE) to impute the values of missing covariate data; (4) multilevel Cox regression models with shared frailty at transplant centers to account for intercenter differences³⁹; (5) different cutoff value (≥60%) to define predominantly White

neighborhoods in high-segregation neighborhoods; (6) associations by age at listing; and (7) correlation coefficients and variance inflation factor to assess correlations between segregation and neighborhood-level variables.

All analyses were conducted using SAS statistical software, version 9.4 (SAS Institute), and Stata 17 MP (StataCorp LLC) installed on a Linux machine. Statistical significance was defined as $P < .05$ with 2-sided tests.

Results

Study Population

Among 162 587 candidates for KT, the mean (SD) age was 51.6 (13.2) years, 65 141 (40.1%) were female, and 80 023 (49.2%) were Black. A total of 74 102 participants (45.6%) had private insurance, and 67 606 (41.6%) had only a high school education.

Candidate Demographics by Residential Neighborhood Segregation

High-segregation residential neighborhoods were characterized by a higher proportion of Black candidates relative to low-segregation residential neighborhoods (high-segregation residential neighborhoods had 69.2% Black candidates; medium-segregation neighborhoods, 47.2%; and low-segregation neighborhoods, 30.2%; $P < .001$) (Table 1; eTables 1-2 in Supplement 1 provide racial stratification).

Access to LDKT by Residential Neighborhood Segregation

Black candidates had a lower cumulative incidence of LDKT than White candidates (Figure 1A). The 3-year cumulative incidence of LDKT by residential neighborhood segregation differed for Black but not White candidates (Black candidates in high-segregation neighborhoods, 7.1% [95% CI, 6.8%-7.4%] vs low-segregation neighborhoods, 9.0% [95% CI, 8.5%-9.5%]; $P < .001$); White candidates in high-segregation neighborhoods, 19.7% [95% CI, 19.0%-20.4%] vs low-segregation neighborhoods, 20.1% [95% CI, 19.6%-20.6%]; $P = .92$) (eTable 3 in Supplement 1).

During the median (IQR) follow-up time of 1.9 (0.6-3.0) years, the association between residential neighborhood segregation and access to LDKT differed by candidate race (adjusted hazard ratio [AHR] = 0.83 [95% CI, 0.79-0.86]; P for interaction = .01) (Figure 2; eTable 4 in Supplement 1). Among Black candidates, residing in higher-segregation neighborhoods was associated with a 10% lower access to LDKT (AHR, 0.90 [95% CI, 0.84-0.97]), relative to their counterparts in low-segregation neighborhoods. However, among White candidates, there was no difference in access to LDKT for those residing in high-segregation vs those in low-segregation neighborhoods (AHR, 1.04 [95% CI, 0.99-1.09]). Additionally, Black candidates residing in high-segregation neighborhoods had 59% (AHR, 0.41 [95% CI, 0.39-0.43]; $P < .001$) lower access to LDKT compared with White candidates residing in low-segregation neighborhoods (eTable 4 in Supplement 1).

Within high-segregation neighborhoods, access to LDKT was lower among candidates residing in predominantly mi-

Table 1. Characteristics of Adult Candidates for Kidney Transplantation Stratified by Segregation Levels for Neighborhood of Residence, 1995 to 2021

No. (%)				
Characteristic	Overall (N = 162 587)	Low segregation (n = 55 451) ^a	Medium segregation (n = 49 515)	High segregation (n = 57 621)
Age, mean (SD), y	51.6 (13.2)	52.1 (13.3)	51.6 (13.3)	51.1 (13.1)
Age group, y				
18-39	31 796 (19.6)	10 347 (18.7)	9840 (19.9)	11 609 (20.1)
40-64	102 306 (62.9)	34 535 (62.3)	30 855 (62.3)	36 916 (64.1)
≥65	28 485 (17.5)	10 569 (19.1)	8820 (17.8)	9096 (15.8)
Sex				
Female	65 141 (40.1)	21 424 (38.6)	19 727 (39.8)	23 990 (41.6)
Male	97 446 (59.9)	34 027 (61.4)	29 788 (60.2)	33 631 (58.4)
Race				
Non-Hispanic Black	80 023 (49.2)	16 752 (30.2)	23 381 (47.2)	39 890 (69.2)
Non-Hispanic White	82 564 (50.8)	38 699 (69.8)	26 134 (52.8)	17 731 (30.8)
BMI, mean (SD)	28.6 (5.8)	28.5 (5.7)	28.5 (5.8)	28.7 (5.9)
BMI category				
≤25	50 797 (31.2)	17 170 (31.0)	15 623 (31.6)	18 004 (31.2)
26-30	52 263 (32.1)	18 139 (32.7)	15 906 (32.1)	18 218 (31.6)
>30	59 527 (36.6)	20 142 (36.3)	17 986 (36.3)	21 399 (37.1)
Blood type				
A	54 094 (33.3)	20 202 (36.4)	16 621 (33.6)	17 271 (30.0)
B	25 474 (15.7)	7583 (13.7)	7542 (15.2)	10 349 (18.0)
AB	6822 (4.2)	2269 (4.1)	2035 (4.1)	2518 (4.4)
O	76 197 (46.9)	25 397 (45.8)	23 317 (47.1)	27 483 (47.7)
Cause of ESKD				
Diabetes	49 784 (30.6)	16 554 (29.9)	15 289 (30.9)	17 941 (31.1)
Hypertension	39 308 (24.2)	10 762 (19.4)	10 907 (22.0)	17 639 (30.6)
Polycystic kidney disease	12 411 (7.6)	5479 (9.9)	3774 (7.6)	3158 (5.5)
Glomerulonephritis	29 189 (18.0)	10 913 (19.7)	9389 (19.0)	8887 (15.4)
Other	31 895 (19.6)	11 743 (21.2)	10 156 (20.5)	9996 (17.3)
Education level				
Less than high school	4541 (2.8)	1265 (2.3)	1407 (2.8)	1869 (3.2)
High school	67 606 (41.6)	20 728 (37.4)	20 088 (40.6)	26 790 (46.5)
Attended college or technical school	45 040 (27.7)	16 025 (28.9)	14 051 (28.4)	14 964 (26.0)
Associate or bachelor's degree	31 504 (19.4)	12 159 (21.9)	9648 (19.5)	9697 (16.8)
Postcollege graduate degree	13 896 (8.5)	5274 (9.5)	4321 (8.7)	4301 (7.5)
Primary health insurance				
Medicare	55 780 (34.3)	17 951 (32.4)	17 022 (34.4)	20 807 (36.1)
Medicaid	12 344 (7.6)	2879 (5.2)	3366 (6.8)	6099 (10.6)
Private	74 102 (45.6)	28 341 (51.1)	22 683 (45.8)	23 078 (40.1)
Other	20 361 (12.5)	6280 (11.3)	6444 (13.0)	7637 (13.3)
Era of listing				
1995-1999	18 088 (11.1)	5779 (10.4)	5695 (11.5)	6614 (11.5)
2000-2004	22 996 (14.1)	7344 (13.2)	7023 (14.2)	8629 (15.0)
2005-2009	32 610 (20.1)	10 851 (19.6)	10 088 (20.4)	11 671 (20.3)
2010-2014	37 893 (23.3)	12 858 (23.2)	11 440 (23.1)	13 595 (23.6)
2015-2021	51 000 (31.4)	18 619 (33.6)	15 269 (30.8)	17 112 (29.7)
Residential neighborhood characteristics^b				
Racial diversity level ^a				
Low racial diversity	54 210 (33.3)	20 871 (37.6)	10 684 (21.6)	22 655 (39.3)
Medium racial diversity	54 213 (33.3)	18 801 (33.9)	16 885 (34.1)	18 527 (32.2)
High racial diversity	54 164 (33.3)	15 779 (28.5)	21 946 (44.3)	16 439 (28.5)

(continued)

Table 1. Characteristics of Adult Candidates for Kidney Transplantation Stratified by Segregation Levels for Neighborhood of Residence, 1995 to 2021 (continued)

No. (%)	Overall (N = 162 587)	Low segregation (n = 55 451) ^a	Medium segregation (n = 49 515)	High segregation (n = 57 621)
Residents with high school degree or higher, %				
≤84.3	42 268 (26.0)	7017 (12.7)	15 790 (31.9)	19 461 (33.8)
84.4-91.5	58 759 (36.1)	19 300 (34.8)	16 584 (33.5)	22 875 (39.7)
>91.5	61 560 (37.9)	29 134 (52.5)	17 141 (34.6)	15 285 (26.5)
Residents with bachelor's degree or higher, %				
≤22.1	50 472 (31.0)	11 370 (20.5)	15 879 (32.1)	23 223 (40.3)
22.2-36.7	55 743 (34.3)	21 665 (39.1)	17 429 (35.2)	16 649 (28.9)
>36.7	56 372 (34.7)	22 416 (40.4)	16 207 (32.7)	17 749 (30.8)
Median household income, \$				
≤53 142	59 257 (36.4)	10 062 (18.1)	17 650 (35.6)	31 545 (54.7)
53 143-74 341	54 100 (33.3)	21 436 (38.7)	17 735 (35.8)	14 929 (25.9)
>74 341	49 230 (30.3)	23 953 (43.2)	14 130 (28.5)	11 147 (19.3)
Urban or rural				
Urban	158 120 (97.3)	52 117 (94.0)	48 492 (97.9)	57 511 (99.8)
Large rural area	4239 (2.6)	3198 (5.8)	931 (1.9)	110 (0.2)
Small rural area	219 (0.1)	131 (0.2)	88 (0.2)	0

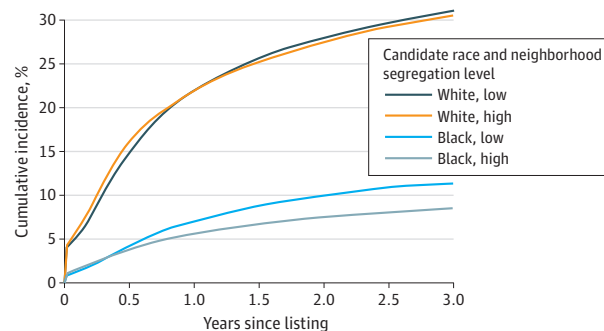
Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); ESKD, end-stage kidney disease.

^a Segregation and racial diversity levels are calculated based on the Multigroup Entropy Index,²⁵ using candidates' 5-digit zip code as a proxy for neighborhoods. See the eMethods in Supplement 1 for the calculation.

^b Neighborhood characteristics were extracted from the American Community Survey 5-year estimates (2017-2021).

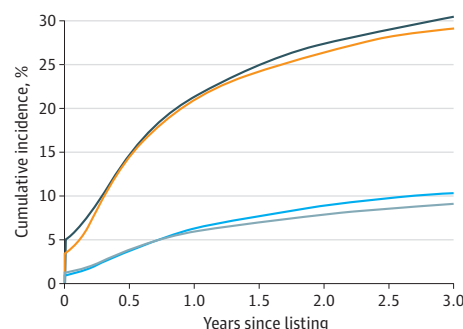
Figure 1. Cumulative Incidence of Live Donor Kidney Transplantation

A Residential neighborhood



No. at risk	1.0	2.0	3.0
White candidate, low segregation	16 402	12 015	6 283
White candidate, high segregation	38 106	21 954	14 579
Black candidate, low segregation	16 216	9 385	9 175
Black candidate, high segregation	37 748	28 188	21 931

B Transplant center neighborhood



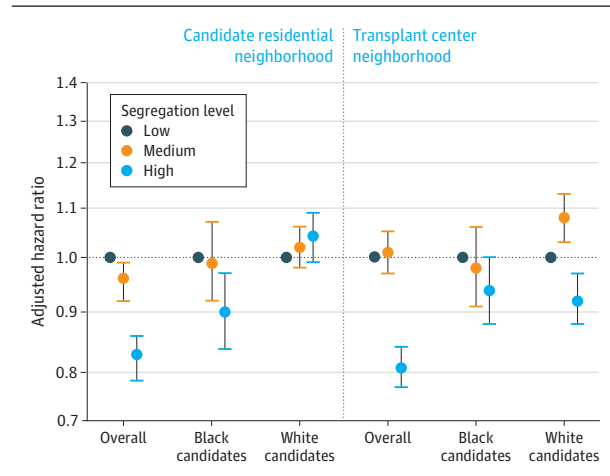
No. at risk	1.0	2.0	3.0
White candidate, low segregation	18 786	10 785	7 345
White candidate, high segregation	34 779	20 489	13 680
Black candidate, low segregation	20 652	15 493	11 829
Black candidate, high segregation	32 620	24 687	19 591

The cumulative incidence of live donor kidney transplantation is stratified by candidate race, segregation level of the neighborhood where the candidate resides (A), and segregation level of the neighborhood where the transplant center is located (B). Individuals' race was designated as one of the following: non-Hispanic Black or non-Hispanic White (referred to as Black and White in the legend). Race variables were based on the categorization provided in the Organ Procurement and Transplantation Network (OPTN) forms.

nority neighborhoods than those in predominantly White neighborhoods (AHR, 0.54 [95% CI, 0.49-0.60]; *P* for interaction < .001) (Table 2).

These findings showed reduced access to LDKT over time for candidates in high-segregation neighborhoods compared with those in low-segregation neighborhoods between 1995 and 2014 (1995-1999: AHR, 0.78 [95% CI, 0.70-0.86]; 2010-2014: AHR, 0.79 [95% CI, 0.73-0.86]); *P* < .001; after 2015, however, the difference in access to LDKT between high- and low-segregation residential neighborhoods was not statistically significant (eTable 5 in Supplement 1).

Figure 2. Disparities in Live Donor Kidney Transplantation by Segregation Level of Candidate's Residential and Transplant Center Neighborhoods



Racial disparities in live donor kidney transplantation are illustrated according to the levels of segregation for the residential neighborhood of the candidate and the transplant center neighborhood. Race variables were based on the categorization provided in the Organ Procurement and Transplantation Network (OPTN) forms.

Demographics by Transplant Center Neighborhood Segregation

All 214 transplant centers in this study were located in neighborhoods classified as urban by the Rural-Urban Commuting Area codes (Table 3; eTables 6-7 in Supplement 1). Candidates listed at transplant centers located in high-segregation neighborhoods had a higher proportion of Black candidates (high-segregation transplant center neighborhoods had 62.7% Black candidates; medium-segregation neighborhoods, 45.8%; low-segregation neighborhoods, 37.5%; *P* < .001). Furthermore, transplant centers located in high-segregation neighborhoods were more likely to be in a neighborhood with lower educational attainment and household income, as well as having a longer median time to DDKT.

Access to LDKT by Transplant Center Neighborhood Segregation

Regardless of transplant center neighborhood segregation, Black candidates had lower access to LDKT compared with their White counterparts (Figure 1B). Both Black (high-segregation neighborhoods, 7.4% [95% CI, 7.1%-7.7%]; low-segregation neighborhoods, 8.5% [95% CI, 8.1%-9.0%, *P* = .001) and White candidates (high-segregation neighborhoods, 18.6% [95% CI, 18.0%-19.3%]; low-segregation neighborhoods, 20.3% [95% CI, 19.8%-20.9%], *P* = .004) had a lower 3-year cumulative incidence of LDKT when listed at a transplant center in a high-segregation neighborhood (eTable 3 in Supplement 1).

After adjustment, candidates listed at transplant centers located in high-segregation neighborhoods had significantly lower access to LDKT compared with those in low-segregation transplant center neighborhoods (AHR, 0.81 [95% CI, 0.78-0.84]). The magnitude of this association was similar regardless of candidate race (*P* for interaction = .64). Both Black and White candidates listed at transplant centers in high-segregation neighborhoods had lower access to LDKT relative to their counterparts in low-segregation neighborhoods (Figure 2). Furthermore,

Table 2. Access to Live Donor Kidney Transplantation in High-Segregation Residential and Transplant Center Neighborhoods by Race

	High-segregation neighborhoods, AHR (95% CI) ^a					
	Candidate residential neighborhood ^b			Transplant center neighborhood ^c		
	≥70% White residents	31%-69% White residents	≤30% White residents	≥70% White residents	31%-69% White residents	≤30% White residents
Overall ^d	1.00 [Reference]	0.77 (0.71-0.84) ^e	0.54 (0.49-0.60) ^e	1.00 [Reference]	0.95 (0.85-1.01)	0.83 (0.75-0.92) ^e
Race ^f						
Black	0.38 (0.31-0.48)	0.36 (0.32-0.41) ^e	0.35 (0.31-0.39) ^e	0.37 (0.31-0.45) ^e	0.38 (0.32-0.44) ^e	0.36 (0.32-0.42) ^e
White	1.00 [Reference]	0.91 (0.83-1.00)	0.89 (0.79-1.00)	1.00 [Reference]	0.91 (0.79-1.06)	0.71 (0.61-0.82) ^e

Abbreviation: AHR, adjusted hazard ratio.

^a Segregation levels are calculated based on Multigroup Entropy Index.²⁵ See the eMethods in Supplement 1 for the calculation. High-segregation neighborhoods identified by tertiles of residential and transplant center neighborhood segregation scores.

^b Proportion of candidate residential high-segregation neighborhoods for predominantly White neighborhoods (≥70% White residents), multiracial neighborhoods (31%-69% White residents), and predominantly minority neighborhoods (<30% White residents): 19.8%, 15.7%, and 64.4%, respectively.

^c Proportion of transplant center high-segregation neighborhoods for predominantly White (≥70% White residents), multiracial composition

(31%-69% White residents), and predominantly minority neighborhoods (<30% White residents): 33.8%, 19.5%, and 46.7%.

^d For overall models: cause-specific hazard model. Adjusted for year of waitlisting, age, sex, body mass index, blood type, cause of end-stage kidney disease, education level, primary health insurance, and neighborhood-level factors (education, income).

^e Indicates statistical significance.

^f For race models: cause-specific hazard model. Adjusted for year of waitlisting, age, sex, body mass index, blood type, cause of end-stage kidney disease, education level, primary health insurance, and neighborhood characteristics (education and income).

Table 3. Characteristics of Transplant Centers Stratified by Segregation Levels for Neighborhood, 1995 to 2021

Kidney transplant center characteristic ^a	Overall (N = 214) ^b	Low segregation (n = 91) ^c	Medium segregation (n = 70)	High segregation (n = 53)	P value
Annual kidney transplants, mean (SD) ^a	16.6 (17.2)	13.5 (15.1)	16.7 (16.4)	21.5 (20.4)	.03
Black patients who underwent kidney transplants >50%, No. (%) ^a	71 (33.2)	17 (18.7)	23 (32.9)	31 (58.5)	<.001
Annual live donor kidney transplants, mean (SD) ^a	6.0 (6.2)	5.3 (5.6)	5.9 (6.1)	7.2 (7.1)	.20
Median time to deceased donor kidney transplant >3 y, No. (%) ^a	31 (14.5)	10 (11.0)	7 (10.0)	14 (26.4)	.02
No. (%)					
Transplant center neighborhood characteristics^d					
Residents with high school degree or higher, %					
≤88.2	75 (35.0)	29 (31.9)	20 (28.6)	26 (49.1)	.06
88.3-96.1	88 (41.1)	41 (45.1)	34 (48.6)	13 (24.5)	
>96.1	51 (23.8)	21 (23.1)	16 (22.9)	14 (26.4)	
Residents with bachelor's degree or higher, %					
≤34.8	69 (32.2)	32 (35.2)	20 (28.6)	17 (32.1)	.34
34.9-63.7	91 (42.5)	38 (41.8)	35 (50.0)	18 (34.0)	
>63.7	54 (25.2)	21 (23.1)	15 (21.4)	18 (34.0)	
Median household income, \$					
≤44 394	66 (30.8)	20 (22.0)	25 (35.7)	21 (39.6)	.02
44 395-81 821	99 (46.3)	49 (53.8)	34 (48.6)	16 (30.2)	
>81 821	49 (22.9)	22 (24.2)	11 (15.7)	16 (30.2)	
No. (%)					
Candidates for kidney transplant characteristic					
Overall (N = 162 587) ^b		Low segregation (n = 53 282) ^c	Medium segregation (n = 50 155)	High segregation (n = 59 150)	
Age, mean (SD), y	51.6 (13.2)	51.7 (13.4)	51.6 (13.4)	51.4 (13.0)	NA
Age group, y					
18-39	31 796 (19.6)	10 419 (19.6)	9793 (19.5)	11 584 (19.6)	NA
40-64	102 306 (62.9)	33 025 (62.0)	31 297 (62.4)	37 984 (64.2)	
≥65	28 485 (17.5)	9838 (18.5)	9065 (18.1)	9582 (16.2)	
Sex					
Female	65 141 (40.1)	21 024 (39.5)	20 096 (40.1)	24 021 (40.6)	NA
Male	97 446 (59.9)	32 258 (60.5)	30 059 (59.9)	35 129 (59.4)	
Race					
Non-Hispanic Black	80 023 (49.2)	19 962 (37.5)	22 978 (45.8)	37 083 (62.7)	NA
Non-Hispanic White	82 564 (50.8)	33 320 (62.5)	27 177 (54.2)	22 067 (37.3)	
BMI, mean (SD)	28.6 (5.8)	28.5 (5.7)	28.5 (5.7)	28.7 (6.0)	
BMI category					
≤25	50 797 (31.2)	16 689 (31.3)	15 543 (31.0)	18 565 (31.4)	NA
26-30	52 263 (32.1)	17 392 (32.6)	16 024 (31.9)	18 847 (31.9)	
>30	59 527 (36.6)	19 201 (36.0)	18 588 (37.1)	21 738 (36.8)	
Blood type					
A	54 094 (33.3)	18 902 (35.5)	16 924 (33.7)	18 268 (30.9)	NA
B	25 474 (15.7)	7633 (14.3)	7498 (14.9)	10 343 (17.5)	
AB	6822 (4.2)	2222 (4.2)	2007 (4.0)	2593 (4.4)	
O	76 197 (46.9)	24 525 (46.0)	23 726 (47.3)	27 946 (47.2)	
Cause of ESKD					
Diabetes	49 784 (30.6)	16 154 (30.3)	15 559 (31.0)	18, 071 (30.6)	NA
Hypertension	39 308 (24.2)	10 479 (19.7)	11 659 (23.2)	17 170 (29.0)	
Polycystic kidney disease	12 411 (7.6)	4784 (9.0)	4027 (8.0)	3600 (6.1)	
Glomerulonephritis	29 189 (18.0)	10 579 (19.9)	9159 (18.3)	9451 (16.0)	
Other	31 895 (19.6)	11 286 (21.2)	9751 (19.4)	10 858 (18.4)	

(continued)

Table 3. Characteristics of Transplant Centers Stratified by Segregation Levels for Neighborhood, 1995 to 2021 (continued)

Kidney transplant center characteristic ^a	Overall (N = 214) ^b	Low segregation (n = 91) ^c	Medium segregation (n = 70)	High segregation (n = 53)	P value
Education level					
Less than high school	4541 (2.8)	1304 (2.4)	1294 (2.6)	1943 (3.3)	
High school	67 606 (41.6)	20 463 (38.4)	20 980 (41.8)	26 163 (44.2)	
Attended college or technical school	45 040 (27.7)	16 059 (30.1)	13 619 (27.2)	15 362 (26.0)	NA
Associate or bachelor's degree	31 504 (19.4)	10 726 (20.1)	9972 (19.9)	10 806 (18.3)	
Postcollege graduate degree	13 896 (8.5)	4730 (8.9)	4290 (8.6)	4876 (8.2)	
Primary health insurance					
Medicare	55 780 (34.3)	17 231 (32.3)	17 398 (34.7)	21 151 (35.8)	
Medicaid	12 344 (7.6)	3214 (6.0)	2991 (6.0)	6139 (10.4)	NA
Private	74 102 (45.6)	25 583 (48.0)	23 165 (46.2)	25 354 (42.9)	
Other	20 361 (12.5)	7254 (13.6)	6601 (13.2)	6506 (11.0)	
Era of listing					
1995-1999	18 088 (11.1)	6304 (11.8)	5904 (11.8)	5880 (9.9)	
2000-2004	22 996 (14.1)	8020 (15.1)	6984 (13.9)	7992 (13.5)	
2005-2009	32 610 (20.1)	10 789 (20.2)	9398 (18.7)	12 423 (21.0)	NA
2010-2014	37 893 (23.3)	11 999 (22.5)	11 418 (22.8)	14 476 (24.5)	
2015-2021	51 000 (31.4)	16 170 (30.3)	16 451 (32.8)	18 379 (31.1)	
Racial diversity level^c					
Low racial diversity	55 981 (34.4)	19 352 (36.3)	17 214 (34.3)	19 415 (32.8)	
Medium racial diversity	56 864 (35.0)	18 269 (34.3)	18 414 (36.7)	20 181 (34.1)	NA
High racial diversity	49 742 (30.6)	15 661 (29.4)	14 527 (29.0)	19 554 (33.1)	

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); ESKD, end-stage kidney disease; NA, not applicable.

^a Center characteristics (transplant center 5-digit zip codes) determined using only the candidates within the analytical cohort.

^b All transplant centers indicated facilities attended by candidates within the analytical cohort.

^c Segregation and racial diversity levels are calculated based on the Multigroup Entropy Index,²⁵ using candidates' 5-digit zip code as a proxy for neighborhoods. See the eMethods in Supplement 1 for the calculation.

^d Neighborhood-level factors were extracted from the American Community Survey 5-year estimates (2017-2021).

Black candidates listed at transplant centers in high-segregation neighborhoods had 61% (AHR, 0.39 [95% CI, 0.37-0.41]; $P < .001$) lower access to LDKT than White candidates listed at transplant centers in low-segregation neighborhoods (eTable 4 in Supplement 1).

Within high-segregation neighborhoods, candidates listed at transplant centers in predominantly minority neighborhoods had 17% lower access to LDKT (AHR, 0.83 [95% CI, 0.75-0.92]) compared with those listed at centers in predominantly White neighborhoods (Table 3).

Additionally, access to LDKT for candidates listed at transplant centers in high-segregation neighborhoods decreased over time compared with those in low-segregation neighborhoods. Specifically, Black candidates listed at transplant centers in high-segregation neighborhoods had persistently lower access to LDKT over time in comparison to White candidates listed at transplant centers in low-segregation neighborhoods (1995-1999: AHR, 0.43 [95% CI, 0.37-0.50]; 2015-2021: AHR, 0.43 [95% CI, 0.39-0.48]) (eTable 5 in Supplement 1).

Sensitivity Analysis

The present findings were robust to the following methods: (1) Fine and Gray subdistribution hazards models (eTable 8 in Supplement 1); (2) using an alternative modeling approach for handling missing data (eTable 9 in Supplement 1); (3) using cause-specific hazard models with multiple imputation to impute missing covariates (eTable 10 in Supplement 1); (4) multilevel Cox model with shared frailty at transplant centers (eTable 11 in Supplement 1); (5) and using an alternate cutoff to define predominantly White high-segregation neighbor-

hoods (eTable 12 in Supplement 1); (6) stratifying by age at listing (eTable 13 in Supplement 1). Overall, older adults demonstrated lower access to LDKT than their younger counterparts, independent of neighborhood segregation (eTable 13, eFigure 3 in Supplement 1). Moreover, the correlation coefficients and variance inflation factor depicted a moderate correlation between residential and transplant center neighborhood segregation and their corresponding neighborhood-level variables (eTable 14 in Supplement 1). Additionally, the results obtained using the Index of Concentration at Extremes-Race-Income to define segregation were consistent with the main findings (eTable 15 in Supplement 1).

Discussion

In this national cohort study spanning 25 years involving 162 587 Black and White adult candidates for KT, both residential and transplant center neighborhood segregation were associated with decreased access to LDKT. Over a median of 1.9 years, Black candidates residing in high-segregation neighborhoods had 10% lower access to LDKT than their counterparts residing in low-segregation neighborhoods; yet, there was no such association among White candidates. Both Black and White candidates listed at transplant centers in high-segregation neighborhoods had lower access to LDKT relative to their counterparts listed at transplant centers in low-segregation neighborhoods (6% and 8%, respectively). Additionally, among transplant centers located in high-segregation neighborhoods, we observed 17% lower likeli-

hood of LDKT for candidates listed at centers in predominantly minority neighborhoods, compared with those in predominantly White neighborhoods; Black candidates listed at centers in predominantly minority neighborhoods had 64% lower access to LDKT than White candidates listed at centers in predominantly White neighborhoods.

We have identified neighborhood segregation as a potential mechanism of structural racism that contributes to racial and ethnic disparities in LDKT,^{4-6,8-10,40,41} an important outcome in transplant health equity because it is associated with superior outcomes relative to DDKT.^{3,42,43} Patients undergoing LDKT depend on both candidates and potential donors accessing the health care system for screening and approval. Although waitlisted candidates have managed to overcome some structural barriers, racial disparities in transplantation after referral to a transplant center persist regardless of socioeconomic factors and comorbidities, whereas disparities in listing were partially explained by such factors.⁴⁴

We noted that Black candidates residing in high-segregation neighborhoods had lower access to LDKT than Black candidates who resided in low-segregation neighborhoods. Residents of segregated neighborhoods experience multifactorial stressors, such as neighborhood disorders (eg, poor living conditions and crime) and environmental stressors (eg, air pollution).^{15,45,46} Furthermore, residents in underinvested neighborhoods also experience limited educational and employment opportunities,^{12,14} reduced social cohesion,^{14,47} and restricted access to quality health care services,⁴⁸ leading to decreased access to LDKT.⁴⁸ Notably, social cohesion and social networks can be instrumental in facilitating improved access to LDKT^{49,50}; one study highlighted that Black women with larger support networks were more likely to undergo pretransplant evaluation.⁵¹ In addition to the aforementioned barriers, segregated neighborhoods are also characterized by social strain and a higher prevalence of comorbidities, especially in predominantly minority neighborhoods.⁵² These upstream multifaceted factors can impede the identification of suitable donors,⁵² as potential donors often come from the same family or neighborhood as the candidates themselves.^{5,53,54} Therefore, it is likely that residing in a highly segregated residential neighborhood may contribute to racial disparities in accessing LDKT, which presents challenges for both candidates and donors.

This observational study also highlights an underexplored aspect of segregation, namely segregation of the transplant centers neighborhood and access to LDKT. These findings align with previous literature, consistently showing that health care facilities in highly segregated neighborhoods experience lower health care quality and greater racial disparities in health care access and outcomes.^{19,55} Health care centers in underinvested neighborhoods may have poorer health care access and quality,⁵⁵⁻⁵⁷ attributed to the scarcity of available resources (ie, clinicians and equipment),¹⁹ which has a substantial impact on health care availability,^{58,59} quality,^{59,60} and utilization.⁶¹ One study found that patients with ESKD undergoing dialysis in neighborhoods with a higher proportion of Black residents had a lower likelihood of undergoing KT.⁶² We also extend findings on lower rates of living donation at centers in predominantly minority neighborhoods

relative to those with fewer minority individuals.⁶³ Segregation in the transplant center neighborhood may have an impact on disparities in access to LDKT through institutional and structural means.¹⁹ A comprehensive examination of this interplay could further elucidate the mechanisms through which transplant center segregation has an impact on disparities in LDKT.

Within high-segregation neighborhoods, Black candidates residing in or listed at transplant centers in predominantly minority neighborhoods had significantly lower access to LDKT compared with White candidates residing and listed for KT in predominantly White neighborhoods. This suggests that neighborhood segregation contributes to racial and ethnic disparities in LDKT. Predominantly White segregated neighborhoods may reap benefits of community investment that have implications for LDKT.⁶⁴ Furthermore, underinvestment in predominantly minority, segregated neighborhoods may explain racial disparities.⁶⁵⁻⁶⁷

These findings highlight the urgent need for interventions addressing disparities in LDKT. Potentially effective approaches to address residential neighborhood segregation should be guided by key lessons learned in the broader health equity literature,⁶⁸⁻⁷⁰ and may include community outreach initiatives,^{15,71-73} such as those that aim to educate, engage, and support potential donors and candidates in highly segregated neighborhoods.^{70,74,75} Ultimately, interventions to reduce social inequity at the structural level will need to address socioeconomic inequities, improve neighborhood investment, promote community development, create affordable housing policies, and address policies and practices that contribute to residential segregation.^{68-70,74,75}

The exploration of segregation at transplant center neighborhoods suggests the need for greater investment in community outreach at transplant centers,⁷⁶ providing more resources to centers in underinvested neighborhoods (transplant coordinators, patient navigators, and support staff to answer patient and donor questions), and to diversify leadership and decision-making committees within these institutions.^{77,78} Moreover, expanding the current metrics to include pretransplant and posttransplant outcome indicators to account for the social determinants of health of candidates can be valuable for evaluating disparities and access at the institutional level within transplant programs recognized by the OPTN. Addressing the structural factors related to segregation of the transplant center neighborhood can create a more equitable health care landscape and reduce the barriers to LDKT faced by historically marginalized communities.⁷⁹

Strengths and Limitations

The strengths of the present analysis include the large size of the cohort and the use of data from a national registry, at both the residential and transplant center levels. However, some limitations exist. First, because SRTR provides zip codes as the smallest available geographic units, we used them as proxies for neighborhoods. Though this measure summarizes the demographics within a neighborhood, such administrative boundaries are susceptible to spatial misclassification and modifiable areal unit problems, that may cause systematic biases in

the analysis.⁸⁰ Moreover, large zip code regions may encompass diverse neighborhoods. However, it is worth noting that they are commonly used ecological units to define neighborhoods.^{81,82} Second, this study uses race and ethnicity variables from the national registry, some of which were clinician-reported, potentially introducing misclassification bias.⁸³ However, these reported variables have been widely used in multiple research areas including health equity research.^{5,35,84} Third, the present study's definitions of segregation that use aggregated demographic information may not fully capture the multidimensional aspects of structural racism in a neighborhood. However, these findings were robust to the way segregation was defined in this study, as well as to an alternative measure of segregation. To overcome this limitation, other measures of structural racism, such as persistent poverty, the organization and prac-

tices within dialysis facilities, national or local policies (including Medicaid expansion), neighborhood disinvestment, and historical redlining should be considered in future analyses.

Conclusions

This national cohort study highlights the considerable role of racial and ethnic segregation in both the candidate's residential neighborhood and the transplant center's neighborhood in shaping access to LDKT. Continued research and collaborative efforts are necessary to ascertain the specific social and built-environmental barriers of residential and transplant center neighborhoods that reinforce structural racism and influence access to LDKT.

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