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Association of a Liver Allocation Policy Change With Domestic Travel for Liver Transplantation

Katie Ross-Driscoll, PhD, MPH,[1,2] Chandrashekhar Kubal, MD, PhD,[1] Arrey-Takor Ayuk-Arrey, MPH,[2] Jonathan Fridell, MD,[1] and David Axelrod, MD, MBA[3]

Background. In 2020, liver allocation policy in the United States was changed to allow for broader organ sharing, which was hypothesized to reduce patient incentives to travel for transplant. Our objective was to describe patterns of travel for domestic liver transplant pre- and post–acuity circle (AC) implementation. **Methods.** Incident adult liver transplant listings between August 16, 2016, and February 3, 2020 (pre-AC) or June 13, 2020, and December 3, 2023 (post-AC) were obtained from the Scientific Registry of Transplant Recipients. We used previously defined geographic catchment areas to classify patients as (1) no travel, (2) travel to a neighboring region, and (3) travel beyond a neighboring region. We used multinomial logistic regression to identify characteristics associated with travel and cause-specific hazards modeling to estimate the association between travel and time to deceased donor transplant, stratified by model for end-stage liver disease (MELD) score and AC era. **Results.** Among 83 033 liver candidates, 76% were listed in their home region. Black race, lower educational attainment, increased neighborhood social deprivation, and Medicaid were significantly associated with decreased odds of traveling beyond a neighboring region. After AC, traveling beyond a neighboring region was associated with an increased hazard of transplant for patients with a MELD score <15 (cause-specific hazard ratio [csHR]: 1.25; 95% confidence interval [CI], 1.11-1.40), MELD score 15–24 (csHR: 1.19; 95% CI, 1.07-1.31), and MELD score 25–34 (csHR: 1.15; 95% CI, 1.01-1.32). **Conclusions.** Travel frequency, geographic patterns of travel, and characteristics associated with travel were largely unchanged after AC. Changes to allocation policy alone may not equalize patient means or desire to travel for transplant care.

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On February 4, 2020, the Organ Procurement and Transplant Network implemented a new policy for deceased donor liver allocation, termed the acuity circle (AC) liver distribution policy. This policy was designed to reduce geographic variation in liver transplant access through the broader sharing of organs. After AC implementation, variance in model for end-stage liver disease (MELD) scores at transplant across Organ Procurement and Transplant Network regions and states decreased.[1] However, AC implementation was also associated with increased logistical burdens[2] and costs[3,4] as organs traveled further distances.

Some have suggested that broader organ sharing may reduce incentives for patients to travel within the United States for transplant care,[5] which has been previously associated with shorter times to transplant.[6,7] In a prior study, we demonstrated that transplant candidates who traveled outside their assigned geographic catchment area for kidney transplants were more likely to be White, have higher educational attainment, and live in low-poverty ZIP codes.[8] If broader organ sharing did decrease incentives to travel, any similar disparity in liver transplantation may be attenuated.

Our objective was to describe geographic patterns of candidate travel for liver transplantation within the United States pre- and post-AC implementation. We identified factors associated with travel and estimated potential effect modification by AC implementation. In addition, we examined whether AC modified the association between travel and time to transplantation.

MATERIALS AND METHODS

Data Source and Study Population

Data were obtained from the Scientific Registry of Transplant Recipients (SRTR). SRTR contains data on all

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[1] Division of Transplantation, Department of Surgery, Indiana University School of Medicine, Indianapolis, IN.

[2] Center for Health Services Research, Regenstrief Institute, Indianapolis, IN.

[3] Division of Transplantation, Department of Surgery, University of Iowa School of Medicine, Iowa City, IA.

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K.R.-D. conceived the idea and performed data analysis. C.K. and D.A. contributed to research design. All authors participated in article writing and review for critical content.

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Correspondence: Katie Ross-Driscoll, PhD, MPH, Division of Transplantation, Department of Surgery, Indiana University School of Medicine, 1101 W 10th St, Indianapolis, IN 46202. (krossdr@iu.edu).

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solid organ transplant candidates and recipients in the United States. Data are available from SRTR on request. Patients were considered eligible for inclusion if they were adults (older than 17 y) listed for a liver transplant. Patients were excluded if they did not have a recorded ZIP code.

AC was implemented on February 4, 2020, contemporaneous with the onset of the COVID-19 pandemic in the United States. In response to the pandemic, SRTR instituted a "blackout" from March 12, 2020, to June 12, 2020, during which any transplants were excluded from outcome assessment.[9] Following this example, we defined our "post-AC" cohort as beginning on the first date after the blackout (March 3, 2020) and ending on December 1, 2023, comprising 1267 d of follow-up. We then defined the "pre-AC" cohort as the 1267 d preceding AC implementation (August 16, 2016–February 3, 2020). We included incident transplant listings in these 2 eras (**Figure S1, SDC,** http://links.lww.com/TXD/A724). Patients who were still waiting at the end of their era were censored.

Defining Travel

We used previously defined geographic catchment areas for transplant centers, termed transplant referral regions (TRRs), to characterize travel. TRRs describe where patients are most likely to seek transplant care based on their ZIP code. TRRs have been previously shown to perform well in describing patterns of patients care[10] and to study travel for kidney transplantation.[8]

We hypothesized that travel to a neighboring TRR may meaningfully differ from more extensive travel. We identified neighboring TRRs as those that shared an edge or a vertex with an index TRR. We defined 3 categories of travel: (1) no travel, (2) travel to a neighboring TRR, or (3) travel beyond a neighboring TRR. Patients who were multiply listed were assigned the travel status of their farthest transplant center.

Predictors of Travel

We evaluated demographic factors hypothesized to be associated with travel for transplant, including age, gender, race and ethnicity, educational attainment, neighborhood social deprivation index (SDI), and insurance. We also assessed clinical factors, including MELD score at the time of transplant listing, body mass index (BMI), underlying cause of liver disease (categorized as hepatitis C, alcohol-associated liver disease, nonalcoholic steatohepatitis, and other), and presence of hepatocellular carcinoma. We classified patients as multiply listed if they had >1 listing for liver transplant within their era (ie, pre- or post-AC). Missing data were imputed using the MICE package in R.

Statistical Analyses

We described patient characteristics stratified by travel category and AC era. We then fit a multivariable, multinomial logistic model to estimate the association between patient characteristics and travel. We identified changes in these relationships after AC implementation by evaluating the significance of statistical interaction terms.

We estimated a cause-specific hazard ratio (csHR) for deceased donor transplants, accounting for the competing risk of death and living donor transplants. These models included a 3-level interaction term between travel, AC era, and MELD score at listing (categorized as <15, 15–24, 25–34, and ≥35) to assess the association before and after AC implementation for patients with varying disease severity. In a sensitivity analysis, we calculated the liver donor risk index (LDRI)[11] for each transplant recipient.

Changes in geographic patterns of travel pre- and post-AC were assessed by calculating migration flows for each TRR (number of patients traveling to the TRR – number of patients traveling away from the TRR). To identify the role that distance may play in travel decisions, we conducted a sensitivity analysis to identify whether patients were listed at their closest transplant center. We also calculated the excess travel distance (ETD), or the difference between the distance from the patient's transplant center and their closest center, for each patient. We conducted 2 sensitivity analyses: first, because Medicaid is a state-based insurance program and patients with Medicaid may be structurally unable to travel to further centers, we repeated this analysis excluding patients with Medicaid or dual Medicaid-Medicare. Second, we repeated this analysis, including ETD as a covariate, to determine whether traveling to or beyond a neighboring TRR was independently associated with the likelihood of transplant after accounting for travel distance. All analyses were performed in R version 4.4.0.

RESULTS

Study Population

Among the 83 033 patients included in the analysis, 76% were listed in the TRR assigned as their home TRR. After AC implementation, the proportion of patients who traveled to a neighboring TRR increased from 18.9% to 20.1%, and the proportion of patients who traveled beyond a neighboring TRR decreased from 5.0% to 4.3%.

The distribution of demographic characteristics by travel category was consistent before and after AC implementation (Table 1); the following are from the pre-AC era. White patients comprised a higher proportion of those who traveled either to (76.3%) or beyond (78.6%) a neighboring TRR than those who stayed in their home TRR (68.0%). Living in a more socially deprived neighborhood (SDI >80) was more prevalent among those who stayed in their home TRR (22.2%) than those who traveled (to a neighboring TRR: 14.7%, beyond a neighboring TRR: 14.1%). Medicaid was much less prevalent among those who traveled beyond a neighboring TRR (3.4%) than those who traveled to a neighboring TRR (16.0%) or remained in their home TRR (19.5%).

Patients who traveled beyond a neighboring TRR had a lower mean MELD score (17.6) than those who either remained in their home TRR (mean MELD: 18.4) or traveled to a neighboring TRR (mean MELD: 18.4). Multiple listing was also more prevalent among those who traveled beyond a neighboring TRR (12.6%) than those who stayed in their home TRR (5.1%) or traveled to a neighboring TRR (6.6%).

Association of Demographic and Clinical Characteristics With Travel

Black, Asian, and Hispanic patients were significantly less likely to travel either to a neighboring TRR or beyond a neighboring TRR relative to White patients (Table 2). Patients with a high school diploma or less had lower odds of traveling beyond a neighboring TRR (odds ratio [OR]: 0.59; 95% confidence interval [CI], 0.55-0.64) than patients with some college or more. SDI score >80 was associated

TABLE 1.

Demographic and clinical characteristics of liver transplant candidates, stratified by acuity circle era and travel status, August 15, 2016–December 1, 2023

	Pre-AC			Post-AC		
Characteristics	**No travel**	**Travel, to neighbor**	**Travel, beyond neighbor**	**No travel**	**Travel, to neighbor**	**Travel, beyond neighbor**
N (%)	30 431 (76.1)	7547 (18.9)	1989 (5.0)	32579 (75.6)	8652 (20.1)	1835 (4.3)
Age, mean (SD)	55.9 (11.0)	55.3 (11.3)	55.0 (12.0)	54.9 (11.7)	54.0 (12.0)	52.7 (13.3)
Race/ethnicity, n (%)						
White	20 693 (68.0)	5579 (76.3)	1563 (78.6)	21 836 (67.0)	6623 (76.5)	1479 (80.6)
Black	2403 (7.9)	554 (7.3)	120 (6.0)	2226 (6.8)	480 (5.5)	92 (5.0)
Asian	1405 (4.6)	239 (3.2)	52 (2.6)	1423 (4.4)	268 (3.1)	60 (3.3)
Hispanic	5434 (17.9)	851 (11.3)	221 (11.1)	6471 (19.9)	1117 (12.9)	168 (9.2)
Other	496 (1.6)	144 (1.9)	33 (1.7)	623 (1.9)	164 (1.9)	36 (2.0)
Sex, n (%)						
Male	18 905 (62.1)	4766 (63.2)	1392 (70.0)	19 818 (60.8)	5356 (61.9)	1194 (65.1)
Female	11 526 (37.9)	2781 (36.8)	697 (30.0)	12 761 (39.2)	3296 (38.1)	641 (34.9)
Education, n (%)						
Some college or higher	16 040 (52.7)	4309 (57.1)	1296 (70.2)	18 255 (56.0)	5075 (58.7)	1297 (70.7)
High school diploma or less	14 390 (47.3)	3236 (42.9)	593 (29.8)	13 353 (41.0)	3352 (38.7)	476 (25.9)
Missing	1 (0.0)	2 (0.0)	0 (0)	971 (3.0)	225 (2.6)	62 (3.4)
Social deprivation index score, n (%)						
0–19	5582 (18.5)	1607 (21.5)	434 (22.2)	6318 (19.6)	1819 (21.2)	463 (24.6)
20–39	5980 (19.8)	1603 (21.5)	449 (23.0)	6697 (20.7)	1908 (22.3)	400 (22.1)
40–59	5841 (19.4)	1618 (21.7)	425 (21.8)	6330 (19.6)	1890 (22.0)	404 (22.3)
60–79	6046 (20.1)	1537 (20.6)	370 (18.9)	6219 (19.2)	1746 (20.4)	18.4 (332)
80–100	6702 (22.2)	1094 (14.7)	276 (14.1)	6746 (20.9)	1209 (14.1)	209 (11.6)
Insurance type, n (%)						
Private	15 213 (50.0)	3833 (50.8)	1086 (54.6)	16 146 (49.6)	4419 (51.1)	949 (51.7)
Medicaid	5930 (19.5)	1208 (16.0)	68 (3.4)	6513 (20.0)	1570 (18.1)	105 (5.7)
Medicare	8503 (27.9)	2057 (27.3)	411 (20.7)	7793 (23.9)	1964 (22.7)	379 (20.7)
Other	784 (2.6)	447 (5.9)	424 (21.3)	1155 (3.5)	375 (5.5)	340 (18.5)
MELD score, mean (SD)	18.4 (9.3)	18.4 (9.2)	17.6 (8.9)	19.9 (9.6)	20.4 (9.8)	18.9 (9.8)
MELD score category, n (%)						
<15	12 705 (41.8)	3171 (42.0)	912 (45.9)	11 529 (35.4)	2977 (34.4)	742 (40.4)
15–24	10 820 (35.6)	2690 (35.6)	683 (34.3)	11 718 (36.0)	3029 (35.0)	644 (35.1)
25–34	4432 (14.6)	1080 (14.3)	267 (13.4)	5918 (18.2)	1646 (19.0)	263 (14.3)
>35	2471 (8.1)	606 (8.0)	127 (6.4)	3409 (10.5)	1000 (11.6)	186 (10.1)
Underlying cause of disease, n (%)						
Alcohol	9144 (30.0)	2279 (30.2)	427 (21.5)	7840 (24.1)	2052 (23.7)	319 (17.4)
Hepatitis C	6018 (19.8)	1365 (18.1)	380 (19.1)	2874 (8.8)	679 (7.8)	155 (8.4)
NASH	7525 (24.7)	1925 (25.5)	428 (21.5)	8175 (25.1)	2247 (26.0)	385 (21.0)
Other	7744 (25.4)	1978 (26.2)	754 (37.9)	13 690 (42.0)	3674 (42.5)	976 (53.2)
HCC, n (%)						
No	26 753 (87.9)	6778 (89.8)	1746 (87.8)	28 373 (87.1)	7663 (88.6)	1608 (87.6)
Yes	3671 (12.1)	766 (10.1)	242 (12.2)	3293 (10.1)	779 (9.0)	184 (10.0)
BMI, mean (SD)	29.2 (6.2)	29.3 (6.4)	28.5 (6.0)	29.0 (6.3)	29.4 (7.0)	28.5 (6.4)
BMI >35						
No	25 754 (84.6)	6320 (83.7)	1737 (87.3)	27 687 (85.0)	7243 (83.7)	1587 (86.5)
Yes	4597 (15.1)	1206 (16.0)	248 (12.5)	4673 (14.3)	1378 (15.9)	232 (12.6)
Multiply listed, n (%)						
No	28 893 (94.9)	7094 (93.4)	1738 (87.4)	31 059 (95.3)	8207 (94.9)	1629 (88.8)
Yes	1538 (5.1)	498 (6.6)	251 (12.6)	1520 (4.7)	445 (5.1)	206 (11.2)

AC, acuity circle; BMI, body mass index; HCC, hepatocellular carcinoma; MELD, model for end-stage liver disease; NASH, nonalcoholic steatohepatitis.

with a lower likelihood of traveling to a neighboring TRR (OR: 0.71; 95% CI, 0.66-0.75) or traveling beyond a neighboring TRR (OR: 0.71; 95% CI, 0.63-0.81) compared with patients with SDI score <20. Patients with Medicaid had significantly lower odds of traveling beyond a neighboring TRR relative to those with private insurance (OR: 0.27; 95% CI, 0.23-0.32). Patients with other insurance were significantly more likely to travel either to (OR: 1.93; 95% CI, 1.78-2.10) or beyond (OR: 7.14; 95% CI, 6.46-7.89) a neighboring TRR.

Patients with a MELD score <15 were more likely to travel beyond a neighboring TRR than patients with a MELD score >35 (OR: 1.24; 95% CI, 1.08-1.42). Patients with hepatocellular carcinoma were less likely to travel to a neighboring

TABLE 2.

Multinomial logistic regression results for the odds of traveling to or beyond a neighboring TRR, relative to remaining in one's home region

	Travel to a neighbor	Travel beyond a neighbor
Age (per year)	0.99 (0.99-0.99)	0.98 (0.98-0.98)
Race		
White	Reference	Reference
Black	0.81 (0.75-0.87)	0.58 (0.50-0.68)
Asian	0.65 (0.59-0.72)	0.53 (0.43-0.65)
Hispanic	0.63 (0.60-0.68)	0.62 (0.55-0.70)
Other	0.97 (0.85-1.11)	0.83 (0.64-1.10)
Sex		
Male	Reference	Reference
Female	0.96 (0.93-0.99)	0.82 (0.76-0.88)
Educational attainment		
High school or less	0.97 (0.93-1.01)	0.59 (0.55-0.64)
Some college or more	Reference	Reference
Social deprivation index		
0–19	Reference	Reference
20–39	0.98 (0.93-1.04)	0.94 (0.85-1.04)
40–59	1.04 (0.98-1.10)	0.99 (0.90-1.10)
60–79	0.99 (0.94-1.05)	0.92 (0.83-1.03)
80–100	0.71 (0.66-0.75)	0.71 (0.63-0.81)
Insurance type		
Private	Reference	Reference
Medicaid	0.94 (0.89-0.99)	0.27 (0.23-0.32)
Medicare	1.03 (0.98-1.08)	0.93 (0.85-1.02)
Other	1.93 (1.78-2.10)	7.14 (6.46-7.89)
MELD score category		
<15	0.98 (0.92-1.05)	1.24 (1.08-1.42)
15–24	0.94 (0.88-1.01)	1.10 (0.96-1.25)
25–34	0.97 (0.91-1.05)	0.98 (0.84-1.13)
>35	Reference	Reference
Underlying cause of disease		
Alcohol	Reference	Reference
Hepatitis C	1.00 (0.94-1.07)	1.56 (1.38-1.77)
NASH	1.11 (1.05-1.17)	1.31 (1.17-1.45)
Other	1.08 (1.03-1.13)	1.86 (1.70-2.04)
HCC	0.92 (0.87-0.98)	1.00 (0.89-1.12)
BMI ≥35 kg/m^2	1.08 (1.03-1.14)	0.91 (0.82-1.00)
Multiply listed	1.18 (1.09-1.27)	2.33 (2.09-2.61)

BMI, body mass index; HCC, hepatocellular carcinoma; MELD, model for end-stage liver disease; NASH, nonalcoholic steatohepatitis; TRR, transplant referral region.

TRR (OR: 0.92; 95% CI, 0.87-0.98), whereas patients with a BMI >35 were more likely to travel to a neighboring TRR (OR: 1.08; 95% CI, 1.03-1.14). Multiple listing was associated with higher odds of travel to (OR: 1.18; 95% CI, 1.09-1.27) or beyond (OR: 2.33; 95% CI, 2.09-2.61) a neighboring TRR.

Associations between race and travel to a neighboring TRR were strengthened for the Black race (*P* = 0.03) and attenuated for educational attainment (*P* = 0.04) after AC implementation (Table 3). The association between age (*P* = 0.01), Hispanic ethnicity (*P* < 0.01), and travel beyond a neighboring TRR were strengthened, whereas the association with gender (*P* = 0.03) and Medicaid (*P* = 0.001) was attenuated (*P* = 0.03). Associations between other insurance types and both types of travel were attenuated after AC implementation (*P* < 0.001). The direction of the association between MELD scores 25–34 and travel beyond a neighbor changed from positive to negative after AC implementation (*P* for interaction = 0.04) but was not statistically significant in either era.

Travel and Time to Deceased Donor Transplant

Pre-AC implementation, traveling to a neighboring TRR was not associated with an increased hazard of deceased donor transplant for any MELD score category (Table 4). Traveling beyond a neighboring TRR was associated with an increased hazard of transplant for patients with MELD score <25 (MELD score <15 csHR: 1.44; 95% CI, 1.31-1.59; MELD score 15–24 csHR: 1.17; 95% CI, 1.06-1.30). After AC implementation, traveling to a neighboring TRR was associated with increased hazard of transplant for patients with lower MELD score (MELD score <15 csHR: 1.09; 95% CI, 1.02-1.16; MELD score 15–24 csHR: 1.07; 95% CI, 1.02-1.13). Traveling beyond a neighboring TRR was associated with an increased hazard of transplant for all patients except for those with a MELD score >35.

Figure S2 (**SDC,** http://links.lww.com/TXD/A724) provides the distribution of the LDRI by travel status, AC implementation, and MELD score category. Both pre- and post-AC, patients with lower MELD scores had a higher LDRI than those with higher MELD scores. Overall, LDR increased after AC implementation for recipients with a MELD score <25. Pre-AC, there was no association between travel and LDRI. Post-AC, LDRI was highest among those who traveled to a neighboring TRR for patients with a MELD score <15 and highest among those who traveled beyond a neighboring TRR for patients with a MELD score of 15–24.

Sensitivity Analyses

Table S1 (**SDC,** http://links.lww.com/TXD/A724) presents the csHR for the association between travel and likelihood of deceased donor transplant, stratified by MELD score and AC, excluding patients with Medicaid or Medicare/Medicaid. Results were similar to the main analysis, with some changes in magnitude after the exclusion of Medicaid patients pre-AC implementation. Pre-AC, traveling to a neighbor was more strongly associated with transplant among patients with a MELD score >35 in the cohort excluding Medicaid (csHR: 1.26; 95% CI, 1.01-1.56), and less strongly associated with transplant among patients with a MELD score <15 (csHR: 1.27; 95% CI, 1.17-140) than the main analyses. After AC, the results of the 2 analyses are very similar.

Table S2 (**SDC,** http://links.lww.com/TXD/A724) presents the results of an analysis controlling for ETD. Accounting for travel distance did attenuate our findings. However, in the post-AC era, traveling beyond a neighboring TRR remained significantly associated with time to transplant even after accounting for geographic distance traveled (csHR: 1.19; 95% CI, 1.04-1.36).

Geographic Patterns of Travel

Figure 1 visualizes the net inflow of traveling beyond a neighbor for each TRR, stratified by AC era. Geographic patterns in travel appear to be largely unchanged by AC implementation. TRRs with a net outflow were roughly located in the West and the Northeast, whereas areas of net inflow included the upper Midwest, the mid-Atlantic, and parts of the Southwest (ie, Arizona).

TABLE 3.

Effect modification of factors associated with traveling for liver transplant, pre– and post–acuity circle implementation

Factors	Pre-AC		Post-AC		Effect modification *P* value	
	Travel to a neighbor	Travel beyond a neighbor	Travel to a neighbor	Travel beyond a neighbor	To a neighbor	Beyond neighbor
Age (per year)	0.99 (0.99-0.99)	0.99 (0.99-1.00)	0.99 (0.99-0.99)	0.98 (0.97-0.98)	0.57	0.01
Race						
White	Reference	Reference	Reference	Reference		
Black	0.89 (0.80-0.99)	0.58 (0.47-0.71)	0.73 (0.65-0.81)	0.55 (0.44-0.70)	0.03	0.73
Asian	0.65 (0.57-0.76)	0.42 (0.31-0.56)	0.66 (0.57-0.75)	0.64 (0.48-0.84)	0.69	0.12
Hispanic	0.66 (0.61-0.72)	0.79 (0.67-0.93)	0.61 (0.57-0.66)	0.50 (0.42-0.60)	0.84	0.001
Other	1.10 (0.91-1.33)	0.90 (0.61- 1.33)	0.87 (0.72-1.04)	0.79 (0.54-1.16)	0.20	0.77
Sex						
Male	Reference	Reference	Reference	Reference		
Female	0.96 (0.91-1.02)	0.74 (0.66-0.82)	0.96 (0.91-1.01)	0.89 (0.80-0.99)	0.96	0.03
Educational attainment						
High school or less	0.94 (0.89-0.98)	0.55 (0.50-0.62)	1.01 (0.96-1.07)	0.63 (0.56-0.71)	0.04	0.44
Some college or more	Reference	Reference	Reference	Reference		
Social deprivation index						
0–19	Reference	Reference	Reference	Reference		
20–39	0.95 (0.88-1.03)	1.01 (0.88-1.17)	1.01 (0.94-1.09)	0.87 (0.75-1.01)	0.23	1.12
40–59	0.99 (0.92-1.08)	1.02 (0.88-1.18)	1.08 (1.00-1.17)	0.97 (0.84-1.12)	0.11	0.63
60–79	0.95 (0.88-1.03)	0.95 (0.81- 1.10)	1.04 (0.96-1.12)	0.90 (0.77-1.05)	0.09	0.56
80–100	0.67 (0.61-0.73)	0.75 (0.63-0.89)	0.75 (0.68-0.81)	0.66 (0.55- 0.79)	0.16	0.08
Insurance type						
Private	Reference	Reference	Reference	Reference		
Medicaid	0.92 (0.86-0.99)	0.22 (0.17-0.29)	0.95 (0.88-1.01)	0.33 (0.27-0.41)	0.08	0.001
Medicare	1.05 (0.99-1.12)	0.81 (0.71- 0.92)	1.02 (0.95-1.09)	1.11 (0.97-1.27)	0.33	0.02
Other	2.44 (2.16-2.77)	9.14 (7.94-10.52)	1.59 (1.43-1.79)	5.90 (5.11-6.82)	<0.001	<0.001
MELD score category						
<15	1.08 (0.98-1.20)	1.33 (1.08-1.63)	0.92 (0.84-1.01)	1.16 (0.97-1.39)	0.96	0.72
15–24	1.02 (0.92-1.12)	1.21 (0.98-1.49)	0.89 (0.82-0.98)	1.01 (0.84-1.20)	0.06	0.06
25–34	1.00 (0.89-1.12)	1.22 (0.97-1.53)	0.97 (0.88-1.06)	0.82 (0.67-1.00)	0.15	0.04
>35	Reference	Reference	Reference	Reference		
Underlying cause of disease						
Alcohol	Reference	Reference	Reference	Reference		
Hepatitis C	0.98 (0.90-1.06)	1.44 (1.23-1.69)	1.03 (0.93-1.15)	1.66 (1.34-2.05)	0.94	0.91
NASH	1.05 (0.98-1.13)	1.32 (1.14-1.53)	1.15 (1.07-1.24)	1.34 (1.13-1.58)	0.67	0.64
Other	1.05 (0.97-1.13)	2.17 (1.90-2.38)	1.09 (1.02-1.16)	1.79 (1.56-2.05)	0.81	0.10
HCC	0.86 (0.70-0.94)	0.95 (0.81-1.11)	0.99 (0.90-1.08)	1.04 (0.87-1.24)	0.29	0.87
BMI ≥35	1.07 (0.99-1.15)	0.87 (0.76-1.01)	1.10 (1.02-1.17)	0.94 (0.81-1.10)	0.33	0.35
Multiply listed	0.87 (1.17-1.45)	2.46 (2.12-2.86)	1.07 (0.96-1.20)	2.19 (1.86-2.58)	0.02	0.48

AC, acuity circle; BMI, body mass index; HCC, hepatocellular carcinoma; MELD, model for end-stage liver disease; NASH, nonalcoholic steatohepatitis.

Among patients who were listed in their home TRR, 51% were listed at their closest center, with a mean ETD of 9.7 miles (SD: 34.4 miles). Among patients listed in a neighboring TRR, 25% were listed at their closest center, with a mean ETD of 104 miles (SD: 156 miles). Among those listed beyond a neighboring TRR, 0.6% were listed at their closest center, with a mean ETD of 1220 miles (SD: 986 miles).

DISCUSSION

In both pre- and post-AC implementation, the majority of patients (>75%) were listed for a liver transplant in their TRR. Vulnerable populations, including racial and ethnic minorities, patients with lower educational attainment, patients living in high-deprivation neighborhoods, and patients with Medicaid, were less likely to travel for transplants in both eras. Even after AC implementation, traveling beyond a neighboring TRR was associated with an increased likelihood of deceased donor transplant for all MELD score groups except those with a MELD score >35. Geographic patterns of travel were largely similar pre- and post-AC. Overall, broader organ sharing did not appear to reduce incentives for patients to travel for liver transplants or disparities in transplant travel. These trends may continue as organ allocation policy moves toward continuous distribution.

One challenge to studies of travel for transplant is identifying patients who are making a deliberate decision to seek care outside of the area in which they would be expected to do so. Prior studies have used varying definitions, including outside of an individual's home state,[12] outside their home donor service area,[13] beyond their closest transplant center,[14] in another United Network for Organ Sharing region and >100 miles from their home ZIP,[15] or multiple listings for

TABLE 4.

Cause-specific hazards of receiving a deceased donor transplant by travel status, AC era, and MELD score at listing, accounting for the competing risk of death and living donor liver transplantation

	Pre-AC		Post-AC	
MELD scores	Traveling to a neighbor	Traveling beyond a neighbor	Traveling to a neighbor	Traveling beyond a neighbor
<15	0.98 (0.92-1.04)	1.44 (1.31-1.59)	1.09 (1.02-1.16)	1.25 (1.11-1.40)
15–24	0.98 (0.92-1.03)	1.17 (1.06-1.30)	1.07 (1.02-1.13)	1.19 (1.07-1.31)
25–34	0.95 (0.88-1.03)	1.04 (0.90-1.19)	1.03 (0.97-1.09)	1.15 (1.01-1.32)
≥35	0.94 (0.85-1.04)	1.05 (0.86-1.29)	1.08 (1.00-1.17)	1.11 (0.95-1.31)

AC, acuity circle; MELD, model for end-stage liver disease.

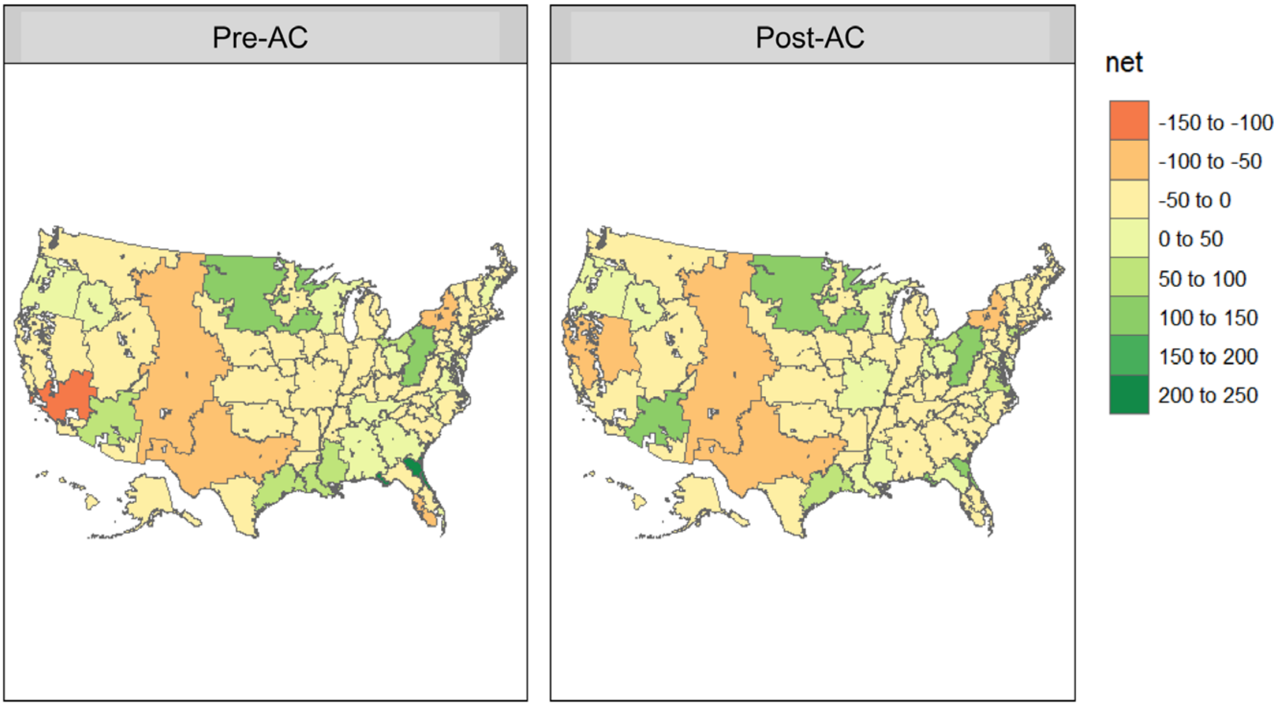

FIGURE 1. Net inflow of patients traveling beyond a neighboring TRR, by TRR, pre- and post-AC implementation.AC, acuity circle; TRR, transplant referral region.

transplant.[7] One major advantage to our approach of using TRRs to define travel is that they are based on historical patterns of listing, not administrative boundaries, as with states or donor service areas. Prior analyses have shown that TRRs perform well in assigning patients to a usual place of transplant care.[8] Our sensitivity analyses examining ETD show that patients traveling to a neighboring TRR are typically not doing so to travel to their closest center, suggesting that our definition may reflect a deliberate decision to travel for transplant care. Furthermore, a sensitivity analysis demonstrated that the benefit of traveling beyond a neighboring TRR was maintained after AC even while accounting for ETD. Although multiple listings were more common among patients who traveled beyond a neighboring TRR, only 10% of these patients had multiple listings within their era. Defining travel based on multiple listings may underestimate the extent of travel.

Our findings that travel is associated with sociodemographic factors are consistent with our prior work in kidney transplantation.[8] As in kidney transplant, we observed that traveling beyond a neighboring TRR for liver transplant was more common among White patients with higher educational attainment who lived in low-deprivation neighborhoods and had private insurance. The implementation of AC did appear to attenuate the association between insurance type and travel, although the association between Medicaid and traveling beyond a neighboring TRR persisted after implementation. However, associations between race, ethnicity, and travel were strengthened in the AC era, and associations between neighborhood deprivation and educational attainment were unchanged. These findings suggest that there are still disparities in which patients have the means and desire to travel for liver transplant care, even after broader organ sharing, which hypothetically reduced the need for travel by bringing organs closer to patients.

In our study, travel was associated with an increased hazard of deceased donor transplant, which is consistent with prior studies that used multiple listings as their definition of travel.[7] We observed that the association between travel and transplant was strongest among patients with a lower MELD score and that patients with a lower MELD score were more likely to travel than patients with a higher MELD score. Liver allocation prioritizes patients with the highest illness severity, and AC implementation has been associated with an increased offer rate to patients with higher MELD scores.[16] Patients with high MELD scores may not have an incentive to travel, as their likelihood of receiving a transplant anywhere is high. Alternately, patients with high MELD scores may be less able to travel due to the acuity of their illness.

Broader organ sharing was intended to reduce geographic variability in access to transplants. Despite this, we found that the geographic patterns of travel did not appear to change significantly after AC implementation. Our observed geographic patterns are consistent with those of Goldberg and Lynch, who found that among patients who traveled beyond a neighboring state for a liver transplant, 48% of patients went to 1 of 4 centers: Ochsner, Mayo Arizona, Mayo Jacksonville, or Mayo Rochester.[12] The Mayo Clinics are known for being aggressive in their utilization of donation after circulatory death (DCD) grafts,[17-19] the number of which available has increased after changes to performance monitoring for organ procurement organizations[20] and the rise in availability of normothermic machine perfusion.[21] Additionally, Giorgakis et al[22] demonstrated that centers may have averted losses in their transplant volume after AC by increasing their utilization of DCD grafts. This is consistent with our observation that the mean LDRI increased after AC implementation for patients with lower MELD scores, particularly among those who traveled for care. Patients who traveled to aggressive centers after AC may have benefitted both from increasing utilization and the higher number of available DCD grafts, resulting in further decreased time to transplant.

There are currently no policies disallowing travel for transplants. Such policies may harm patients with unique clinical needs or patients who do not meet selection criteria (ie, age, BMI) at their local center but would at another. However, some authors have suggested that allowing travel violates the principles of social justice.[7] One method to promote equity may be to provide financial and logistical support to patients who may benefit from traveling but cannot do so. A precedent for this exists in the travel reimbursement for living organ donors provided by the National Living Donor Assistance Center.[23]

This analysis has several limitations. AC implementation occurred contemporaneously with changes in how organ procurement organizations are regulated and changes in the use of normothermic machine perfusion in liver transplant, which may have confounded the association between AC implementation and transplant rates by increasing DCD availability, as discussed earlier. Although we believe TRRs are appropriate for this analysis, there is still the possibility of misclassification of travel status, particularly if the patient lives on the border of 2 TRRs. Our sensitivity analysis examining distance suggests a difference in the distance traveled for patients traveling to a neighboring TRR relative to those remaining in their home catchment. We only have information about patients once they are on the transplant waiting list. It is unknown if patients who traveled to other TRRs did so because they were denied by transplant centers closer to home or if they deliberately chose to bypass those centers. Among patients who traveled, we do not know if they were traveling for increased transplant access or other reasons, such as family support in that area, insurance requirements, or specialized diagnoses. Future qualitative work may explore these questions and identify priorities for patients when choosing a transplant center. Finally, the current analysis is limited to the TRR level, but observed patterns are likely driven by specific centers within each TRR. Future analyses of high "inflow" areas may reveal intra-TRR variation and additional insight into which transplant center practices are associated with "pull" for patients to travel.

In summary, we found racial and socioeconomic differences in travel for liver transplants that persisted after AC implementation. Patients who traveled to or beyond a neighboring TRR for a transplant were more likely to receive one. This association was strengthened after AC implementation and was strongest among patients with lower MELD scores and patients who traveled beyond a neighboring TRR. Geographic patterns in travel were similar pre- and post-AC. Changes to allocation policy alone may not equalize patient means or desire to travel for transplant care, and these trends may continue under coming continuous distribution allocation policies.

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