ORIGINAL ARTICLE

Impact of Broader Sharing on the Transport Time for Deceased Donor Livers

Sommer E. Gentry,[1,2] **Eric K. H. Chow,**[1] **Corey E. Wickliffe,**[1] **Allan B. Massie,**[1,3] **Tabitha Leighton,**[4] **and Dorry L. Segev**[1,3]

[1]*Department of Surgery, Johns Hopkins University School of Medicine, Baltimore, MD;* [2]*Department of Mathematics, US Naval Academy, Annapolis, MD;* [3]*Department of Epidemiology, Johns Hopkins School of Public Health, Baltimore, MD; and* [4]*Scientific Registry of Transplant Recipients, Minneapolis, MN*

Recent allocation policy changes have increased the sharing of deceased donor livers across local boundaries, and sharing even broader than this has been proposed as a remedy for persistent geographic disparities in liver transplantation. It is possible that broader sharing may increase cold ischemia times (CITs) and thus harm recipients. We constructed a detailed model of transport modes (car, helicopter, and fixed-wing aircraft) and transport times between all hospitals, and we investigated the relationship between the transport time and the CIT for deceased donor liver transplants. The median estimated transport time was 2.0 hours for regionally shared livers and 1.0 hour for locally allocated livers. The model-predicted transport mode was flying for 90% of regionally shared livers but for only 22% of locally allocated livers. The median CIT was 7.0 hours for regionally shared livers and 6.0 hours for locally allocated livers. Variation in the transport time accounted for only 14.7% of the variation in the CIT, and the transport time on average composed only 21% of the CIT. In conclusion, nontransport factors play a substantially larger role in the CIT than the transport time. Broader sharing will have only a marginal impact on the CIT but will significantly increase the fraction of transplants that are transported by flying rather than driving. ***Liver Transpl 20:1237-1243, 2014***. © **2014 AASLD.**

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Livers, previously offered locally first, are now offered first at the regional level for status 1 candidates[1] and for those with Model for End-Stage Liver Disease scores greater than or equal to 35.[2] Even broader sharing, such as the offering of all organs at the regional level first for all candidates, has been proposed[3] as a solution to geographic inequity.[4-6] We have also reported that optimal redistricting through a broader sharing paradigm is needed to reduce geographic disparities in liver allocation.[7]

It has been hypothesized that broader sharing will increase the travel burden and the cold ischemia time

Abbreviations: CIT, cold ischemia time; DRI, donor risk index; IQR, interquartile range; NPIAS, National Plan of Integrated Airport Systems; OPO, organ procurement organization; OPTN, Organ Procurement and Transplantation Network; SRTR, Scientific Registry of Transplant Recipients.

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Address reprint requests to Sommer E. Gentry, Ph.D., Department of Mathematics, US Naval Academy, 572-C Holloway Road, Mail Stop 9E, Annapolis, MD 21402. Telephone: 410-293-6724; E-mail: gentry@usna.edu

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(CIT), but the impact has not been quantified. A prolonged CIT negatively affects patient and graft survival.[8-11] The components of the CIT include activities at the donor hospital (hepatectomy, packaging, and other possible delays), the transport time, and activities at the recipient hospital (back-table preparation, recipient hepatectomy, and other possible delays). However, only the transport time is affected by changes in the liver allocation system. Unfortunately, the time required to transport the organ has not been studied in a national setting, presumably because it is not recorded in national databases. Although the simple straight-line distance has been used as a proxy for the transport time,[3,12] the relationship between these metrics is clearly nonlinear because the mode of transport can shift from driving to flying.

To better understand the relationship between the transport time and the CIT, we created a detailed model to estimate transport times that considered the alternatives of driving, helicopter flight, and fixed-wing charter flight. Using the street addresses of every transplant center and recovery hospital in the United States, we estimated driving times with actual direct street routes between hospitals and between hospitals and the nearest airports. We surveyed organ procurement organizations (OPOs) about their transport practices (eg, when they switched from driving to flying and whether they used helicopters), and we estimated the total transport times accordingly. Finally, we investigated the relationships between the estimated transport time, the distance, and the CIT.

MATERIALS AND METHODS

OPO Survey

The Johns Hopkins Institutional Review Board reviewed this study and determined that it qualified for an exemption under 45CFR 46.101 (b). A brief survey was administered to all OPOs in September 2012, and 100% participated. The OPOs reported whether and how often they used helicopters in transporting liver allografts and also whether and how often they used a central facility for organ recovery.[13] The OPOs also indicated at what distance they switched from driving to flying.

Identification of Transplant Centers, Recovery Hospitals, and Airports

Centers that performed at least 1 adult liver transplant (n = 111) and hospitals that recovered at least 1 deceased donor liver (n = 1284) in 2010 were identified with data from the Scientific Registry of Transplant Recipients (SRTR). The SRTR data system includes data on all donors, wait-listed candidates, and transplant recipients in the United States [submitted by the members of the Organ Procurement and Transplantation Network (OPTN)] and has been described elsewhere.[14] The Health Resources and Services Administration (US Department of Health and Human Services) provides oversight for the activities of the OPTN and SRTR contractors.

Public, private, and military-owned airports (n = 809) included in the National Plan of Integrated Airport Systems (NPIAS) database were considered for organ transportation. The NPIAS, maintained by the Federal Aviation Administration, represents all US airports with significance for air transportation.

Geolocation

From hospital names and zip codes, we determined the exact geographic coordinates (street addresses, latitudes, and longitudes) of transplant centers and recovery hospitals. We found the geographic coordinates of the airports by merging the NPIAS database[15] with the National Transportation Atlas Databases 2010 (Bureau of Transportation Statistics, Research and Innovative Technology Administration) in ArcGIS (Environmental Systems Research Institute).

Estimated Transport Time

Driving times between transplant centers and recovery hospitals and between hospitals and their nearest airports were estimated with Google Maps application programming interface scripts (Google, Mountain View, CA) written in Python 2.6.1 (Python Software Foundation).

We estimated that helicopters travel 140 miles/hour along a straight line from the recovery hospital to the transplant center, and we added an additional 15 minutes of transport time from the operating room to the helicopter pad and another 15 minutes of time from the helicopter pad to the receiving team. We approximated the time of fixed-wing flights with a linear fit [flight time = 0.002 $\times$ distance (miles) + 0.745 hours] based on scheduled commercial flight times of 42 jet and turboprop direct flights and airport-to-airport arc distances. The estimated time for transport by fixed-wing flight included the drive time from the donor hospital to the nearest airport, the estimated airport-to-airport flight time, and the drive time from the nearest airport to the transplant center.

Examples of car, helicopter, and fixed-wing aircraft routes between a donor hospital and a transplant center are shown in Figure 2.

Transport Mode Selection

Driving times, helicopter times, and fixed-wing flight times were estimated for all recovery hospital/transplant center pairs; on the basis of these estimates, 1 travel mode was selected for each donation pair (Fig. 1). For OPOs using helicopters, if the driving time was less than 1.5 hours, the modeled transport mode was driving; otherwise, the modeled transport mode was flying by helicopter if the distance was less than or equal to 100 miles or flying by fixed-wing aircraft if the distance was greater than 100 miles. For OPOs not using helicopters, if the driving time was less than 2 hours, then the modeled transport mode was driving; otherwise, the modeled transport mode was flying from the nearest airport. In the unusual case that the

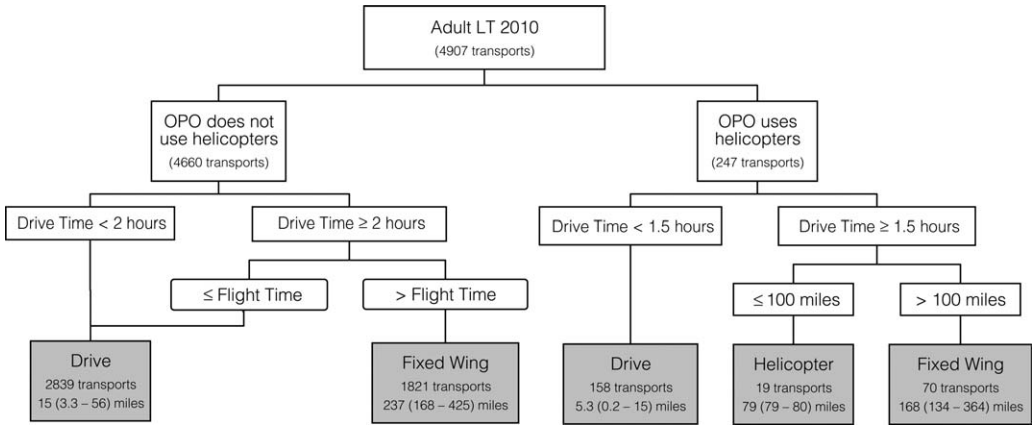

Figure 1. Transport mode selection (n = 4907 transports). The times required for transportation by car, helicopter, and airplane were estimated for adult liver transplants in 2010. Transports were assigned to 1 of the 3 transport modes shown in the flow chart. The number of livers estimated to have been transported by each mode is shown along with the median transport distances (IQRs are shown in parentheses).

flying time exceeded the driving time, driving was selected as the transport mode.

CIT and Distance

CITs for 4907 transplants that occurred in 2010 were reported through the SRTR. Transplants for recipients younger than 18 years and transplants with reported CITs longer than 16 hours were excluded. The arc distance between the recovery hospital and the transplant center was calculated with geolocated latitudes and longitudes.

Donor Quality

The donor risk index (DRI)[16] was calculated with the donor age, cause of death, race, type of procedure (partial/split), donor height, type of share (regional/national), and CIT. An adjusted DRI for donor-only characteristics was calculated, with all transports set as local with a CIT of 8 hours. Subgroup comparisons were evaluated for significance with *t* tests, and Bonferroni correction was used to account for multiple comparisons.

Statistical Analysis

After aggregating both the populations and the areas of the counties that composed the donor service area for each OPO, we calculated the population density for each OPO as the ratio of the population to the area. Median CITs, estimated transport times, distances, and estimated travel modes for locally allocated organs were tabulated by quartiles of population density.

Correlation coefficients between CITs, estimated transport times, and arc distances were calculated. The relationship between the CIT and the estimated transport time was explored in a linear regression model adjusted for the body mass index, procedure type (whole, split, or partial), and disposition (local, regional, or national). CITs, estimated transport times, and distances for locally allocated organs were summarized by quartiles of OPO population density. The statistical analysis was performed with R 3.0 (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

OPO Survey

Fifty-eight OPOs were surveyed with a 100% response rate. Forty-eight OPOs (83%) reported no use of helicopters for organ transport, 8 (14%) used helicopters infrequently, and 2 OPOs in Maryland and Virginia used helicopters frequently. Three OPOs used central organ recovery facilities, and 3 other OPOs were in the planning or testing phases of establishing central facilities. For the 3 OPOs that reported using a central organ recovery facility, the central facility handled 10%, 30%, and 85% of deceased donor liver recoveries, respectively.

Donor Quality

The DRI of nationally shared organs was higher than the DRI of locally or regionally shared organs, whereas no difference was found in the DRIs for local and regional sharing (*t* tests with Bonferroni correction, $P < 0.001$). The same was found with the model adjusted for the DRI with donor-only characteristics. Donors of nationally shared organs were significantly older than donors of both locally and regionally shared organs (*t* tests with Bonferroni correction, $P < 0.001$).

Transport Metrics

CITs were reported through the SRTR. Distances were calculated as the great circle distances between each recovery hospital and transplant center. Because the transport time and the transport mode are not reported to the OPTN or SRTR, reports herein of transport times and transport modes come from model estimates described previously.

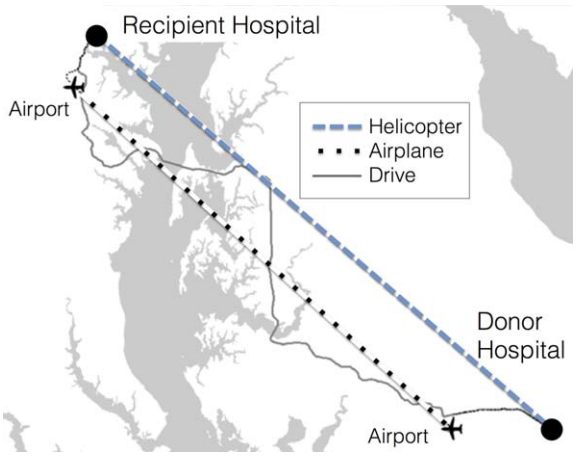

Figure 2. Examples of car, helicopter, and fixed-wing aircraft routes between a donor hospital and a transplant center. Transports by car were estimated on the basis of directions provided by Google Maps. Transports by helicopter were estimated on the basis of departures and arrivals from the hospital helipad (or the nearest helipad within 15 minutes). Transports by flight were estimated on the basis of flights between the nearest airports, with driving directions between the hospital and the airport provided by Google Maps. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

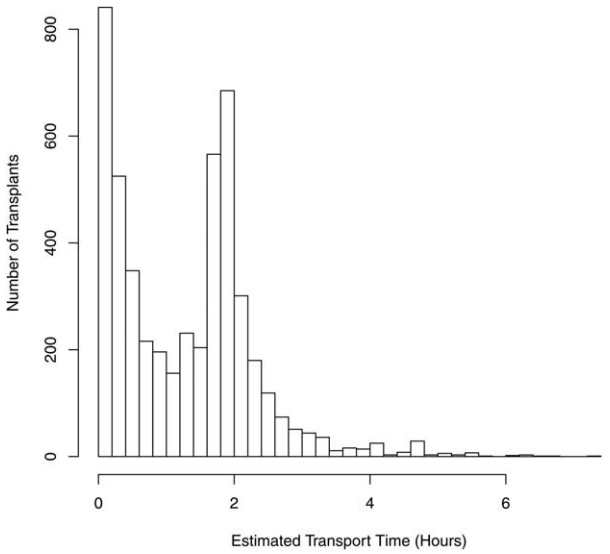

Figure 3. Distribution of estimated transport times: a histogram of all 2010 adult liver transplants (n = 4907).

Transport Metrics by Share Type

There were 4907 transplants studied: 3702 (75%) were allocated locally, 995 (20%) were allocated regionally, and 210 (4%) were allocated nationally. Overall, the estimated transport mode was driving for 2997 (61%), flying by helicopter for 19 (<1%), and flying by fixed-wing aircraft for 1891 (39%). The estimated transport time was distributed bimodally (Fig. 3).

The median distance was 65 miles [interquartile range (IQR) = 8.4-190 miles] overall, 29 miles (IQR = 4.5-96 miles) for local transports, 260 miles (IQR = 170-460 miles) for regional transports, and 790 miles (IQR = 480-1020 miles) for national transports. The median CIT was 6.2 hours (IQR = 5.0-8.0 hours) overall, 6.0 hours (IQR = 5.0-7.6) for local transports, 7.0 hours (IQR = 5.7-8.6 hours) for regional transports, and 9.0 hours (IQR = 7.4-10 hours) for national transports. The median estimated transport time was 1.4 hours (IQR = 0.33-1.9 hours) overall, 1.0 hour (IQR = 0.39-1.8 hours) for locally allocated organs, 2.0 hours (IQR = 1.8-2.4 hours) for regionally allocated organs, and 3.0 hours (IQR = 2.5-3.5 hours) for nationally allocated organs (Table 1). The estimated transport mode for the majority of within-OPO transports was driving (78%), but for the majority of regional transports, it was flying (90%).

Relationship Between CIT, Distance, and Estimated Transport Time

The relationship between the CIT and the estimated transport time was explored with multiple linear regression. After adjustments for the body mass index and the procedure type (whole, partial, or split), the intercept was 5.4 hours (95% confidence interval = 5.3-5.5 hours, $P < 0.001$); this was the estimated baseline CIT before any transport time was added (eg, for within-center donors). Added to this, each hour of transport time was associated with a CIT increase of 0.86 hours (95% confidence interval = 0.80-0.92 hours, $P < 0.001$). The adjusted model for the estimated transport time had an adjusted R^2 value of 14.7%. In a parallel model exploring the relationship between the CIT and the transport distance that was adjusted for the body mass index and the procedure type, each 100 miles of distance increased the CIT by 0.27 hours (95% confidence interval = 0.25-0.29 hours, $P < 0.001$). The adjusted model for distance had an adjusted R^2 value of 11.6%.

For organs with estimated transport times of 0 to 1 hours, the median CIT was 6.0 hours. The median CIT increased steadily with each hour increase in the transport time as shown in Fig. 4. The variance of the observed CIT decreased significantly for organs estimated to require 3 or more hours of transport time versus organs estimated to require less than 3 hours of transport time (F test, $P = 0.02$). The estimated travel time was not a simple function of distance because organs could be transported by car, helicopter, or fixed-wing aircraft (Fig. 5). Nearly all observed CITs were longer than the estimated transport time: 0.5% were longer by 1 hour or less, 3.2% were longer by 1 to 2 hours, 9.7% were longer by 2 to 3 hours, 17.3% were longer by 3 to 4 hours, and 19.6% were longer by 4 to 5 hours (the larger of each interval boundary was included only in the higher interval.). The remaining 49.7% of transports had a CIT at least 5 hours greater than the estimated transport time.

Transport Metrics for Local Transports by the OPO Population Density Quartile

The majority of the organs were allocated locally, but these locally allocated organs incurred different transport burdens according to the OPO population density (Table 2). Our model estimated that in the most

TABLE 1. Donor, Recipient, and Transport Characteristics by Share Type

	Local (n = 3702)	Regional (n = 995)	National (n = 210)	Overall (n = 4907)
Donor characteristics				
Age (years)*	43 (26-54)	42 (27-55)	53 (39-66)	43 (27-55)
Cause of death [n (%)]				
Anoxia	848 (22.9)	211 (21.2)	53 (25.2)	1112 (22.7)
Cardiovascular accident/stroke	1489 (40.2)	400 (40.2)	109 (51.9)	1998 (40.7)
Trauma	1270 (34.3)	351 (35.3)	40 (19.0)	1661 (33.8)
Other (not trauma)	95 (2.6)	33 (3.3)	8 (3.8)	136 (2.8)
Ethnicity [n (%)]				
African American	675 (18.2)	226 (22.7)	48 (22.9)	949 (19.3)
White	2438 (65.9)	641 (64.4)	143 (68.1)	3222 (65.7)
Other (not white)	589 (15.9)	128 (12.9)	19 (9.0)	736 (15.0)
Height (cm)*	173 (165-180)	170 (163-178)	170 (163-178)	173 (165-180)
DRI*†	1.93 (1.62-2.34)	2.15 (1.83-2.66)	2.97 (2.36-3.51)	2.01 (1.67-2.44)
DRI (donor-only characteristics)*‡	1.97 (1.65-2.38)	1.94 (1.66-2.41)	2.29 (1.86-2.75)	1.97 (1.66-2.41)
Recipient characteristics				
Age (years)*	56 (50-61)	56 (49-61)	58 (53-63)	56 (50-61)
Status 1A/1B [n (%)]	94 (2.5)	131 (13.2)	8 (3.8)	233 (4.7)
Allocation Model for End-Stage Liver Disease score*§	25 (22-31)	27 (22-34)	22 (17-25)	25 (22-31)
Partial/split [n (%)]	29 (0.8)	7 (0.7)	—	31 (0.6)
Transport characteristics				
Distance (miles)*	29 (4.5-96)	260 (170-460)	790 (480-1020)	65 (8.4-190)
CIT (hours)*	6.0 (5.0-7.6)	7.0 (5.7-8.6)	9.0 (7.4-10)	6.2 (5.0-8.0)
Estimated transport time (hours)*	1.0 (0.39-1.8)	2.0 (1.8-2.4)	3.0 (2.5-3.5)	1.4 (0.33-1.9)
Estimated transports by car [n (%)]	2898 (78.3)	97 (9.7)	2 (1.0)	2997 (61.1)

*The data are presented as medians and IQRs.
†Calculated.
‡All transports were set as local with a CIT of 8 hours.
§The Model for End-Stage Liver Disease score can range from 6 to 40.

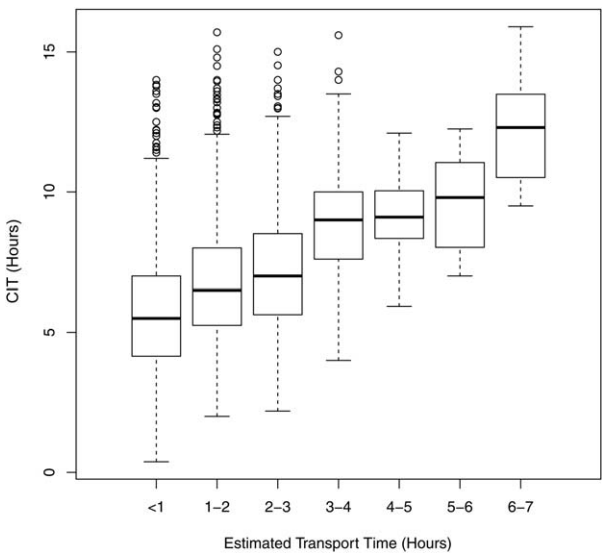

Figure 4. Distribution of CITs by categories of estimated transport times for 2010 adult liver transplants (n = 4907). (The larger of each interval boundary was included only in the higher interval.)

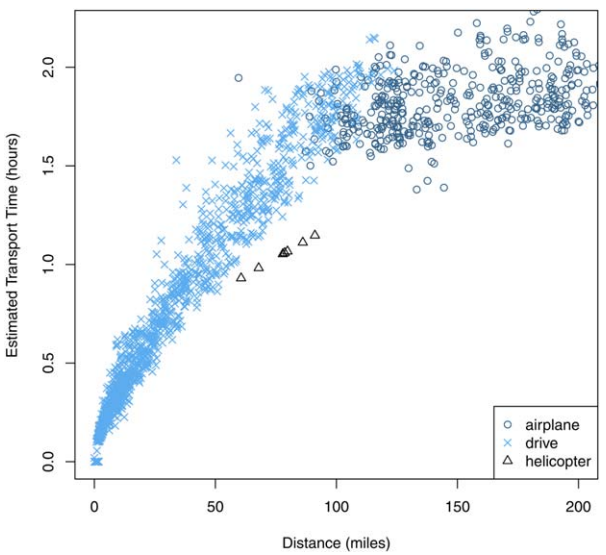

Figure 5. Relationship of the estimated transport time and the transport distance. The estimated transport modes are indicated by shapes as shown. Transports with distances less than 200 miles are shown (3781/4907 transports). The median distance was 65 miles (IQR = 8.4-190 miles). The median estimated transport time was 1.4 hours (IQR = 0.33-1.9 hours). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

densely populated OPOs, locally allocated organs were almost never transported by plane (3%), but nationwide, approximately 22% of locally allocated organs were transported by plane or helicopter. The

TABLE 2. Locally Allocated Transplants by OPO Quartiles of Population Density

	Quartile of Population Density				
	<77 Persons/Mile^2	77-157 Persons/Mile^2	157-341 Persons/Mile^2	>341 Persons/Mile^2	All Local
Mean population per OPO (millions)	4.14	5.54	5.51	6.05	5.31
Mean population density per OPO (persons/mile^2)	39.7	117	217	790	292
Mean transplant centers per OPO*	1.6 (1-3)	2.3 (1-5)	2.4 (1-5)	2.7 (1-8)	2.2 (1-8)
Mean transplants per OPO*	48 (20-82)	87 (6-164)	84 (14-147)	82 (15-190)	75 (6-190)
Distance (miles)†	33 (4.9-110)	67 (4.3-170)	34 (4.7-98)	15 (4.8-46)	28 (4.7-96)
CIT (hours)†	6.4 (5.0-8.2)	6.0 (4.3-7.5)	5.8 (4.7-7.0)	6.0 (4.8-7.4)	6.0 (4.6-7.5)
Estimated transport time (hours)†	0.80 (0.20-1.7)	1.4 (0.22-1.9)	0.85 (0.25-1.7)	0.50 (0.24-1.0)	0.71 (0.22-1.7)
Estimated transports by car [(%)]	(75)	(65)	(76)	(97)	(78)

*Ranges are presented in parentheses.
†The data are presented as medians and IQRs.

median CIT for locally allocated organs was approximately 6 hours for OPOs in all quartiles of population density. In a univariate linear regression model, the CIT was not significantly related to the population density. However, the transport time correlated with the population density, with each increase of 1000 persons/mile^2 in the population density decreasing the transport time by a mean of 14 minutes (95% confidence interval = 11-17 minutes, $P < 0.001$).

DISCUSSION

In this national study of the transport burden associated with liver transplants, we found that the estimated transport time explained only a small fraction of the observed variation in the CIT. Although each hour of transport time extended the CIT by approximately 0.86 hours (95% confidence interval = 0.80-0.92 hours), the baseline CIT without any transportation was 5.4 hours. Regional sharing was associated with an extra hour of estimated transport time, but this meant that the CIT increased only nominally from 6.0 to 7.0 hours. The magnitude of this difference in the median CITs for local and regional share types was similar to the magnitude of the differences in the median CITs for purely local-share livers among OPOs in different quartiles of population density (5.8-6.4 hours). The estimated transport time for livers composed only 21% of the CIT and explained only 14.7% of the variance of the CIT.

The range of the horizontal axis in Fig. 5 was chosen to highlight the range of travel distances over which broader sharing will primarily shift allocation. For instance, regionally allocated organs were transported a median of 260 miles, which is roughly a factor of 9 greater than the median of 29 miles for locally allocated organs. However, the median transport time for regionally allocated organs was only a factor of 2 greater than the median for locally allocated organs (2.0 versus 1.0 hours). Our model predicted that with broader sharing, more organs would be transported by plane, and fewer would be transported by car. In other words, changing the travel mode moderated the impact of broader sharing on transport times.

Previous studies of the tradeoffs involved in broader sharing have used the transport distance as the metric for the organ transport burden.[3] However, it has been noted that the distance is not strongly correlated with the CIT.[12] In this study, we also found that the transport time is likewise not strongly correlated with the CIT and explains <15% of the variance in the CIT.

Some limitations of our study should be acknowledged. Many centers appear to have reported CITs to the nearest hour because CITs cluster at whole hours. Although the CIT could have been treated with a categorical analysis, we treated the CIT as a continuous variable. Our estimated transport times neglected road conditions, road closures, poor weather, and traffic. However, organs might have been sped through traffic with an ambulance transport. Also, we assumed that chartered flights were immediately available and were unaffected by the direction of flight (east to west versus west to east) or weather patterns. The difference in

flight times depending on direction was significant only for longer flights, and fewer than 3% of transports were longer than 1000 miles. Finally, we neglected the transport-related delay of packaging the organ for transport and unpacking it when it arrived. Because these inaccuracies missed factors that might have extended transport times, the estimated transport times provided in this study might represent a lower bound of transport times. Also, the historical data examined here cannot reflect potential changes in center or OPO practices that might affect transport times.

An increased transport time along with its impact on CIT is only one of the possible concerns about broader sharing of liver allografts. One related issue is whether increased travel might increase costs,[17] but we do not address this concern here except to describe the distribution of likely transport modes. The cost impact of broader sharing goes beyond the cost of transporting organs, so we defer this discussion to an upcoming article that will also consider costs of pretransplant and posttransplant care. Also, longer distances to procurements might burden transplant physicians with both increased work hours and increased risks when they are flying in helicopters or chartered planes.[18] OPOs might establish dedicated organ recovery teams, establish central organ recovery facilities,[13] or use local recovery teams to alleviate these burdens. Lynch et al.[19] investigated alternate recovery procedures for Michigan organ procurements, including donor transport and the use of local recovery teams, to reduce the risks of organ recovery travel.

In conclusion, an increased transport burden under broader sharing would only slightly lengthen CITs for liver allografts. With broader sharing, more organs would be allocated at a regional level, and fewer would be allocated at the local level, in comparison with the present system. Our estimates of liver transport times are approximately 2 hours for regional organs and 1 hour for local organs. We found greater variation than this in CITs among transplants with similar transport times; the IQR of CITs for transplants that traveled less than 1 hour was 4 to 7 hours. The median CIT was longer than 6 hours, so a 1-hour increase in the CIT would be at most marginally relevant clinically. Each hour of transport time extended the CIT by less than 1 hour, and this shows that transplant centers can and do buffer transport times by executing some transplant preparations in parallel with the organ transport. Because transport times are the only component of the CIT directly affected by organ distribution and offer priority, analyzing how an allocation policy affects the CIT requires an understanding of how it affects transport times.

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