Mathematical Methods to Reduce Geographic Disparities in Organ Availability

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Organ availability

- The liver allocation system prioritizes candidates by Status 1 and then in decreasing order of MELD/PELD
- Transport time limitations and geographic boundaries prevent some organs from reaching the highest-priority candidates
  - If each liver were teleported instantaneously to the highest-priority candidate anywhere in the country, that allocation system would be one where geography has no influence
Balancing supply and demand

- Geographic disparities in organ availability are caused by uneven distribution of liver disease, listings, and eligible deaths
- Eligible deaths vary 4-fold among DSAs
- Listings for liver transplant vary 14-fold among DSAs
- Deaths due to liver disease vary 19-fold among DSAs
Geographic disparities in supply and demand have consequences for candidates

- Liver transplant candidates have 20% lower risk of death and 74% higher chance of being transplanted if they transferred from their initial listing OPO to a different one
  [Dzebisashvili et al. 2013]
  - Transferring to a different OPO is highly correlated with socioeconomic status
- Geographic disparities explain the observed disparities between liver transplant rates for Caucasians and Hispanics, because these populations live in different places
  [Volk et al. 2009]
- Median MELD at transplant varies by 10 points and 90-day survival for MELD 38 varies 4-fold among OPOs
OPO performance

- OPO performance metrics vary by less than 2-fold across DSAs
- Geographic disparities are not correlated with organ procurement organization performance
- If all OPOs had 100% conversion rate, huge differences in supply and demand would remain
- OPO performance improvements can increase transplants but can not resolve geographic imbalance in supply and demand
Liver committee’s efforts to redesign allocation

- June 2009: Evaluation of Allocation Systems using Regional Sharing or Concentric Circle Sharing above various MELD/PELD Thresholds
- February 2010: Data request models multiple allocation systems
- June 2010: LSAM evaluation of organ distance traveled for 27 proposed allocation systems
- October 2010: Simulated waiting list deaths by MELD/PELD for various allocation systems
- March 2011: Analysis of Region 8 Alternative Allocation System
Percent Shared vs. Decrease in Total Deaths

- Percent shared outside of local
- Decrease in deaths
Broader sharing not sufficient to reduce disparity -- actually worse with existing regions

- Fully regional sharing is not predicted to reduce disparity in MELD at transplant; paradoxically, fully regional sharing increases disparity [Gentry et al. Am J Trans 2013]
- Share-35 is a partial step toward regional sharing in the existing regions. Actual data from Share-35 shows increase in disparity of median MELD at transplant.
Percent Shared vs. Decrease in Total Deaths

Decrease in deaths

Percent shared outside of local
Geographic disparity metrics

• Total number of waitlist deaths is not a disparity metric. While reducing waitlist death is important, reducing overall waitlist death might not reduce disparity, as we have seen.
• Geographic disparity refers to the extent to which accidents of geography determine whether a candidate will have access to a liver transplant.
• The primary aim of redistricting is not to reduce total waitlist deaths, it is to reduce disparity in availability of organs to candidates waiting in different parts of the country. This represents a change of focus for the liver committee’s allocation efforts. [OPTN Board Resolution 11/2012]
Geographic disparity metrics

- Variance in median MELD at transplant: The OPTN’s liver committee was tasked by the Board to choose a metric of geographic disparity in liver allocation, and this was the metric it chose. (March 2013)
- Supply and demand: Our redistricting optimization minimizes the absolute difference between supply (livers transplanted in 2010) and demand (high-priority incident listings in 2010) in each district
  - Changes to MELD exception points have limited impact
- Other geographic disparity metrics: variance in waitlist death, variance in raw transplant rate, ad infinitum.
Liver committee alternatives considered

- The liver committee decided in 2013, after examining many alternatives, to undertake an extensive study of redistricting
  - Optimization is a quantitative alternative to ad hoc adjustments, and is transparent, parsimonious, understandable to the entire transplant community
  - Redistricting retains existing DSA boundaries and only reorganizes at the regional level
  - Plan: use optimization to design the district maps, and then use simulation modeling (LSAM) to perform detailed analysis of redistricting impacts – variance of median transplant MELD, deaths prevented, transport, cost.
Liver Committee’s design constraints

• Districts should respect the existing DSA boundaries and should be contiguous.*
• The number of districts should be at least 4 and no more than 8.
• The maximum median transplant-volume-weighted transport time between DSAs is 3 hours.
• Each district must contain at least 6 transplant centers.
• Districts should be designed to minimize geographic disparity, and must not increase waitlist death.
\[ I = \mathcal{K} \quad \{1,2,3, \ldots , 57\} \text{ DSAs} \]

\[ w_{ik} = 1 \text{ if DSA } i \text{ is in the district with center at DSA } k, \text{ and } 0 \text{ if not} \]

\[ Y_k = 1 \text{ if DSA } k \text{ is selected as the center of a district, and } 0 \text{ if not} \]

\[ c_k = \text{active liver transplant centers in DSA } k \]

\[ \delta_{ij} = \text{volume-weighted distance from DSA } i \text{ to } j \]

\[ \tau_{ij} = \text{volume-weighted transport time between DSAs } i \text{ and } j \]

\[ d_k = \text{livers available in DSA } k \]

\[ p_k = \text{number of livers that should go to DSA } k \text{ if geography were not a factor in allocation} \]

[Gentry, Chow, Massie, Segev. To appear, Interfaces, 2015.]
Objective: minimize geographic disparity in liver availability by minimizing the number of misdirected livers.
Each DSA is assigned to one district
[Retain DSA boundaries]

If a DSA $k$ is assigned as the center of the
district containing DSA $i$,
$Y_k$ should be 1

[Number of districts is between 4 and 8]
Number of districts is $N$
[Number of districts between 4 and 8]

Require at least $\bar{h}$ transplant centers in each district
[Each district has 6 or more transplant centers]
\[ W_{ik} \tau_{ik} \leq \bar{\tau} \quad \text{for all } i \in \mathcal{I} \text{ and } k \in \mathcal{K} \]

Maximum volume-weighted transport time from each district to its district center is \( \bar{\tau} \) [Transport time less than 3 hours]
\[ \sum_{k \in K} \alpha_{ijk} W_{ik} \leq 1 - Y_j \] for all \( i \in \mathcal{I} \) and \( j \in \mathcal{K} \)

\( \delta_{ij} \) = volume-weighted distance from DSA \( i \) to \( j \)

\( \alpha_{ijk} = \begin{cases} 1 & \text{if } \delta_{ik} > \delta_{ij}, \ 0 & \text{if not} \end{cases} \)

Every DSA is assigned to its nearest district center

(Daskin, Service Science, 2010)

[Districts should be contiguous]
Mathematical optimization for redistricting

- The only data used for designing the sharing districts are the # donors per OPO and # new liver transplant candidates at various MELDs (supply/demand per OPO)
  - Maps under consideration were designed using 2010 data
  - These counts are stable: maps designed using 2006 data also significantly reduced geographic disparity and reduced waiting list and total deaths when applied to 2010 simulations (Gentry et al., AJT 2013)
  - These counts are broadly stable even since Share-35
Optimized 8 District Map
Optimized 4 District Map
Summary: Optimized redistricting

- Disparity can only be resolved by sharing among DSAs; optimized redistricting defines best sharing groups
- The mathematical optimization that designed the redistricting alternatives shown is transparent and parsimonious, representing exactly the limits of feasibility in allocation as selected by the liver committee
- Redistricting design considers only geography, supply, demand
- Under redistricting, livers flow from areas with greater-than-expected eligible deaths and fewer-than-expected listings toward areas with fewer-than-expected eligible deaths and greater-than-expected listings

Summary: Reducing Geographic Disparity

• Improvements in OPO performance, while certainly welcomed, can not solve the geographic imbalance between supply and demand
  ▪ OPO performance varies over a much smaller range than does demand and supply, and OPO performance is not correlated with metrics of organ supply and demand across the country
• Full sharing in optimized districts is predicted by the Liver Simulated Allocation Model to greatly reduce geographic disparity and reduce waitlist deaths and total deaths
  ▪ LSAM played no role in designing the maps under consideration
Thank You

Contact the Scientific Registry of Transplant Recipients:

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Concentric Circle Modeling Results

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Alternative to redistricting

- Instead of sharing within optimized sharing districts, livers could be shared to all transplant centers within a fixed distance of the donor hospital
  - Note that this is a very different allocation rule than the proximity points method discussed earlier today
- The OPTN’s liver committee has studied many variations of concentric circle allocation policies at different times over the past several years
Percent Shared vs. Decrease in Total Deaths

Percent shared outside of local

Decrease in deaths
Comparing Concentric Circles to redistricting

• Responding to public comment, the Committee asked us to simulate concentric circle systems that would be similar in transport impacts to the 4 district and 8 district concepts.
  ▪ We present results using 400 mile circles, which are comparable to the 8 district concept in terms of transport impacts, and using 700 mile circles, which are comparable to the 4 district concept.
  ▪ Concentric circle designs require longer transport distances and more flying, and do not reduce total deaths or geographic disparity as effectively as redistricting.
Concentric circle allocation rules tested

- We used only 2 geographic levels of allocation: inside a circle of radius 400 miles (700 miles) and outside that circle.
- Livers are offered in this order:
  - Status 1 in circle
  - Status 1 out of circle
  - MELD/PELD >15 in circle
  - MELD/PELD >15 out of circle
  - MELD/PELD <15 in circle
  - MELD/PELD <15 out of circle
## Concentric Circles: Transport and Sharing

<table>
<thead>
<tr>
<th></th>
<th>Local</th>
<th>Regional</th>
<th>Median Transport Time</th>
<th>Median distance (miles)</th>
<th>Flying</th>
<th>Variance Median Transplant MELD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 Districts</strong></td>
<td>26.9%</td>
<td>69.6%</td>
<td>1.9</td>
<td>245</td>
<td>74.2%</td>
<td>3.61</td>
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<tr>
<td><strong>Circles 400</strong></td>
<td>23.7%</td>
<td>29.0%</td>
<td>1.9</td>
<td>261</td>
<td>77.4%</td>
<td>4.12</td>
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<tr>
<td><strong>4 Districts</strong></td>
<td>16.4%</td>
<td>81.7%</td>
<td>2.2</td>
<td>419</td>
<td>84.3%</td>
<td>2.60</td>
</tr>
<tr>
<td><strong>Circles 700</strong></td>
<td>14.6%</td>
<td>22.0%</td>
<td>2.2</td>
<td>440</td>
<td>85.6%</td>
<td>2.60</td>
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</tbody>
</table>
## Concentric Circles: Disparity and Deaths

<table>
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<tr>
<th></th>
<th>Waitlist Deaths Prevented</th>
<th>Variance of Median Transplant MELD</th>
</tr>
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<td>59</td>
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<tr>
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<td>2.60</td>
</tr>
</tbody>
</table>
Summary

• The OPTN’s liver committee has studied a wide range of policy changes to reduce geographic disparity in liver allocation.
• Concentric circle allocation, if the circles are large enough, might significantly reduce geographic disparity.
• Simulations predict that concentric circle allocation with slightly larger travel impacts than redistricting would yield a slightly smaller reduction in waitlist deaths and geographic disparity than redistricting.
• With these results, the liver committee chose to pursue redistricting instead of concentric circle allocation (March 2013).
Thank You

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