Fairness, Efficiency and Flexibility in Organ Allocation for Kidney Transplantation

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Background

Treatments for end-stage renal disease
- Dialysis: 12 hours/week
- Transplantation (living or deceased donor): improves quality of life, resume regular life activities

2009
- 33,671 new additions
- 16,829 transplantations
- 10,442 transplantations from deceased donors
- 6,384 transplantations from living donors
Background

National Organ Transplant Act (NOTA), 1984
- Donor organs are national resources
- Their sale is strictly prohibited
- Allocation based on priority method

Organ Procurement and Transplantation Network (OPTN), 1984
- Maintain national registry for organ matching

Organ Procurement Organizations (OPO) – non-profit
- Evaluate, procure, and allocate the donated organs
Background

Challenges

- Fairness constraints: equal access to organs, e.g. lower bound on the organs allocated to a particular population (blood type O)
- Efficiency: number of quality adjusted life years should be high
- Prioritization criteria: based on the characteristics of the patients and organs, not discriminatory
- Simplicity: patients should understand the allocation mechanism and the probability of getting an organ
- Implementation: balance between prioritization criteria, while satisfying fairness constraints and efficiency
Organ Distribution Process

1. Organ Procured from an OPO
2. OPTN generates list of medically compatible patients, based on patient and organ physiological characteristics
3. OPO uses priority method to rank the patients (organ is preserved up to 36-48 hours, so priority mostly given to local patients)
4. A patient that receives an organ offer has to decide whether to accept or not within limited time
5. If patient doesn’t accept, the next patient according to the priority received the offer, etc.
6. After 36-48 hours, if no patient accepted the offer, the organ is discarded
Point System or Scoring rule

Kidney Allocation Score (KAS)

\[ KAS(p, o) = \sum_j w_j f_{j,(p,o)} \]
- \( f_{j,(p,o)} \): jth score component given patient p and organ o
- \( w_j \): jth score weight
Criteria of score components

- Tissue matching between patient p and organ o
- Age of patient p and organ o
- Wait time of patient p – years registered on waitlist
- Dialysis time of patient p
- Blood type of patient and donor
- Expected post transplant survival of patient p receiving organ o
- Expected waitlist survival of patient p
- Quality-adjusted life years gained of patient p when receiving organ o (compared to dialysis)
- Donor profile index indicating the quality of the organ – [0,1]: 0 highest quality
- Calculated panel reactive antibody indicating the sensitization of patient – [0,100]: 0 lowest level
Example

- The Kidney Transplantation Committee considered more than 40 scoring rules
- Simulations to decide on weights and evaluate performance

Dominant proposal (Is this the best we can do?):

\[ KAS(p, o) = 0.8LYFT(p, o) \times (1 - DPI(o)) + 0.8DT(p) \times DPI(o) + 0.2DT(p) + 0.04CPRA(p) \]

- If the organ is of good quality (DPI close to 0), then more weight is given to the life years from transplant
- If the quality is low (DPI close to 1), then more emphasis is given on the dialysis duration

For DPI(o)=0.55
- 0.8*(1-0.55)=0.36 points for every year expected to gain from transplantation
- 0.8*0.55+0.2=0.64 points for every additional year the patient has been on dialysis
- 0.04 points for every point on the calculated panel reactive antibody score of the patient
Methodology

Input
- Historical data
- Pre-specified score components
- Fairness constraints

Output
- Score weights

Goal
- Maximize efficiency of policy (life years from transplant gains)
Definitions

\[ C = \{(p, o): \text{patient } p \text{ is eligible to receive } o\} \]

- Patient registered at the waiting list and medically compatible

\[ \forall (p, o) \in C: x_{(p, o)} = 1, \text{ if the organ is assigned to patient, } 0 \text{ otherwise} \]
Step 1

Assumptions:
◦ Life years for all eligible pairs is known
◦ Patients accept all organs offered to them

x fractional: probability of assigning organ o to patient p in a randomized policy

Solve LP to obtain dual values y

\[
\text{maximize } \sum_{(p,o) \in C} \text{LYFT}(p, o)x_{(p,o)} \\
\text{subject to } \sum_{o: (p,o) \in C} x_{(p,o)} \leq 1, \quad \forall p \\
\sum_{p: (p,o) \in C} x_{(p,o)} \leq 1, \quad \forall o \\
Ax \leq b \\
x \geq 0.
\]
Step 2

maximize \( \sum_{(p,o) \in C} \text{LYFT}(p,o)x_{(p,o)} - y^T Ax + y^T b \)

subject to \( \sum_{o:(p,o) \in C} x_{(p,o)} \leq 1, \forall p \)

\( \sum_{p:(p,o) \in C} x_{(p,o)} \leq 1, \forall o \)

\( x \geq 0. \)

- Matching problem
- The objective can be written as \( c^T x + y^T b \), where \( c_{(p,o)} = \text{LYFT}(p,o) - (y^T A)_{(p,o)} \) \( \forall (p,o) \in C \)
Step 3

\[
\text{minimize } \sum_{(p,o) \in C} \left( c_{(p,o)} - w_0 - \sum_{j=1}^{n} w_j f_j(p,o) \right)^2 \\
\text{subject to } w \in S,
\]

- Set \( S \): clinical and ethical requirements
- Use linear regression to find the weights: \( c_{(p,o)} = w_0 + w_1 f_1(p,o) + \cdots + w_n f_n(p,o) \)
Case Study 1

- Score components: 4 most significant
- Fairness constraints: same as the dominant proposal (percentage distributions of the different groups)

\[
KAS(p, o) = \text{LYFT}(p, o) + g(DT(p)) + 0.08 \text{CPRA}(p) + 0.5 \mathbb{I}(\text{AGE}(p) \geq 50),
\]

\[
g(DT) = \begin{cases} 
0.65 \text{DT}, & 0 \leq \text{DT} \leq 5, \\
\text{DT} - 1.75, & 5 \leq \text{DT} \leq 10, \\
0.2 \text{DT} + 6.25, & 10 \leq \text{DT}.
\end{cases}
\]

- 7.8% increase in life year gains compared to the dominant proposal
Case Study 2

- Score components: similar to Case Study 1
- Fairness constraints: different age distribution requirements (higher for groups 50-65, 65+)

\[
\text{KAS}(p, o) = \text{LYFT}(p, o) + h(DT(p)) + 0.12 \text{CPRA}(p) + 2.5 \mathbf{1}(\text{AGE}(p) \geq 50) + \mathbf{1}(\text{AGE}(p) \geq 65),
\]

\[
h(DT) = \begin{cases} 
0.75 DT, & 0 \leq DT \leq 5, \\
DT - 1.25, & 5 \leq DT \leq 10, \\
0.5 DT + 3.75, & 10 \leq DT. 
\end{cases}
\]

- Similar life year gains to dominant policy
Case Study 3

- Sensitivity Analysis
- Add slack parameter $s$ to the fairness constraints

- Solid: dialysis time
- Dashed: sensitization

- Up to 30% increase in gains