Welfare and Equity Consequences of Transplant Organ Allocation Policies

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Organ Transplantation

- Transplantation is the preferred treatment for the failure of human organs including Kidney, Lung, Liver, Heart, and Pancreas.
- Traditional monetized markets for human organs are mostly disapproved throughout the world:
  - World Health Organization condemns monetary transactions for organs.
  - In the US, the 1984 National Organ Transplant Act (NOTA) makes paying for an organ for transplantation a felony:

  "It shall be unlawful for any person to knowingly acquire, receive or otherwise transfer any human organ for valuable consideration for use in human transplantation."
Organ Transplantation

- Hence donation is the only viable source of organs.
- There is a world-wide shortage for transplant organs.
- Donation is governed through different technologies around the world for different organs.
  - Deceased Donation
  - Live Donation
  - Live-Donor Organ Exchange (possible when live donation is feasible)
Medical Constraint: ABO Blood Type Compatibility

- There are four blood types: A, B, AB and O.
- Blood-type donation compatibility is partial order $\triangleright$:
  
  $O \triangleright A, B \triangleright AB.$

In the absence of other complications:
- Type O organs can be transplanted into any patient;
- type A organs can be transplanted into type A or type AB patients;
- type B organs can be transplanted into type B or type AB patients;
- type AB organs can only be transplanted into type AB patients.

- Type O patients are disadvantaged because of this “natural injustice”.


Medical Constraint: Tissue Type Compatibility

- Tissue type or Human Leukocyte Antigen (HLA) type: Combination of several pairs of antigens on Chromosome 6.

For kidney donation, HLA proteins A, B, and DR are especially important.

Prior to transplantation, the potential recipient is tested for the presence of preformed antibodies against donor HLA. If the level of antibodies is above a threshold (positive crossmatch), then the transplant cannot be carried out.
Donation Technologies

- **Deceased Donation**: Centralized priority allocation. Waiting time is always prioritized, however to different degrees for different organs. For kidneys, essentially allocated as a first-in–first-out (FIFO) queue in the US.

- **Live Donation**: Mostly loved ones of the patient come forward, and if one of them is compatible, the donation is carried out.

- **Live-Donor Organ Exchange**: If the live donor is incompatible with his intended recipient, his organ is exchanged with an organ from a similar patient-donor pair to find a compatible organ for both patients.
**Institutional Constraint:** All transplants in one closed exchange has to be done *simultaneously* to prevent voluntary or involuntary reneging of a donor whose patient already received a transplant.
The emerging field of Market Design applies insights and tools from economic theory to solve real-life resource allocation problems.

In early 2000s, we observed that the two main types of kidney exchanges conducted in the U.S. correspond to the most basic forms of exchanges in house allocation model of Abdulkadiroğlu & Sönmez (1999).

Building on the existing practices in kidney transplantation, Roth, Sönmez, & Ünver (2004, 2005, 2007) analyzed how an efficient and incentive-compatible system of exchanges might be organized, and what its welfare implications might be.

The methodology and techniques advocated in this research program provided the backbone of several kidney exchange programs in the U.S. and the rest of the world.
Even in the absence of more elaborate exchanges, merely organizing the paired-exchanges may result in increased efficiency.
Optimization is Important

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Additional live-donor transplants may be possible through three-way, four-way, . . . , exchanges.

Three-way exchange is especially important!
Simultaneity is not critical when a kidney-chain starts with a donation from an altruistic donor. **Hence large kidney-chains can be utilized!**
Typically a blood-type compatible pair participates in kidney exchange only when the donor is tissue-type incompatible with the intended recipient.

In contrast, a blood-type incompatible pair is automatically referred to a kidney exchange program.

Hence there are many more blood-type incompatible pairs in kidney exchange programs than blood-type compatible pairs!

\[ \# \text{ O Patients} \gg \# \text{ O Donors} \]

This disparity can be minimized if compatible pairs can also be included in kidney exchange.
There are “Economies of Scale” in Kidney Exchange

- Larger kidney exchange programs (such as national programs) provide a more efficient system than several smaller ones.
- Larger programs are especially beneficial for hard to match patients such as those who are tissue type incompatible with a large fraction of donor population (aka highly sensitized patients).
Current Stage of Kidney Exchange

Number of Kidney Exchanges

- A handful of kidney exchanges in the U.S. prior to 2004, increased to 93 in 2006 and to 553 in 2010.
- Currently kidney exchanges in the U.S. account for about 10% of all live donor kidney transplants.
Progress of Kidney Exchange in the Last Decade

1. **Organization and Optimization of Kidney Exchange**
   Roth, Sönmez & Ünver (RSÜ) 2004, 2005a, 2007

2. **Utilizing Gains from Larger Exchanges**
   RSÜ 2007, Saidman et al. 2006

3. **Integration of Altruistic Donors via Kidney Chains**
   RSÜ et al. 2007, Rees et al. 2009

4. **Inclusion of Compatible Pairs for Increased Efficiency**

5. **Higher Efficiency via Larger Kidney Exchange Programs**
   RSÜ 2004, 2005b
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To what extent these insights have been utilized so far?
A Life-Saving Option

The New England Program for Kidney Exchange offers new life-saving options to those seeking a kidney transplant, but whose potential living donor is not a good biological "match" due to either blood type incompatibility or cross-match incompatibility. This option is known as kidney exchange, kidney paired donation, or kidney swap.

NEPKE uses a computer program to find cases where the donor in an incompatible pair can be matched to a recipient in another pair. By exchanging donors, a compatible match for both recipients may be found. You can learn more about the program [HERE](http://www.nepke.org/) and read our newsletter [HERE](http://www.nepke.org/).

NEPKE can also find potential kidney recipients for those generous people who seek to become non-directed living donors (otherwise known as Good Samaritan Donors or Altruistic Donors). Information about that process is available [HERE](http://www.nepke.org/).

NEWS:

Transplant centers are being provided with brochures to provide information about this program to their kidney patients.

More News


eouncement Chains.

Alliance for Paired Donation – Saving Lives through Kidney Paired Donation

More than 84,000 people in America are waiting for a kidney transplant; sadly, about 12 of these patients die every day because there aren’t enough donors. Many kidney patients have someone who is willing to donate, but because of immune system or blood type incompatibilities, they are not able to give a kidney to their loved one.

The Alliance for Paired Donation can help. Kidney paired donation matches one incompatible donor/recipient pair to another pair in the same situation, so that the donor of the first pair gives to the recipient of the second, and vice versa. In other words, the two pairs swap kidneys.

APD has also pioneered a new way of using altruistic, or good Samaritan, donors, so that the transplants no longer have to be performed simultaneously. Non-simultaneous Extended Altruistic Donor Chains (NEAD Chains) allow donors to "pay it forward" after their loved one receives a transplant.

To learn more about the program, visit [www.theNEAD.com](http://www.theNEAD.com).

View the Article

Click Here to View Video

Click Here to View Video

Paying it Forward:

Saving Lives Through Paired Kidney Exchange

Watch the Video

Thank you for caring enough to get involved.

If you find our efforts worth supporting, would you consider making a donation today?

Alliance for Paired Donation, Inc.

3661 Briarfield Boulevard, Suite 105, Maumee, Ohio 43537

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Practical Progress of Kidney Exchange in the Last Decade

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Utilizing Gains From Larger Exchanges

Incredible 3-way kidney swap

Mike and Susan Williams of Bantim

Massive transplant effort pairs 13 kidneys to 13 patients

By Val Willingham, CNN
December 14, 2009 8:49 a.m. EST

Washington (CNN) -- Renee Patterson's most precious present this Christmas won't be under her tree, and it didn't come from a store. This holiday, she said, she got her life back.

The Upper Marlboro, Maryland, resident learned nine years ago she had kidney disease. One of her kidneys began to deteriorate, and she had to begin regular dialysis. Because she couldn't find a family match, her former colleague and friend, Michael Williams, offered to donate one of his kidneys. Problem was, Patterson and Williams didn't match either. But Patterson's doctor suggested they look into the paired kidney donation program at Washington Hospital Center in Washington, D.C.

She became part of a massive mix-and-match transplant effort in the U.S., involving more than a dozen kidneys.
Practical Progress of Kidney Exchange in the Last Decade

1. Organization & Optimization of Kidney Exchange ✓
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3. Integration of Altruistic Donors via Kidney Chains
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60 Lives, 30 Kidneys, All Linked

FROM START TO FINISH A donation by a Good Samaritan, Rick Ruzzamenti, upper left, set in motion a 60-person chain of transplants that ended with a kidney for Donald C. Terry Jr., bottom right.
Integration of Altruistic Donors via Kidney Chains

Practical Progress of Kidney Exchange in the Last Decade

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Very limited implementation of this idea.

Limited or no incentives for compatible pairs to participate in kidney exchange.
Practical Progress of Kidney Exchange in the Last Decade

- Organization & Optimization of Kidney Exchange ✓
- Utilizing Gains from Larger Exchanges ✓
- Integration of Altruistic Donors via Kidney Chains ✓
- Inclusion of Compatible Pairs for Increased Efficiency 😞
- Higher Efficiency via Larger Kidney Exchange Programs
When RSÜ initially helped found New England Program for Kidney Exchange, it was unclear whether kidney exchange is in violation of NOTA.

In particular, it was unclear whether kidney exchange was considered to involve transfer of a human organ for valuable consideration.

In Dec 2007, an amendment of NOTA has passed in the Senate, clarifying that kidney exchange is legal and removing the barrier from establishment of national kidney exchange in the US.

**Amendment of the National Organ Transplant Act**

The preceding sentence does not apply with respect to human organ paired donation.

The term ‘human organ paired donation’ means the donation and receipt of human organs under the following circumstances:

(A) An individual (referred to in this paragraph as the ‘first donor’) desires to make a living donation of a human organ specifically to a particular patient (referred to in this paragraph as the ‘first patient’), but such donor is biologically incompatible as a donor for such patient.

(B) A second individual (referred to in this paragraph as the ‘second donor’) desires to make a living donation of a human organ specifically to a second particular patient (referred to in this paragraph as the ‘second patient’), but such donor is biologically incompatible as a donor for such patient.

(C) Subject to subparagraph (D), the first donor is biologically compatible as a donor of a human organ for the second patient, and the second donor is biologically compatible as a donor of a human organ for the first patient.

(D) If there is any additional donor-patient pair as described in subparagraph (A) or (B), each donor in the group of donor-patient pairs is biologically compatible as a donor of a human organ for a patient in such group.

(E) All donors and patients in the group of donor-patient pairs (whether 2 pairs or more than 2 pairs) enter into a single agreement to donate and receive such human organs, respectively, according to such biological compatibility in the group.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,
In 2010, a pilot national kidney exchange program in US (UNOS-KPD) is launched.

However, in part because of its late establishment, activity in the UNOS-KPD is relatively modest compared to major programs.
Practical Progress of Kidney Exchange in the Last Decade

1. Organization & Optimization of Kidney Exchange ✓
2. Utilizing Gains from Larger Exchanges ✓
3. Integration of Altruistic Donors via Kidney Chains ✓
4. Inclusion of Compatible Pairs for Increased Efficiency 😞
5. Higher Efficiency via Larger Kidney Exchange Programs 😞
Inclusion of Compatible Pairs in Exchange is Important!

- Typically a **blood-type compatible pair** participates in exchange only when the donor is tissue-type incompatible with the intended patient.
- In contrast, a **blood-type incompatible pair** is automatically referred to an exchange program.
- Hence there are many more blood-type incompatible pairs in kidney exchange programs than blood-type compatible pairs!

  \[ \# \text{O Patients} \gg \# \text{O Donors} \]

- This disparity can be minimized if compatible pairs can also be included in kidney exchange.
Establishing Larger Exchange Programs are Important!

- Larger kidney exchange programs (e.g. national programs) provide a more efficient system than several smaller regional programs.
- Large national programs are especially beneficial for difficult-to-match patients such as those who are tissue-type incompatible with a large fraction of donor population (aka highly sensitized patients).
Establishing Larger Exchange Programs are Important!

- In the US, due to vagueness of original NOTA regarding legality of exchanges NOTA had to be amended and the national kidney exchange program started late.

- Currently in the US, most activity is organized locally in regional programs, only “leftover” difficult-to-match pairs participate in the national program.

- Problem is even more severe than just a first-mover advantage: RSÜ 2009 showed that there is no efficient and incentive compatible exchange system that would make all regional programs reveal their all pairs to the centralized national program.
Contribution of the Paper: Policy

- **New Proposal (Incentivizing the Participation of Compatible Pairs to Kidney Exchange):** If a compatible pair with a “more valuable” donor blood type than patient blood type participates in exchange, then prioritize the patient of this pair on the deceased-donor queue in case the transplant fails in the future.
  - 15% of the transplants are repeat transplants for kidneys.
  - A valuable insurance policy for the patient of the compatible pair.
  - Living donors already receive a similar priority for their altruism.

- Deceased-donor queue is regulated and governed in the US by UNOS, which also governs the national kidney exchange program.

  If this proposal is adopted by UNOS, it will likely derive the regional exchange programs “out of business” making the national kidney exchange program essentially a monopoly.
Contribution of the Paper: Model

- The first **dynamic general equilibrium** model combining all donation technologies together:
  - deceased donor allocation,
  - live donation, and
  - live-donor exchange.

- A test–bed to quantify, predict, and estimate the welfare and equity consequences of existing as well as our proposed transplant allocation policies.

- **Comparative statics:** Effects of medical modalities regarding suppression of tissue-type and blood-type incompatibilities (aka desensitization protocols).
The Model: Patients

Model: Patients with an Organ Failure

- Each patient is represented by his blood type:
  \[ X \in \mathcal{T} = \{A,B,AB,O\} \]

- Measure \( \pi_X \) of \( X \) blood-type patients arrive (get sick) per week.

- \( F(t) \): The probability of a patient dying within \( t \) weeks after arrival.

- \( T \): Maximum amount of time that can be survived with organ failure.

\[ F(T) = 1 \]

- The rate of live \( X \) blood-type patients after \( t \) weeks of arrival (in the absence of transplantation): \( \pi_X [1 - F(t)] \)

- Long-run total mass of alive \( X \) blood-type patients:

\[ \int_0^T \pi_X [1 - F(t)] dt \]
Patients with an Organ Failure
Rate $\delta_X$ of $X$ blood-type deceased donors arrive per week.

$$\delta_X < \pi_X$$

First-in–first-out (FIFO) deceased-donor allocation protocol.

$\theta \in [0, 1)$: The probability of tissue-type incompatibility between a patient and a random donor.

Two allocation policies:
- **ABO-identical (ABO-i):** $X$ blood-type organs are only transplanted to $X$ blood-type patients.
- **ABO-compatible (ABO-c):** $X$ blood-type organs can be transplanted to any compatible patient.
Re-Entry Due to Eventual Failure of Transplant

- $\phi^d$: Fraction of deceased donor transplant recipients who reenter the queue due to failure of transplanted organ.

- In the US, reentrant survival function on the queue is “similar to” that of primary entrants.

  **Assumption:** Survival function of reentrants is the same as the new patients.

- $\phi^d \delta_X$: The weekly rate of $X$ blood-type reentrants under ABO-i deceased donor allocation policy.
Lemma (FIFO Matching Protocol)

Consider the FIFO matching protocol. Suppose that there is an ordered $\omega$ measure of $X$ blood-type patients available in the queue and a $\sigma \leq \omega$ measure of blood-type compatible donors arrive. Then

- if $\sigma = \omega$, the number of donors who may remain almost surely unmatched is finite (and thus of 0 measure); and
- if $\sigma < \omega$, there exist no donors who may remain almost surely unmatched.

**Remark:** Since $\delta_X < \pi_X$ for all $X$, all deceased donor organs can be immediately allocated by the above lemma.
ABO-i Deceased Donation

Theorem (ABO-i Deceased Donation)

Under the ABO-i FIFO deceased donor allocation policy, at steady state, the waiting time for $X$ blood-type patients in the deceased-donor queue subject to survival is

$$t_i^X = F^{-1}\left(1 - \frac{\delta_X}{\pi_X + \phi^d \delta_X}\right),$$

and the mass of their deceased-donor queue is

$$\int_0^{t_X} (\pi_X + \phi^d \delta_X)[1 - F(t)]dt.$$
ABO-i Deceased Donation

Reentry of Deceased Donation Recipients

Deceased Donation

Patient Inflow

Waiting Time

\[ \pi_X + \phi^d \delta_X \]
Definition: Blood types in set $S$ are pooled if

1. donors of blood types in $S$ donate organs only to patients of blood types in $S$,
2. patients of blood types in $S$ receive organs only from donors of blood types in $S$, and
3. there is no proper subset of $S$ with (1) and (2).

We can repeatedly apply the next theorem to determine which blood types are to be pooled together under ABO-c FIFO policy.
ABO-c Deceased Donation

Theorem (ABO-c Deceased Donation)

Let $Y$ have the longest, and $X$ have the shortest ABO-i waiting time among blood types with $X \triangleright Y$. Then

1. $X$ and $Y$ patients will be pooled together (possibly with other types), and

2. we can treat $X$ and $Y$ as a composite blood type $C$ with
   - deceased donor inflow of $(\delta_X + \delta_Y)$,
   - patient inflow of $(\pi_X + \pi_Y)$, and
   - for any $Z \in T$

$$\exists W \in \{X, Y\} \text{ s.t. } W \triangleright Z \implies C \triangleright Z,$$

$$\exists W \in \{X, Y\} \text{ s.t. } Z \triangleright W \implies Z \triangleright C.$$
Live Donation

- $\lambda$: Fraction of patients with a willing live donor.
- $p_X$: Probability that a live donor is of blood type $X$.
- $X - Y$: A pair with $X$ blood type patient and $Y$ blood type donor.
  - $p_Y\lambda\pi_X$: Inflow measure of $X - Y$ pairs.
- $\phi^l < \phi^d$: Fraction of live donor transplant recipients who reenter the queue due to failure of transplanted organ.
- $p^l_X$: Odds of a type $X$ patient to be compatible with his live donor:

  $$
  p^l_O = (1 - \theta)p_O \quad p^l_A = (1 - \theta)(p_A + p_O) \\
  p^l_B = (1 - \theta)(p_B + p_O) \quad p^l_{AB} = (1 - \theta)
  $$
The Model: Live Donation

1. **λ**: Fraction of patients with a willing live donor.
2. **p_X**: Probability that a live donor is of blood type X.
3. **X – Y**: A pair with X blood type patient and Y blood type donor.
   - **p_Yλπ_X**: Inflow measure of X – Y pairs.
4. **φ^l < φ^d**: Fraction of live donor transplant recipients who reenter the queue due to failure of transplanted organ.
5. **p^l_X**: Odds of a type X patient to be compatible with his live donor:
   - \( p^l_O = (1 - \theta)p_O \)
   - \( p^l_A = (1 - \theta)(p_A + p_O) \)
   - \( p^l_B = (1 - \theta)(p_B + p_O) \)
   - \( p^l_{AB} = (1 - \theta) \)

   - In much of the world \( p_B < p_A \) \( \Rightarrow \) \( p^l_O < p^l_B < p^l_A < p^l_{AB} \)
Adding Live Donation to Deceased Donation

**Theorem (ABO-i Deceased & Live Donation)**

*ABO-i FIFO deceased donor waiting time with live donation is*

\[
t_{X}^{L,i} = F^{-1}\left(1 - \frac{\delta_{X}}{\pi_{X} - c_{X} + \phi^{d}\delta_{X}}\right)
\]

where net patient outflow is given by \(c_{X} = p_{X}^{l}\lambda\pi_{X} - \phi^{l}p_{X}^{l}\lambda\pi_{X}\).

*All patient groups (with or without live donor) benefit from live donation. However the benefit is not uniform across blood types. For the benchmark case of uniform \(\frac{\delta_{X}}{\pi_{X}}\) across all blood types*

- **O** patients benefit the **least**,
- **AB** patients will benefit the **most**, and
- **A** patients benefit **more than** **B** patients assuming \(p_{A} > p_{B}\).
Live Donation and Deceased Donation

- **Live Donation**
  - \( \pi_{X} + \phi^d \delta_X \)
  - Reentry of live donation recipients

- **Deceased Donation**
  - \( \pi_{X}^{L,i} [1 - F(t)] \)

Diagram shows the patient inflow \( \delta_X \) and the waiting time \( t_X^{L,i} \) with a steady state waiting time \( T \).
Live-Donor Exchange

- Only **incompatible pairs** participate in two-way exchange.

- **Assumption:** \( Y \succ X \implies \theta \pi_X p_Y < \pi_Y p_X \)
  
  That is, incompatible \( X - Y \) pairs (who are blood-type compatible but tissue type incompatible) arrive to exchange pool at a smaller rate than \( Y - X \) pairs (who are blood-type incompatible).

**Remark:** In the context of kidney exchange, \( \theta \approx 0.1 - 0.15 \), and thus the assumption easily holds.

- **Categorize the pair types:**
  - Overdemanded types: A-O, B-O, AB-O, AB-A, AB-B
  - Underdemanded types: O-A, O-B, O-AB, A-AB, B-AB
  - Self-demanded types: A-A, B-B, O-O, AB,AB
  - Reciprocally demanded types: A-B, B-A

- **Assumption (w.l.o.g.):** \( p_A \pi_B \leq p_B \pi_A \)
Theorem (ABO-i Exchange is Optimal)

For any patient-donor type $X - Y$, matching the longest-waiting pairs of type $X - Y$ with the longest-waiting pairs of the reciprocal type $Y - X$ constitutes an optimal live-donor exchange policy.
Live-Donor Exchange and Deceased Donation

- Pairs of the following types **never wait** in exchange pool under any optimal exchange policy and they get matched immediately: B-A, Self-demanded types, and Overdemanded types.
- In contrast, A-B and Underdemanded type pairs simultaneously wait in the deceased-donor queue and exchange pool.
- **Assumption:** Conditional on survival, patients accept exchange or deceased donation, whichever becomes available first.
- $\pi^e_{X-Y}$: The inflow rate of **incompatible** $X-Y$ pairs.
- $\pi^d_X$: The inflow rate of **reentering** and **new** type $X$ patients without live donors.
Theorem (ABO-i Live-Donor Exchange and Deceased Donation)

To find the ABO-i exchange waiting time for Underdemanded/A-B pairs use the following pooling procedure:

If \( \frac{\delta_X}{\pi_X} > \frac{\pi^e_{Y-X}}{\pi^e_{X-Y}} \) and \( X - Y \) has the lowest such ratio among all Underdemanded/A-B pairs with \( X \) patients, then

1. \( X - Y \) pairs both receive exchange and deceased donation, and
2. they get pooled with patients without live donors.

- Pool the donor rate as \( \delta_X + \pi^e_{Y-X} \)
- Pool the patient rate as \( \pi^d_X + \pi^e_{X-Y} \)

Repeat the above procedure for remaining Underdemanded/A-B pairs using the adjusted donor/patient rates when relevant.
Optimal Live-Donor Exchange

Exchange, Live Donation, and Deceased Donation

Incompatible A-A & A-O Pairs Exchange
Reentry of live-donor exchange participants

A-B Pairs Exchange

Some A-AB Pairs Exchange

Some A-AB Pairs Receive Deceased Donation

Deceased Donation

Figure: Example: A Patients
Proposal: Incentivizing Compatible Pairs to Join Exchange

- **We propose**: Compatible pairs’ patients who participate in exchange and whose organs fail in the future get a **priority** in their respective blood-type deceased-donor queue upon reentry.

- **Assumption**: Compatible pairs who are given this **insurance** policy participate in exchange.

- **Incentivized Exchange Burden**: For any ABO compatible type of patient-donor pairs $X - Y$ with $X \neq Y$, a rate

\[
\phi^I(1 - \theta)p_Y \lambda \pi_X
\]

of **returning** type $X$ patients will receive **priority** in the deceased donor queue.
New Policy Proposal: Incentivizing Compatible Pairs

New Policy: Compatible Pairs in Exchange

Theorem (Incentivization of Compatible Pairs to Participate in Exchange)

- Weakly more patients are matched from each patient group.
- Waiting time for incompatible pairs strictly decreases and more of them are matched.
- Waiting time for A, B and AB patients without live donors can increase, while waiting time for O weakly decreases (mitigating the unbalanced benefit across blood types caused by live-donation, as well as exchange).
- If required, this new imbalance can be softened by assigning released type O deceased donors (originally assigned to Underdemanded pairs with O patients) to other blood type patients without live donors.
New Policy Proposal: Incentivizing Compatible Pairs

New Policy: Compatible Pairs in Exchange

Figure: Example: A Patients
Consider the following Participation Game:

- Suppose there are $n + 1$ live-donor exchange programs $P_0, P_1, \ldots, P_n$.
- Program $P_0$ is the national exchange program and is the only one allowed to prioritize reentering compatible pair patients.
- Patient-donor pairs choose in which program to participate based on the expected waiting time.
- Each program uses an optimal exchange policy.
Impact of New Policy on National Exchange

Theorem (A National Monopoly for Kidney Exchange)

*If compatible pair exchange is linked to deceased donation as described above, all patient-donor pairs participate in the national exchange program under the unique Nash equilibrium.*
Interim Summary

Practical Progress of Kidney Exchange in the Last Decade

1. Organization & Optimization of Kidney Exchange ✓
2. Utilizing Gains from Larger Exchanges ✓
3. Integration of Altruistic Donors via Kidney Chains ✓
4. Inclusion of Compatible Pairs for Increased Efficiency 😊
5. Higher Efficiency via Larger Kidney Exchange Programs 😊
So far we assumed that $\theta$, the odds of tissue-type incompatibility, is an exogenous parameter.

In practice it is governed by the current state of the transplant technology and immunosuppression drugs.

- The titer level of antibodies has to be below a certain threshold so that the donor is deemed tissue-type compatible with the patient.
- Moreover, with the advancement of immunosuppression techniques, the threshold can be increased.
- Different countries, even different transplant programs often adopt different thresholds to define positive crossmatch.

Hence, $\theta$ is conceivably a variable rather than a constant.
Comparative Statics: Increasing $\theta$

- In the absence of exchange, a reduction in the tissue-type incompatibility increases the amount of patients receiving transplant. Ironically, this is not the case when organ exchange is available.

**Theorem (Hurting Patients by Increased Technology)**

*In the presence of live donor exchange, the amount of patients who receive transplant decreases as the tissue-type incompatibility (i.e $\theta$) decreases.*

- **Remark:** This happens because tissue-type incompatibility is the only reason there are any type O donors in the exchange pool.
Impact of Desensitization Protocols

- Under **ABO desensitization** a patient is able to receive a blood-type incompatible transplant.
- Similarly, under **HLA desensitization** a patient is able to receive a tissue-type incompatible transplant.
- These medical modalities are less preferred and expensive, but occasionally used because of the shortage of transplant organs.

**Theorem (Desensitization Protocols: Good or Bad?)**

*In the presence of live donor exchange:*

- **ABO desensitization increases** the amount of patients who receive transplants.
- **In contrast HLA desensitization decreases** the amount of patients who receive transplants.
Summary

- **New policy proposal**: Incentivize compatible pair participation through prioritization of their patients in case he reenters the queue.
- To measure the welfare and equity effects formally, we introduce new machinery, a new dynamic entry-reentry model.
- We use the model for measuring, quantifying, estimating various effects of new and old policies on patient groups.
- Our new policy also helps the natural selection of a single exchange program among the many to utilize the economies of scale in exchange.
- We have also shown that HLA desensitization protocols can hurt the patient population.