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:

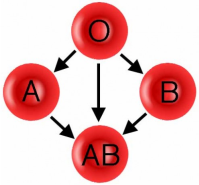
    "It shall be unlawful for any person to knowingly acquire, receive or otherwise transfer any human organ for valuable consideration for use in human transplantation."

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:

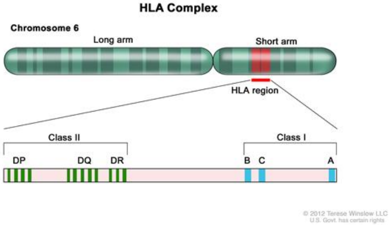
- Type O organs can be transplanted into any patient;
- type A organs can be transplanted into type A or type AB patients;
- type B organs can be transplanted into type B or type AB patients;
- type AB organs can only be transplanted into type AB patients.

- 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.

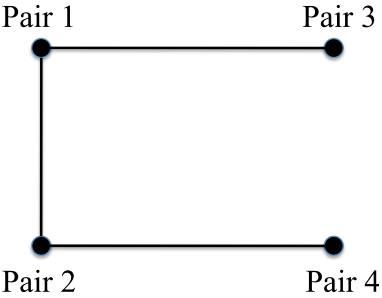
Donation Technologies: Live-Donor Organ Exchange

- 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.

Kidney Exchange as a Market Design Problem

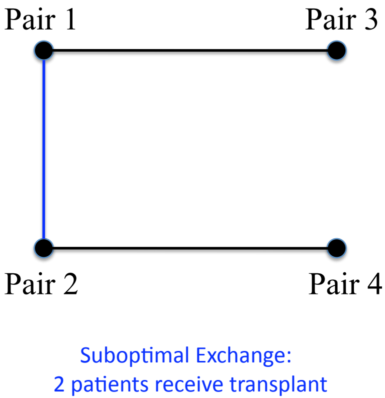
- The emerging field of Market Design applies insights and tools from economic theory to solve real-life resource allocation problems.
- In early 2000s, we observed that the two main types of kidney exchanges conducted in the U.S. correspond to the most basic forms of exchanges in house allocation model 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.

Organized Exchange & Optimization is Important



- 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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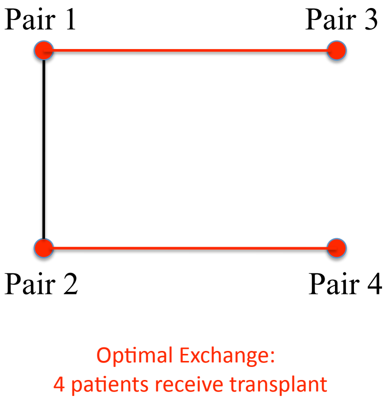
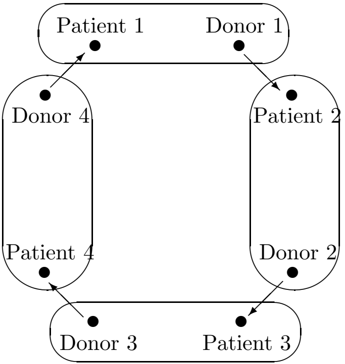


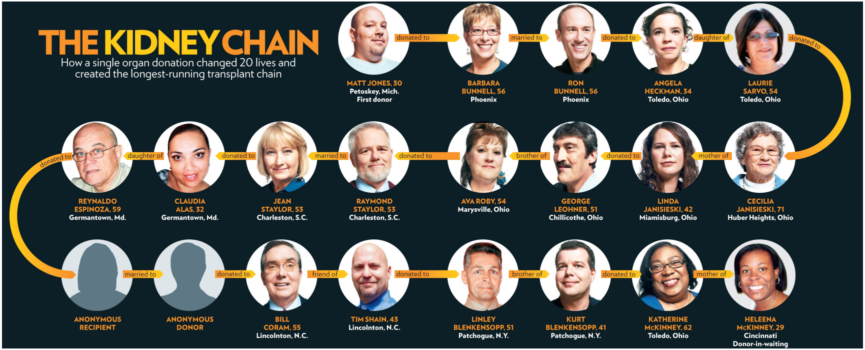
- Even in the absence of more elaborate exchanges, merely organizing the paired-exchanges may result in increased efficiency.

Gains from Larger Exchanges are Considerable



- Additional live-donor transplants may be possible through three-way, four-way, . . . , exchanges.
- Three-way exchange is especially important!

Gifts of Altruistic Donors Can Be Multiplied via Chains



- Simultaneity is not critical when a kidney-chain starts with a donation from an altruistic donor. Hence large kidney-chains can be utilized!

Inclusion of Compatible Pairs is Important

- 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!

$$\# \text{ O Patients} >> \# \text{ O Donors}$$

- 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).

Number of Kidney Exchanges

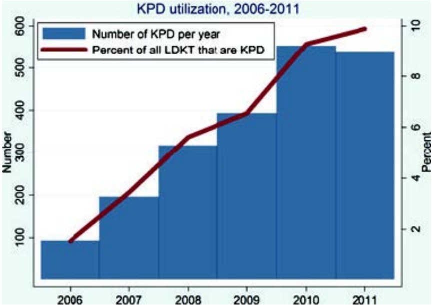


Figure from Massie et al AJT 2013

- 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

   RSÜ 2004, 2008, Sönmez & Ünver 2010
5. Higher Efficiency via Larger Kidney Exchange Programs

   RSÜ 2004, 2005b

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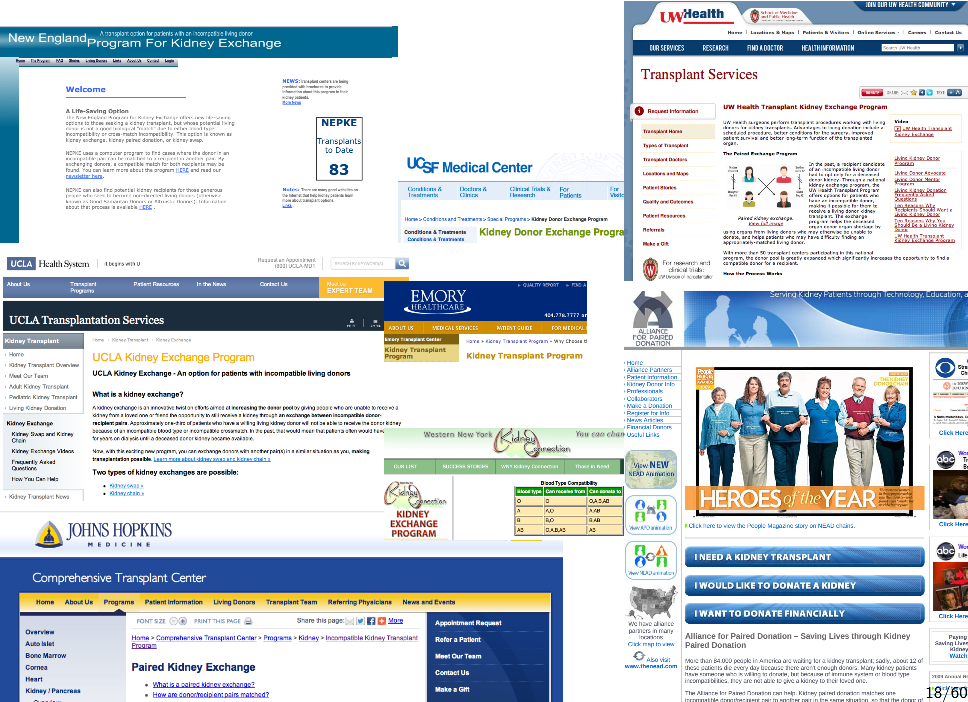
5. Higher Efficiency via Larger Kidney Exchange Programs
   RSÜ 2004, 2005b

To what extent these insights have been utilized so far?



New England Program For Kidney Exchange
A transplant option for patients with an incompatible living donor
Home The Program FAQ Stories Living Donors Links About Us Contact Login
Welcome
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 and read our newsletter here.
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 .
NEWS: Transplant centers are being provided with brochures to provide information about this program to their kidney patients.
More News
NEPKE
Transplants to Date
83
Notes: There are many good websites on the Internet that help kidney patients learn more about transplant options.
Links
UCSF Medical Center
Conditions & Treatments
Doctors & Clinics
Clinical Trials & Research
For Patients
Home > Conditions and Treatments > Special Programs > Kidney Donor Exchange Program
Kidney Donor Exchange Program
UW Health
JOIN OUR UW HEALTH COMMUNITY
Home | Locations & Maps | Patients & Visitors | Online Services | Careers | Contact Us
OUR SERVICES RESEARCH FIND A DOCTOR HEALTH INFORMATION
Transplant Services
Request Information
Transplant Home
Types of Transplant
Transplant Doctors
Locations and Maps
Patient Stories
Quality and Outcomes
Patient Resources
Referrals
Make a Gift
UW Health Transplant Kidney Exchange Program
UW Health surgeons perform transplant procedures working with living donors for kidney transplants. Advantages to living donation include a scheduled procedure, better conditions for the surgery, improved patient survival and better long-term function of the transplanted organ.
The Paired Exchange Program
Paired kidney exchange.
View full image
In the past, a recipient candidate of an incompatible living donor had to opt only for a deceased donor kidney. Through a national kidney exchange program, the UW Health Transplant Program offers options for patients who have an incompatible donor, making it possible for them to receive a living donor kidney transplant. The exchange program helps the deceased organ donor organ shortage by using organs from living donors who may otherwise be unable to donate, and helps patients who may have difficulty finding an appropriately-matched living donor.
With more than 50 transplant centers participating in this national program, the donor pool is greatly expanded which significantly increases the opportunity to find a compatible donor for a recipient.
How the Process Works
Video
UW Health Transplant Kidney Exchange
Living Kidney Donor Program
Living Donor Advocate
Living Donor Mentor Program
Living Kidney Donation Frequently Asked Questions
Ten Reasons Why Recipients Should Want a Living Kidney Donor
Ten Reasons Why You Should Be a Living Kidney Donor
UW Health Transplant Kidney Exchange Program
For research and clinical trials: UW Division of Transplantation
UCLA Health System
Request an Appointment (800) UCLA-MD1
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UCLA Transplantation Services
Kidney Transplant
Home
Kidney Transplant Overview
Meet Our Team
Adult Kidney Transplant
Pediatric Kidney Transplant
Living Kidney Donation
Kidney Exchange
Kidney Swap and Kidney Chain
Kidney Exchange Videos
Frequently Asked Questions
How You Can Help
Kidney Transplant News
UCLA Kidney Exchange Program
UCLA Kidney Exchange - An option for patients with incompatible living donors
What is a kidney exchange?
A kidney exchange is an innovative twist on efforts aimed at increasing the donor pool by giving people who are unable to receive a kidney from a loved one or friend the opportunity to still receive a kidney through an exchange between incompatible donor-recipient pairs. Approximately one-third of patients who have a willing living kidney donor will not be able to receive the donor kidney because of an incompatible blood type or incompatible crossmatch. In the past, that would mean that patients often would have for years on dialysis until a deceased donor kidney became available.
Now, with this exciting new program, you can exchange donors with another pair(s) in a similar situation as you, making transplantation possible. Learn more about kidney swap and kidney chain »
Two types of kidney exchanges are possible:
Kidney swap »
Kidney chain »
EMORY HEALTHCARE
404.778.7777
ABOUT US MEDICAL SERVICES PATIENT GUIDE
Emory Transplant Center
Kidney Transplant Program
Home » Kidney Transplant Program » Why Choose
Kidney Transplant Program
Western New York Kidney Connection
OUR LIST SUCCESS STORIES WNY Kidney Connection Those in Need
KIDNEY EXCHANGE PROGRAM
Blood Type Compatibility
Blood type | Can receive from | Can donate to
O | O | O,A,B,AB
A | A,O | A,AB
B | B,O | B,AB
AB | O,A,B,AB | AB
ALLIANCE FOR PAIRED DONATION
Home
Alliance Partners
Patient Information
Kidney Donor Info
Professionals
Collaborators
Make a Donation
Register for Info
News Articles
Financial Donors
Useful Links
View NEW NEAD Animation
View APD animation
View NEAD animation
We have alliance partners in many locations
Click map to view
Also visit www.thenead.com
HEROES of the YEAR
Click here to view the People Magazine story on NEAD chains.
I NEED A KIDNEY TRANSPLANT
I WOULD LIKE TO DONATE A KIDNEY
I WANT TO DONATE FINANCIALLY
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.
JOHNS HOPKINS MEDICINE
Comprehensive Transplant Center
Home About Us Programs Patient Information Living Donors Transplant Team Referring Physicians News and Events
Overview
Auto Islet
Bone Marrow
Cornea
Heart
Kidney / Pancreas
FONT SIZE PRINT THIS PAGE Share this page: More
Home > Comprehensive Transplant Center > Programs > Kidney > Incompatible Kidney Transplant Program
Paired Kidney Exchange
What is a paired kidney exchange?
How are donor/recipient pairs matched?
Appointment Request
Refer a Patient
Meet Our Team
Contact Us
Make a Gift
Click Here

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

Incredible 3-way kidney swap

Mike and Susan Williams of Banton

By DAVID GRAHAM
Published on **Friday 5 August 2011 14:00**

TOP STORIES
Tower strategy aims

Massive transplant effort pairs 13 kidneys to 13 patients

By Val Willingham, CNN
December 14, 2009 8:40 a.m. EST

Renee Patterson (left) meets her donor Leslie Wolfe. Both were part of a 26-person kidney exchange.

1 2

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 a massive mix-and-match transplant effort in the U.S., involving more than a dozen kidneys.

STORY HIGHLIGHTS

- **NEW:** Renee Patterson met her donor, Leslie Wolfe, on Monday
- Patterson joined program that connects patients with willing donors
- Patterson's friend donated kidney to compatible recipient;

DENVER AND THE WEST

Selflessness, to the third power

PRINT EMAIL
0 COMMENTS

3 kidney transplants to occur simultaneously across country

By Brian Malnes
The Denver Post

POSTED: 07/30/2008 12:30:00 AM MDT

With clocks synchronized, three kidney transplants will happen simultaneously at three hospitals in three time zones around the country this morning.

At 7:30 a.m. Denver time, the three-state kidney exchange will begin with patients in North Carolina, in Alabama and at the University of Colorado Hospital in Aurora.

"It's the first time in U.S. history that three transplants will be happening at the same time," said Vonnie Bagwell, the living donor coordinator at CU Denver Health Center.

Maggie Mrva, foreground, is to receive a kidney today from Martha Hansen, rear, at the CU Hospital in Aurora. All three transplant operations are to begin at 7:30 a.m. Denver time. (Brian Lehmann, Pool)

World's Largest Kidney Exchange Gives 14 People New Chance at Life

abc WORLD NEWS WITH DIANE SAWYER

By LISA STARK (@LisaStark) and BRADLEY BLACKBURN
June 15, 2010

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182 1

In the nation's capital, a circle of strangers is now connected for life.

Beginning last month, 14 donors gave their kidneys to 14 people who desperately needed them in the largest kidney exchange in history.

Washington kidney exchange is largest ever

By Melanie D.G. Kaplan | December 1, 2009, 4:00 AM PST

The largest-ever single-city kidney exchange took place this summer in Washington. The seven-way exchange, which involved 14 patients, occurred at **Georgetown University Hospital** and **Washington Hospital Center** over four days in July. It was the brainchild of **Dr. Keith Melancon**, director of **Georgetown's Kidney and Pancreas Transplant Surgery**, who used a procedure called ***plasmapheresis*** to address not only donor compatibility but racial disparity.

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The New York Times

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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.

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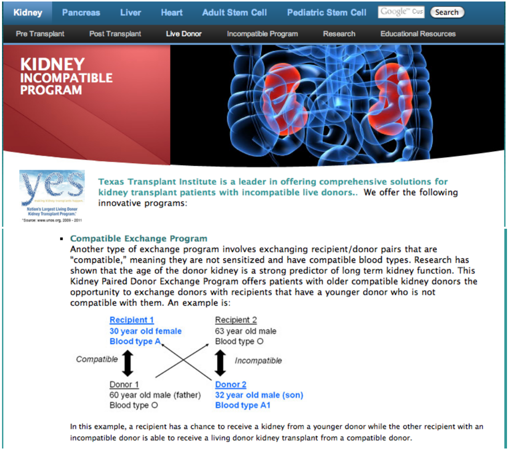

- Very limited implementation of this idea.
- Limited or no incentives for compatible pairs to participate in kidney exchange.

Practical Progress of Kidney Exchange in the Last Decade

- Organization & Optimization of Kidney Exchange $\checkmark$
- Utilizing Gains from Larger Exchanges $\checkmark$
- Integration of Altruistic Donors via Kidney Chains $\checkmark$
- Inclusion of Compatible Pairs for Increased Efficiency
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Amendment of the National Organ Transplant Act

- 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.

One Hundred Tenth Congress
of the
United States of America

AT THE FIRST SESSION

Begun and held at the City of Washington on Thursday, the fourth day of January, two thousand and seven

An Act

To amend the National Organ Transplant Act to provide that criminal penalties do not apply to human organ paired donation, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Charlie W. Norwood Living Organ Donation Act".

SEC. 2. AMENDMENTS TO THE NATIONAL ORGAN TRANSPLANT ACT.

Section 301 of the National Organ Transplant Act (42 U.S.C. 274e) is amended—

(1) in subsection (a), by adding at the end the following: "The preceding sentence does not apply with respect to human organ paired donation."; and

(2) in subsection (c), by adding at the end the following: "(4) 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.

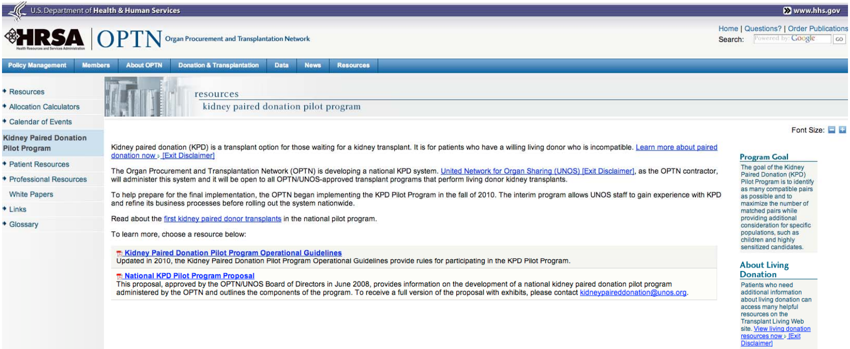
"(C) Subject to subparagraph (D), the first donor is biologically compatible as a donor of a human organ for the second patient, and the second donor is biologically compatible as a donor of a human organ for the first patient.

"(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.

US National Kidney Paired Donation Pilot Program

- 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.



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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!

$$\# \text{ O Patients} >> \# \text{ O Donors}$$

- 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 aw 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).

Model: Patients with an Organ Failure

- Each patient is represented by his blood type:

$$X \in \mathcal{T} = \{\text{A,B,AB,O}\}$$

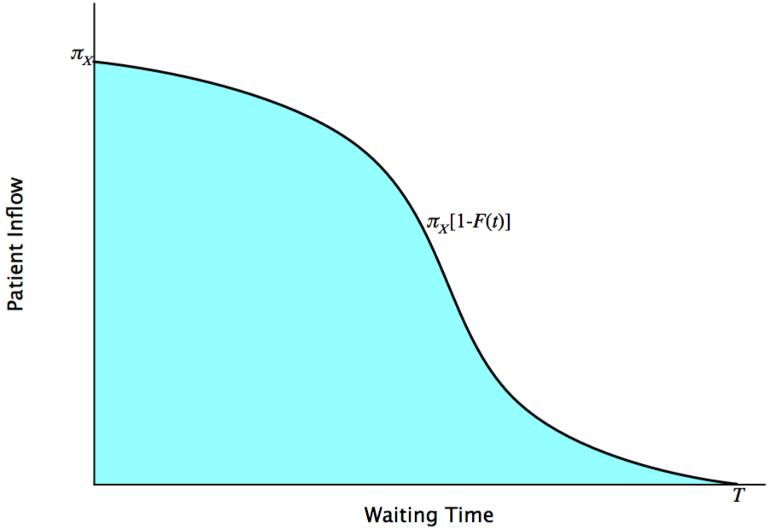
- Measure π_X of X blood-type patients arrive (get sick) per week.
- $F(t)$: The probability of a patient dying within t weeks after arrival.
- T: Maximum amount of time that can be survived with organ failure.

$$F(T) = 1$$

- 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



Transplant Technology: Deceased Donation

- Rate δ_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

- ϕ^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.

Deceased Donation and Tissue-type Incompatibility

Lemma (FIFO Matching Protocol)

Consider the FIFO matching protocol. Suppose that there is an ordered ω 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)

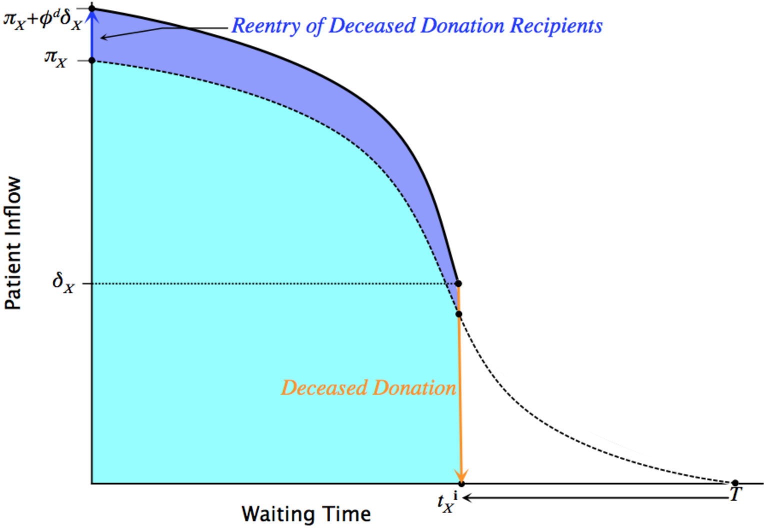
Under the ABO-i FIFO deceased donor allocation policy, at steady state, the waiting time *for X blood-type patients in the deceased-donor queue subject to survival is*

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

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



ABO-c Deceased Donation

- Definition: Blood types in set $\mathcal{S}$ are pooled if
  1. donors of blood types in $\mathcal{S}$ donate organs only to patients of blood types in $\mathcal{S}$,
  2. patients of blood types in $\mathcal{S}$ receive organs only from donors of blood types in $\mathcal{S}$, and
  3. there is no proper subset of $\mathcal{S}$ 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 $Z \in \mathcal{T}$*

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

Live Donation

- λ: 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_X^l: Odds of a type X patient to be compatible with his live donor:

$$\begin{array}{rr} p_O^l = (1-\theta)p_O & p_A^l = (1-\theta)(p_A + p_O) \\ p_B^l = (1-\theta)(p_B + p_O) & p_{AB}^l = (1-\theta) \end{array}$$

Live Donation

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- $\phi^l < \phi^d$: 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:

$$\begin{aligned} p^l_O &= (1-\theta)p_O & \quad p^l_A &= (1-\theta)(p_A + p_O) \\ p^l_B &= (1-\theta)(p_B + p_O) & \quad p^l_{AB} &= (1-\theta) \end{aligned}$$

- In much of the world $p_B < p_A \implies p^l_O < p^l_B < p^l_A < p^l_{AB}$

Adding Live Donation to Deceased Donation

Theorem (ABO-i Deceased & Live Donation)

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

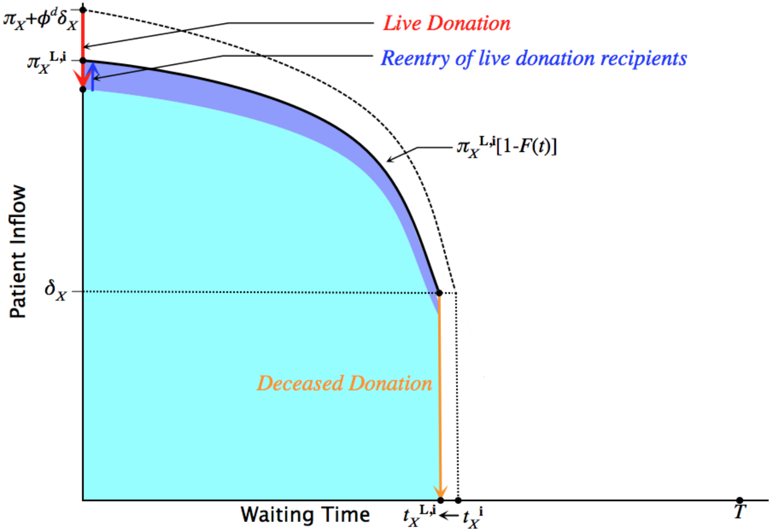
$$t_X^{\mathbf{L},\mathbf{i}} = F^{-1}\left(1 - \frac{\delta_X}{\pi_X - c_X + \phi^d \delta_X}\right)$$

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-Donor Exchange

- Only incompatible pairs participate in two-way exchange.
- Assumption: $Y \triangleright X \implies \theta \pi_X p_Y < \pi_Y p_X$

  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.): $p_A \pi_B \leq p_B \pi_A$

Live-Donor Exchange

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.
- π^e_{X-Y}: The inflow rate of incompatible $X - Y$ pairs.
- π^d_X: The inflow rate of reentering and new type X patients without live donors.

Live-Donor Exchange and Deceased Donation

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 $\frac{\delta_X}{\pi^d_X} > \frac{\pi^e_{Y-X}}{\pi^e_{X-Y}}$ *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.

Exchange, Live Donation, and Deceased Donation

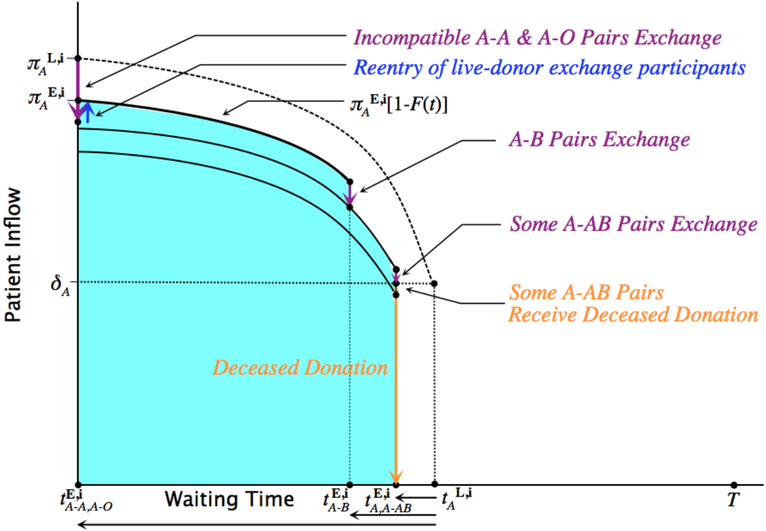


Figure: Example: A Patients

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: 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: Compatible Pairs in Exchange

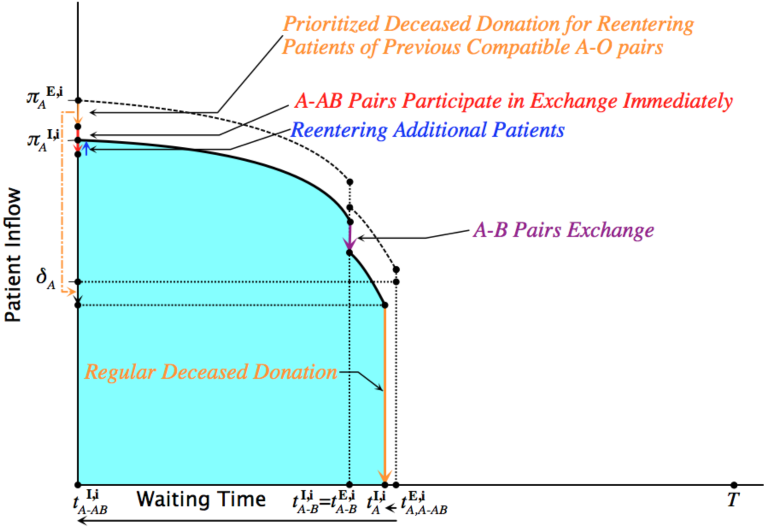


Figure: Example: A Patients

Impact of New Policy on National Exchange

Consider the following Participation Game:

- Suppose there are $n + 1$ live-donor exchange programs $P_0, P_1, ..., P_n$.
- 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 ☺

Transplantation Immunology & Organ Exchange

- So far we assumed that θ, 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, θ is conceivably a variable rather than a constant.

Comparative Statics: Increasing θ

- 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 θ) 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.