A Kidney Exchange Clearinghouse in New England

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In September, 2004, the Renal Transplant Oversight Committee of New England approved the establishment of a clearinghouse for kidney exchange, proposed by Drs. Francis Delmonico, Susan Saidman, and the three authors of this paper. We outline here the potential gains from kidney exchange, and discuss practical constraints encountered as we begin designing and implementing a matching mechanism.

Background:

In 2003 there were 8,665 transplants of deceased donor kidneys for the approximately 60,000 patients waiting for such transplants in the U.S. While waiting, 3,436 patients died. There were also 6,464 kidney transplants from living donors (http://www.ustransplant.org/srtr.php.). Live donation is an option for kidneys, since healthy people have two, and can remain healthy with one. While it is illegal to buy or sell organs, there have started to be kidney *exchanges* involving two donor-patient pairs such that each (living) donor cannot give a kidney to the intended recipient because of blood type or immunological incompatibility, but each patient can receive a kidney from the other donor. So far these have been rare: e.g. as of December 2004, only 5 exchanges had been performed in the fourteen transplant centers in New England. One reason there have been so few kidney exchanges is that there haven't been databases of incompatible patient-donor pairs: incompatible donors were simply sent home. (Databases are now being assembled not only in New England, but also in Ohio and Baltimore.)

Ross et al. (1997) discussed the possibility of exchange between incompatible patient-donor pairs. Not only have a few such 2-way exchanges been performed, but two 3-way exchanges (in which the donor kidney from one pair is transplanted into the patient in a second pair, whose donor kidney goes to a third pair, whose donor kidney goes to the first pair) have been performed at Johns Hopkins. There have also been a number of "*list exchanges*" in which an incompatible patient-donor pair makes a donation to someone on the waiting list for a cadaver kidney, in return for the patient in the pair receiving high priority for a cadaver kidney when one becomes available.

Scope and design of a kidney clearinghouse:

Roth, Sönmez, and Ünver (2004a) considered how to efficiently organize all these kinds of exchanges, in a way that would give patients and their doctors straightforward incentives. (Because medical information is decentralized, some of the procedures for allocating cadaver organs have experienced incentive problems.) We modeled patients as having strict preferences over compatible kidneys, and allowed exchanges among any number of patient-donor pairs (including not only incompatible pairs, but also compatible pairs who might nevertheless be able, through exchange, to obtain a preferred kidney). We allowed list exchanges to be integrated with live exchanges, so a patient-donor pair who decided to exchange their kidney for priority on the deceased donor list would not necessarily donate their kidney to someone on the list, but might instead donate their kidney to another patient-donor pair who would in turn donate a kidney to the list (or to another pair who would in turn donate a kidney to the list, etc.).

In our model each agent is a patient and her donor(s). Agents have strict preferences over other agents (based on compatibility, closeness of tissue match, age of donor), and over priority on the cadaver waitlist.

If we exclude list exchange, this is the “housing market” of Shapley and Scarf (1974), and Gale’s method of top trading cycles (TTC) produces efficient, core allocations. There is a unique such allocation (Roth and Postlewaite 1977), and the mechanism that selects it is dominant-strategy incentive-compatible (Roth, 1982).

TTC works as follows: Each agent points to her most preferred agent (the patient with the agent’s favorite donor). There is at least one *cycle* (an ordered list of agents $(a_1, a_2, \ldots, a_n)$ in which each agent points to the next , and agent a_n points to a_1), and no agent can be part of more than one cycle. The implied exchange in each cycle is carried out and the procedure continues with each remaining agent pointing to her favorite among the remaining agents.

When list exchange is included the model is close to the “room assignment” of Abdulkadiroğlu and Sönmez (1999). At some point of the TTC procedure there may be no cycles, but only “w-chains” in which a_n is pointing to the waiting list. An agent may be part of several w-chains and therefore the procedure needs a selection rule for w-chains. In Roth, Sönmez, and Ünver (2004a) we called this class of procedures *top trading cycles and chains* (TTCC) and identified a version that is Pareto efficient and dominant-strategy incentive-compatible.

To solve one aspect of the incentive problem, all surgeries in a live-donor exchange are conducted simultaneously. So a 2-way exchange (involving just two patient-donor pairs) involves four simultaneous surgeries, a 3-way exchange involves six, etc.

Logistical constraints:

Our medical colleagues worried that, at least initially, they couldn't manage exchanges larger than 2-way. And they were inclined to exclude list exchanges, and to allow only incompatible patient-donor pairs to participate. Also, as a first approximation, their feeling was that a patient should be indifferent between any compatible exchanges.

So in Roth, Sönmez, and Ünver (2004b), each agent is a patient with incompatible donors, and is indifferent between all donors compatible with her. No exchange larger than 2-way is feasible. Building on well-known results in graph theory we showed there are constrained-efficient dominant-strategy incentive-compatible mechanisms. These include deterministic "priority" mechanisms like those organ banks use for to allocate cadaver organs, and stochastic mechanisms that address equity considerations .

The gains from kidney exchange will depend on several factors including:

1. The size of the patient-donor database.
2. Will list exchanges be included?

While list exchanges have distributional implications for the deceased donor waitlist, their inclusion increases the potential gains from exchange.

3. What is the maximum number of transplants that can be simultaneously carried out? Equivalently what is the size of largest feasible cycle and/or *w*-chain?
4. Whether compatible patient-donor pairs can participate in exchange.

Consider pairs A and B: donor A is compatible with both patients but donor B is compatible only with patient A. While donor A can directly give her kidney to patient A, both patients receive a kidney if pairs A and B exchange. Such an exchange is called an *altruistically unbalanced exchange* (Woodle and Ross 1998), and is unlikely to be recommended to couple A as long as exchanges are unusual. But if patients have strict preferences over donors, it could be that both pairs obtain a preferred kidney from such an exchange. (Consideration of compatible pairs, and altruistically unbalanced exchanges, will help us estimate an upper bound on the gains that can be achieved.)

We turn to simulations to estimate the impact of each of these factors on the number of patients who can benefit from exchange.

Simulations:

For simplicity we consider non-blood-related patient-donor pairs. Distributions of blood types (48% O, 34% A, 14% B, 4%AB), PRA levels (discussed below) and gender of the patients (41% female), and percentage of spouses among the unrelated donors (49%) are from the UNOS/OPTN data.[i]

Tissue-type incompatibility (a *positive crossmatch*) arises when a patient has antibodies against a donor protein. (The positive crossmatch probability between female patients and their husbands is approximately 33%, compared to approximately 11% between random pairs (Zenios, Woodle and Ross 2000), because antibodies can develop during childbirth.) Patients in the UNOS database are divided into three groups based on the odds that they have a crossmatch with a random donor. For simplicity we simulate patients in discrete PRA (*Percent Reactive Antibody*) levels:

- 70% low PRA patients, each of whom has a positive crossmatch probability of 5% with a random donor,
- 20% medium PRA patients, each of whom has a positive crossmatch probability of 45%,
- 10% high PRA patients, each of whom has a positive crossmatch probability of 90%.

We randomly simulate patient-donor pairs using Monte-Carlo simulation size of 100 random population constructions for each of the 16 scenarios described below:

1. We consider two population sizes: 25 and 100.
2. We consider including compatible pairs in exchange as well as excluding them. (So e.g. in a population of 25 patient-donor pairs, if compatible pairs are excluded from exchange, only the smaller number of incompatible pairs will be available for exchange, and these will have a different distribution of characteristics than the general population; O donors will be rare, and high PRA patients will be more common.)
3. Either:
    a) List exchanges are unavailable, or
    b) List exchanges are available but only 40% of incompatible pairs consider a transplant from a deceased donor and only if a live donor is unavailable.
4. The largest feasible cycle/w-chain is either 2 or unbounded.

These possibilities yield 2×2×2×2 = 16 scenarios, and for each realization we search for a feasible exchange that includes the maximum number of patients.

For simplicity we assume patients are indifferent between compatible live donors but prefer any such donor to priority on the deceased donor waitlist. We use versions of Edmond's (1965) algorithm to find a maximal exchange when the largest feasible cycle/*w*-chain is 2. We know of no exact algorithm to determine a maximal exchange when cycle/*w*-chain size is unbounded. In these scenarios we search for a maximal exchange among efficient matchings via the TTCC algorithm.

Table 1 makes clear that the gains from all kinds of exchange increase as the population n of patient-donor pairs grows. The exchanges that are initially likely to be achievable are those involving no list exchange (0% waitlist), and only incompatible patient-donor pairs. When only 2-way exchanges are feasible, exchange yields on average an additional 3.96 such transplants when n=25 (16% of the patient population), but 23.04 when n=100.

Allowing list exchange, or allowing larger than 2-way exchanges each gives a comparable increase in the number of transplants that can be achieved.

The largest gains in the table come from including compatible pairs in the population eligible for exchange. As the bottom of Table 1 indicates, it is at least conceivable that in a large population in which all patient-donor pairs could participate in exchange, virtually every patient with a willing donor would be able to receive a kidney. But we emphasize that this is an upper bound, since for many *compatible* pairs, exchange will not be desirable.

Conclusions:

Kidney exchange is likely to proceed incrementally, starting with the simplest cases (2-way exchange) and the patients who can benefit most (incompatible pairs).

Roth, Sönmez, and Ünver (2005) show that most of the gain from larger than 2-way exchange comes from 3-way exchange, and so we are hopeful that it will be possible to achieve these gains in the near term also. It may also be possible to include list exchanges and non-directed donors (altruistic living donors who do not specify a particular patient). Each of these increases in the scope of exchange will necessitate design changes in the clearinghouse, and there are open theoretical problems remaining for some of them (as is to be expected, cf. the examples in Roth, 2002).

It seems likely that until exchange becomes well established, only incompatible patient-donor pairs will be included, as surgeons will be reluctant to advise compatible pairs not to proceed with their own transplant. However, as exchange becomes more routine, there will be opportunities for mutually beneficial exchange between e.g. a 25-year-old patient with a compatible 50-year-old donor and a 50-year-old patient with an *in*compatible 25-year-old donor.

Fortunately, the gains from even the simplest exchanges are large, and achievable.

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Table 1. Simulation results: Average number of patients receiving a transplant in each scenario, total, through own-donor, through an exchange, through being sent to the top of the waiting list. In this table *Own* refers to the number of patients receiving own donor kidneys, *Ex.* refers to the number of patients participating in an exchange, and *w-List* refers to the number of patients who get priority in the waiting list through list exchange.

Exchange Type	**Compatible Pairs**	**Population Size**	**% waitlist option**	**Total Transplants**		
				Own	**Ex.**	**w-List**
2-way	**Out**	**n=25**	**0 %**	15.52		
				11.56	3.96	0
			40 %	21.03		
				11.56	5.76	3.71
		n=100	**0 %**	70.53		
				47.49	23.04	0
			40 %	87.76		
				47.49	28.79	11.48
	In	**n=25**	**0 %**	20.33		
				1.33	19.00	0
			40 %	23.08		
				1.33	19.63	2.12
		n=100	**0 %**	91.15		
				1.01	90.14	0
			40 %	97.06		
				1.01	91.35	4.70
Unrestricted	**Out**	**n=25**	**0 %**	16.89		
				11.56	5.33	0
			40 %	21.70		
				11.56	6.32	3.82
		n=100	**0 %**	76.20		
				47.49	28.71	0
			40 %	89.69		
				47.49	30.38	11.82
	In	**n=25**	**0 %**	21.74		
				1.44	20.30	0
			40 %	23.99		
				1.50	20.29	2.20
		n=100	**0 %**	94.35		
				1.67	92.68	0
			40 %	98.83		
				1.61	92.55	4.67

Footnotes:

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[i] UNOS/OPTN 2003 Annual Report, 1993-2002, http://www.optn.org on 11/22/2004. Patient characteristics from new waiting list registrations, living donor relational type from living donor transplants data.