

A Speed Read: WHERking to Meet the Need for Kidneys with NEAD Chains

Project: Kidney Exchange

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Decision Models
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Overview

The Problem

Methodology

Model

Analysis & Conclusion

The Problem

Why focus on kidney disease?



1 out of every 3 Americans is at risk of CKD due to high blood pressure (hypertension), family history of CKD, or diabetes

590,000,000+

Americans have experienced kidney failure

adults in the U.S. with chronic kidney disease (CKD)

20MM

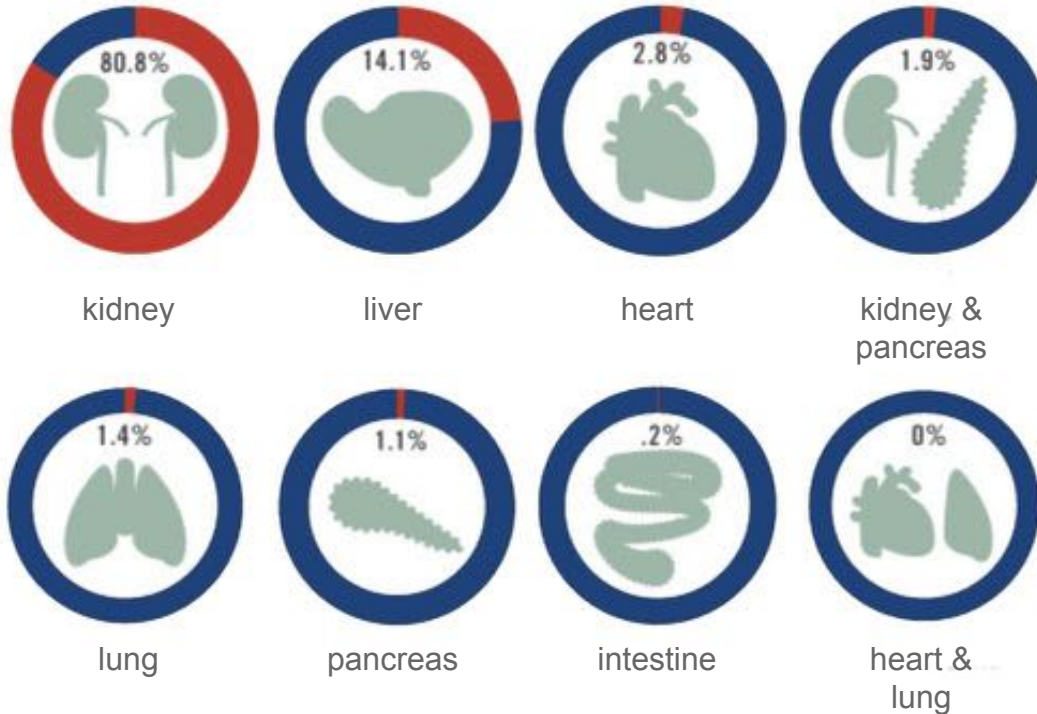
9th

leading cause of death in the United States

people in need of a kidney transplant

95,000

Kidneys are the organs in highest demand.



What happens without a kidney donation?



1. Most patients' family & friends aren't matches.

There are 3 hurdles to receiving a kidney from a donor.

Healthy



Hurdle #1

Blood Compatible



Hurdle #2

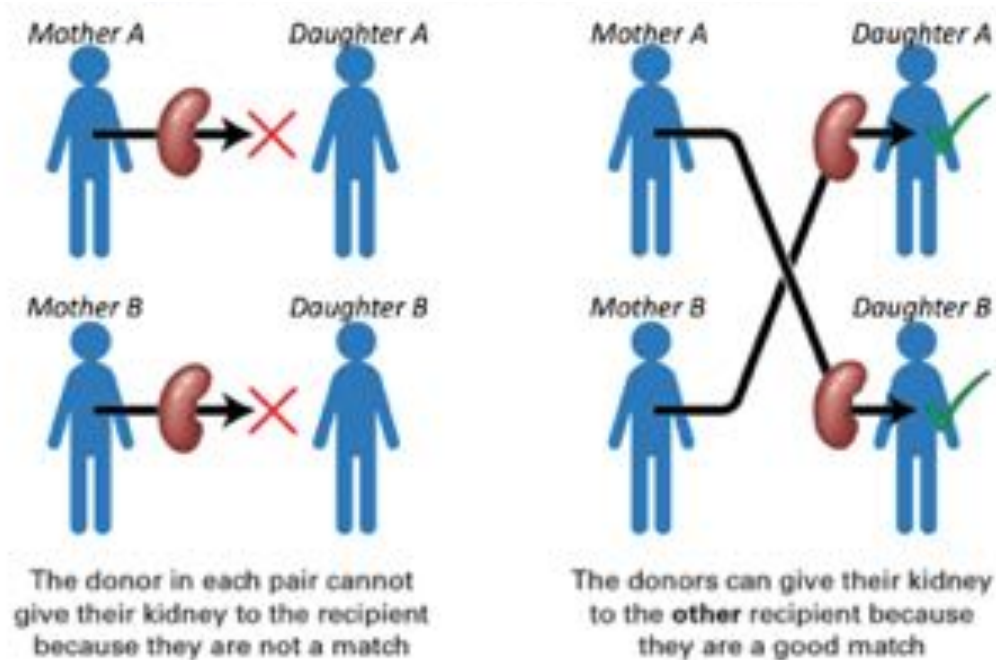
Tissue Compatible



Hurdle #3

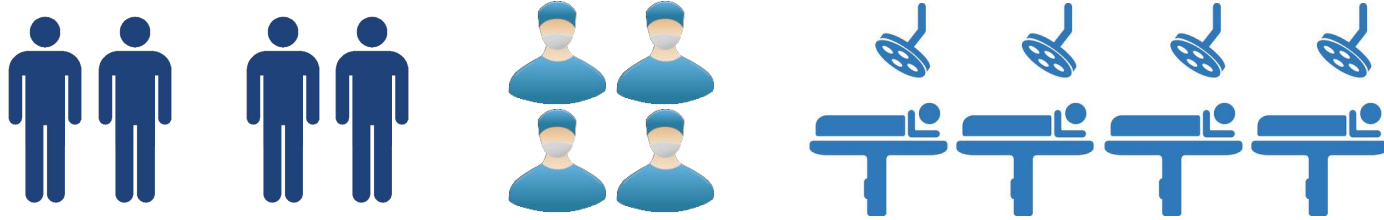
In families, brothers and sisters only have a 25% chance of matching.

2. Paired Exchanges are difficult to find.

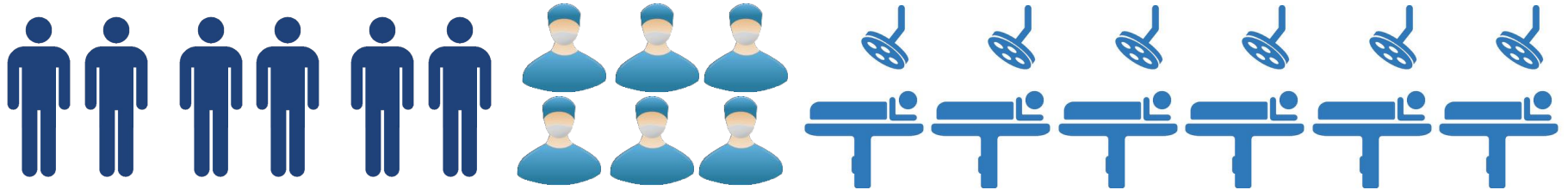


3. Law requires simultaneous surgeries for paired exchanges.

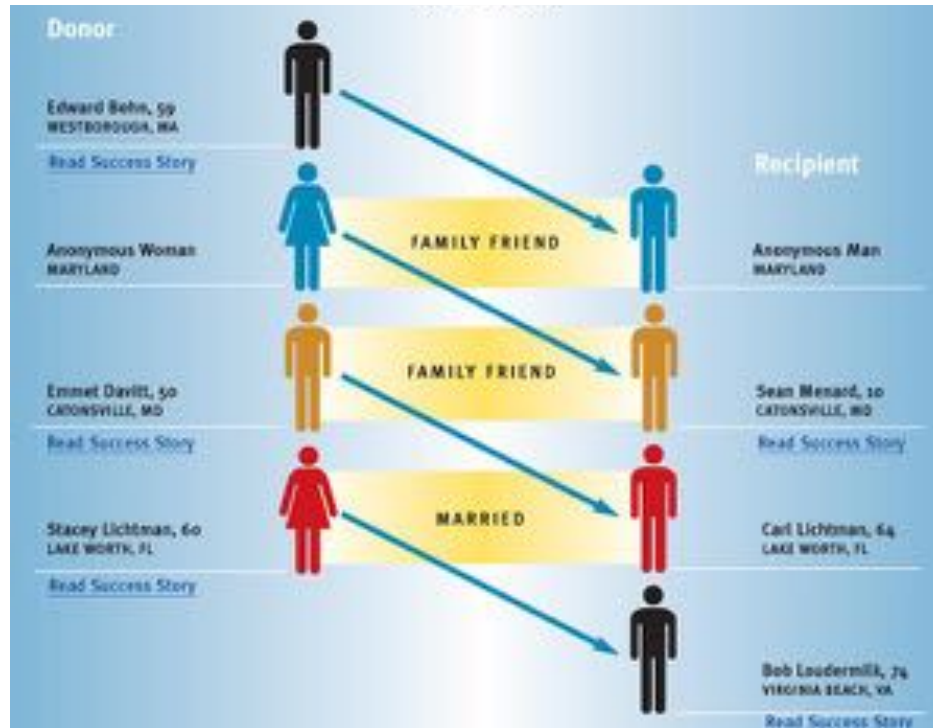
A cycle of 2 pairs requires 4 surgeons and 4 surgery rooms



A cycle of 3 pairs requires 6 surgeons and 6 surgery rooms



The solution: Non-simultaneous Extended Altruistic Donor (NEAD) Chains



University of Maryland Medical Center
November 2009

Methodology

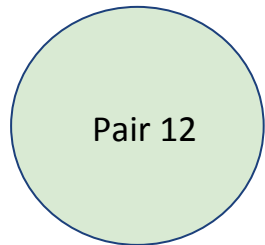
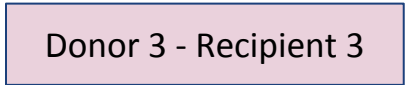
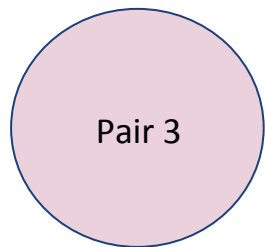
Simplification & Assumptions

- ❖ 1 living, altruistic non-directed donor (NDD) and 19 pairs
- ❖ The first donor is a living, altruistic non-directed (NDD) donor
- ❖ Only 2 tissue types: Rare (10% of population) and Frequent (90%)
- ❖ No constraint on chain length

Step 1: Generation of 20 donors and 19 recipients

Blood Type	Frequency
O	48.14%
A	33.73%
B	14.28%
AB	3.85%

Tissue Type	Frequency
Frequent	90.00%
Rare	10.00%



*Assume D1-R1 to always be the living NDD

	A	B	C	D	E
1					
2					
3					
4	Pair	D-Blood	O-Tissue	B-Blood	B-Tissue
5	D1-R1	O	Frequent		
6	D2-R2	B	Frequent	B	Frequent
7	D3-R3	B	Rare	B	Frequent
8	D4-R4	AB	Rare	B	Frequent
9	D5-R5	A	Frequent	B	Rare
10	D6-R6	AB	Rare	O	Frequent
11	D7-R7	A	Frequent	AB	Frequent
12	D8-R8	AB	Rare	O	Rare
13	D9-R9	B	Frequent	O	Rare
14	D10-R10	A	Frequent	A	Rare
15	D11-R11	O	Frequent	O	Rare
16	D12-R12	AB	Rare	B	Rare
17	D13-R13	O	Frequent	O	Rare
18	D14-R14	O	Frequent	B	Rare
19	D15-R15	B	Frequent	AB	Rare
20	D16-R16	A	Rare	A	Rare
21	D17-R17	A	Frequent	O	Frequent
22	D18-R18	A	Rare	O	Rare
23	D19-R19	O	Frequent	O	Frequent
24	D20-R20	B	Rare	O	Rare

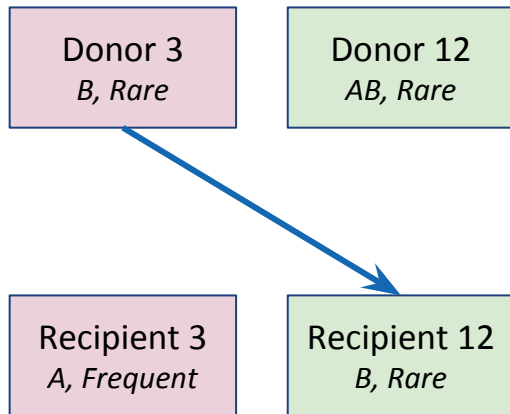
Step 2: Extract possible pair matches

Donor Blood Type	Possible Recipient Blood Types
O	O, A, B, AB
A	A, AB
B	B, AB
AB	AB

Tissue Type	Possible Recipient Tissue Types
Frequent	Frequent
Rare	Rare, Frequent

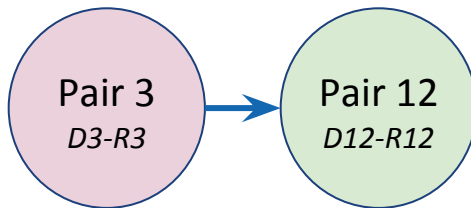
Example

Given blood and tissue types,
Donor 3 can donate to Recipient 12



=

Pair 3 can donate to Pair 12



Network Nodes

Step 3: Network optimization model

Decision Variables

$$y_{i,j} \begin{cases} 1 & \text{if pair } i \text{ donates a kidney to pair } j \\ 0 & \text{if pair } i \text{ does not donate to pair } j \end{cases}$$

Objective Function

$$\text{maximize} \quad \sum_{i=1}^{\text{no. of pairs}} Y_{i,j} \text{ for all } j$$

Maximize the number of kidneys donated

Constraints

$$\sum_{i=1}^{\text{no. of pairs}} Y_{NDD,i} - \sum_{i=1}^{\text{no. of pairs}} Y_{i,NDD} = 1$$

Non-directed donor (D1-R1) must donate first

$$\sum_{i=1}^{\text{no. of pairs}} Y_{i,j} - \sum_{i=1}^{\text{no. of pairs}} Y_{j,i} = 0$$

Inter-nodes conservation of flow

$$\sum_{i=1}^{\text{no. of pairs}} Y_{\text{end pair},i} - \sum_{i=1}^{\text{no. of pairs}} Y_{i,\text{end pair}} = -1$$

End of chain — last pair does not donate

$$\sum_{i=1}^{\text{no. of pairs}} Y_i + \sum_{i=1}^{\text{no. of pairs}} i \leq 1 + \sum_{i=1}^{\text{no. of pairs}} i$$

Each pair can only donate one kidney

Implemented Model

Step 1: Generation of 1 NDD and 19 pairs on Crystal Ball

	A	B	C	D	E	F	G	H	I
1	Bucket	Blood Type	Frequency		Bucket	Tissue Type	Frequency		
2	1	O	0.4834		1	Rare	0.1		
3	2	A	0.3373		2	Frequent	0.9		
4	3	B	0.2834						
5	4	AB	0.0385						
6									
7	DonorB	D-Blood	DonorT	D-Tissue		RecipientB	R-Blood	RecipientT	R-Tissue
8		4 AB		1 Rare			1 B		2 Frequent
9		1 O		2 Frequent			1 B		2 Frequent
10		4 AB		1 Rare			4 AB		1 Rare
11		1 O		1 Rare			4 AB		1 Rare
12		2 A		1 Rare			4 AB		2 Frequent
13		4 AB		2 Frequent			1 O		1 Rare
14		1 O		1 Rare			2 A		2 Frequent
15		3 B		2 Frequent			2 A		2 Frequent
16		3 B		1 Rare			1 O		2 Frequent
17		1 O		1 Rare			2 A		2 Frequent
18		4 AB		1 Rare			1 O		2 Frequent
19		4 AB		2 Frequent			1 O		1 Rare
20		3 B		1 Rare			1 O		2 Frequent

- **DonorB:** Donor blood type given by CB.Custom
- **DonorT:** Donor tissue type given by CB.Custom
- **RecipientB:** Donor blood type given by CB.Custom
- **RecipientT:** Donor tissue type given by CB.Custom
- V-lookup to return associating text

Donor	Receiving Ref	Receiving Age	Sex	Donor	Receiving		
1	11441	11441	M	11441	11441	11441	11441
2	11442	11442	M	11442	11442	11442	11442
3	11443	11443	M	11443	11443	11443	11443
4	11444	11444	M	11444	11444	11444	11444
5	11445	11445	M	11445	11445	11445	11445
6	11446	11446	M	11446	11446	11446	11446
7	11447	11447	M	11447	11447	11447	11447
8	11448	11448	M	11448	11448	11448	11448
9	11449	11449	M	11449	11449	11449	11449
10	11450	11450	M	11450	11450	11450	11450
11	11451	11451	M	11451	11451	11451	11451
12	11452	11452	M	11452	11452	11452	11452
13	11453	11453	M	11453	11453	11453	11453
14	11454	11454	M	11454	11454	11454	11454
15	11455	11455	M	11455	11455	11455	11455
16	11456	11456	M	11456	11456	11456	11456
17	11457	11457	M	11457	11457	11457	11457
18	11458	11458	M	11458	11458	11458	11458
19	11459	11459	M	11459	11459	11459	11459
20	11460	11460	M	11460	11460	11460	11460
21	11461	11461	M	11461	11461	11461	11461
22	11462	11462	M	11462	11462	11462	11462
23	11463	11463	M	11463	11463	11463	11463
24	11464	11464	M	11464	11464	11464	11464
25	11465	11465	M	11465	11465	11465	11465
26	11466	11466	M	11466	11466	11466	11466
27	11467	11467	M	11467	11467	11467	11467
28	11468	11468	M	11468	11468	11468	11468
29	11469	11469	M	11469	11469	11469	11469
30	11470	11470	M	11470	11470	11470	11470
31	11471	11471	M	11471	11471	11471	11471
32	11472	11472	M	11472	11472	11472	11472
33	11473	11473	M	11473	11473	11473	11473
34	11474	11474	M	11474	11474	11474	11474
35	11475	11475	M	11475	11475	11475	11475
36	11476	11476	M	11476	11476	11476	11476
37	11477	11477	M	11477	11477	11477	11477
38	11478	11478	M	11478	11478	11478	11478
39	11479	11479	M	11479	11479	11479	11479
40	11480	11480	M	11480	11480	11480	11480
41	11481	11481	M	11481	11481	11481	11481
42	11482	11482	M	11482	11482	11482	11482
43	11483	11483	M	11483	11483	11483	11483
44	11484	11484	M	11484	11484	11484	11484
45	11485	11485	M	11485	11485	11485	11485
46	11486	11486	M	11486	11486	11486	11486
47	11487	11487	M	11487	11487	11487	11487
48	11488	11488	M	11488	11488	11488	11488
49	11489	11489	M	11489	11489	11489	11489
50	11490	11490	M	11490	11490	11490	11490
51	11491	11491	M	11491	11491	11491	11491
52	11492	11492	M	11492	11492	11492	11492
53	11493	11493	M	11493	11493	11493	11493
54	11494	11494	M	11494	11494	11494	11494
55	11495	11495	M	11495	11495	11495	11495
56	11496	11496	M	11496	11496	11496	11496
57	11497	11497	M	11497	11497	11497	11497
58	11498	11498	M	11498	11498	11498	11498
59	11499	11499	M	11499	11499	11499	11499
60	11500	11500	M	11500	11500	11500	11500
61	11501	11501	M	11501	11501	11501	11501
62	11502	11502	M	11502	11502	11502	11502
63	11503	11503	M	11503	11503	11503	11503
64	11504	11504	M	11504	11504	11504	11504
65	11505	11505	M	11505	11505	11505	11505
66	11506	11506	M	11506	11506	11506	11506
67	11507	11507	M	11507	11507	11507	11507
68	11508	11508	M	11508	11508	11508	11508
69	11509	11509	M	11509	11509	11509	11509
70	11510	11510	M	11510	11510	11510	11510
71	11511	11511	M	11511	11511	11511	11511
72	11512	11512	M	11512	11512	11512	11512
73	11513	11513	M	11513	11513	11513	11513
74	11514	11514	M	11514	11514	11514	11514
75	11515	11515	M	11515	11515	11515	11515
76	11516	11516	M	11516	11516	11516	11516
77	11517	11517	M	11517	11517	11517	11517
78	11518	11518	M	11518	11518	11518	11518
79	11519	11519	M	11519	11519	11519	11519
80	11520	11520	M	11520	11520	11520	11520
81	11521	11521	M	11521	11521	11521	11521
82	11522	11522	M	11522	11522	11522	11522



Chain of 8
transplants in
a sample of 19
pairs with 82
possible
matches

Extending the Model: Stochastic Data

Stochastic Model: Data Generation

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Blood		Tissue														
2	D		R														
3	D		R														
4	D		R														
5	D		R														
6	D		R														
7	D		R														
8	D		R														
9	D		R														
10	D		R														
11	D		R														
12	D		R														
13	D		R														
14	D		R														
15	D		R														
16	D		R														
17	D		R														
18	D		R														
19	D		R														
20	D		R														
21	D		R														
22	D		R														
23	D		R														
24	D		R														
25	D		R														
26	D		R														
27	D		R														
28	D		R														
29	D		R														
30	D		R														
31	D		R														
32	D		R														
33	D		R														
34	D		R														
35	D		R														
36	D		R														
37	D		R														
38	D		R														
39	D		R														
40	D		R														
41	D		R														
42	D		R														
43	D		R														
44	D		R														
45	D		R														
46	D		R														
47	D		R														
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49	D		R														
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81	D		R														
82	D		R														
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87	D		R														
88	D		R														
89	D		R														
90	D		R														
91	D		R														
92	D		R														
93	D		R														
94	D		R														
95	D		R														
96	D		R														
97	D		R														
98	D		R														
99	D		R														
100	D		R														

Custom Probability Distributions

Donor Blood Type	Possible Recipient Blood Types
O	48.14%
A	33.73%
B	14.28%
AB	3.85%

Tissue Type	Possible Recipient Tissue Types
Frequent	90%
Rare	10%

Finding Feasible Pairs: Macro

```
Function checkFeasibility(Donor As String, Recipient As String)
  Select Case Donor
    Case "A"
      If Recipient = "A" Or Recipient = "AB" Then checkFeasibility = 1
    Case "B"
      If Recipient = "B" Or Recipient = "AB" Then checkFeasibility = 1
    Case "AB"
      If Recipient = "AB" Then checkFeasibility = 1
    Case "O"
      If Recipient = "A" Or Recipient = "B" Or Recipient = "AB" Or Recipient = "O" Then
checkFeasibility = 1
    Case "Frequent"
      If Recipient = "Frequent" Then checkFeasibility = 1
    Case "Rare"
      If Recipient = "Rare" Or Recipient = "Frequent" Then checkFeasibility = 1
  End Select
End Function
```

Overall Flow of Model



Combined Model w/ Stochastic Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1																
2																
3	Count	Donating Pair	Receiving Pair	Pair Feasibility	Give			Donor	Net Flow					Pair Feasibility	=	1
4	1	D1-R1	D2-R2	1				D1-R1	0	+		1				
5	1	D1-R1	D3-R3	1				D2-R2	0	+		0				
6	1	D1-R1	D4-R4	0				D3-R3	0	+		0				
7	1	D1-R1	D5-R5	0				D4-R4	0	+		0				
8	1	D1-R1	D6-R6	0				D5-R5	0	+		0		Maximum		
9	1	D1-R1	D7-R7	0				D6-R6	0	+		0				
10	1	D1-R1	D8-R8	0				D7-R7	0	+		0				
11	1	D1-R1	D9-R9	1				D8-R8	0	+		0				
12	1	D1-R1	D10-R10	0				D9-R9	0	+		0				
13	1	D1-R1	D11-R11	1				D10-R10	0	+		0				
14	1	D1-R1	D12-R12	0				D11-R11	0	+		0				
15	1	D1-R1	D13-R13	0				D12-R12	0	+		0				
16	1	D1-R1	D14-R14	0				D13-R13	0	+		0				
17	1	D1-R1	D15-R15	1				D14-R14	0	+		0				
18	1	D1-R1	D16-R16	0				D15-R15	0	+		0				
19	1	D1-R1	D17-R17	1				D16-R16	0	+		0				
20	1	D1-R1	D18-R18	0				D17-R17	0	+		0				
21	1	D1-R1	D19-R19	0				D18-R18	0	+		0				
22	1	D1-R1	D20-R20	0				D19-R19	0	+		0				
23	1	D2-R2	D1-R1	0				D20-R20	0	+		-1				
24	1	D2-R2	D3-R3	1												
25	1	D2-R2	D4-R4	1												
26	1	D2-R2	D5-R5	0												
27	1	D2-R2	D6-R6	0				D1-R1	0	+		0.052651579				
28	1	D2-R2	D7-R7	1				D2-R2	0	+		0.052651579				
29	1	D2-R2	D8-R8	1				D3-R3	0	+		0.052651579				
30	1	D2-R2	D9-R9	1				D4-R4	0	+		0.052651579				
								D5-R5	0	+		0.052651579				

Each pair can only donate one kidney

Additional Constraint to Incorporate Stochastic Data

$$Pair\ Feasibility_{ij} \geq Give_{ij}$$

Potential Results from Incorporating Stochastic

- ❖ Effects of altruistic donor's blood & tissue type on the optimal chain generated (i.e. Given a large enough pool of patients, does it matter if the first donor is O & R versus AB & F?)
- ❖ Optimal chain length (convergence rate of simulated chain lengths)

Analysis & Conclusion

Our Model's Solution

Length of chain = 8

Success rate of $8/19 = 42\%$

restricting donor pair

D1-R1 to D19-R19

D19-R19 to D6 R6

D6-R6 to D15-R15

D15-R15 to D2-R2

D2-R2 to D4-R4

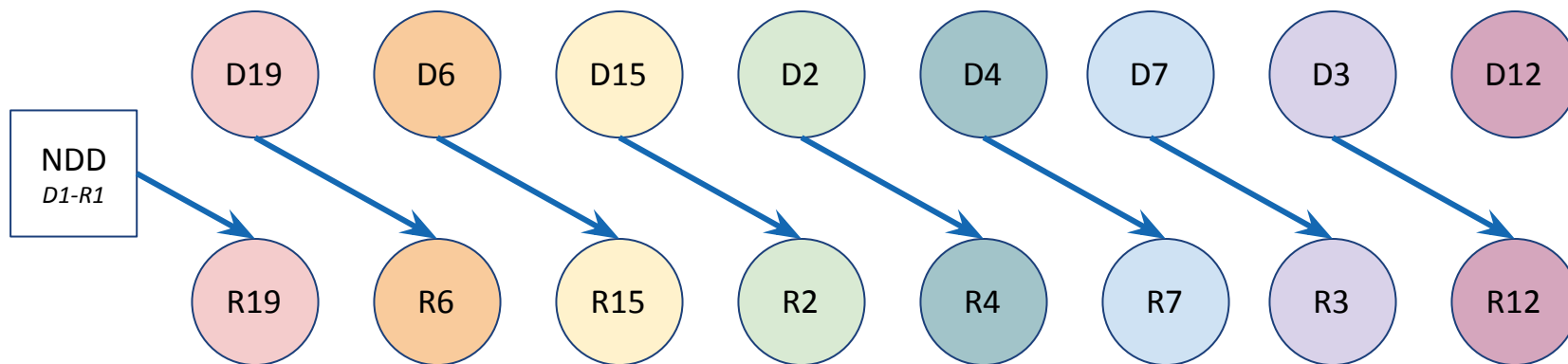
D4-R4 to D7-R7

D7-R7 to D3-R3

D3-R3 to D12-R12

sole receiver

8 Lives Saved!



Limitations

- ❖ Integrating stochastic data with network optimization model
- ❖ Lack of actual patient data



Refining the Model

❖ Incorporating weights for each edge that takes into account

- ❖ PRA percentages instead of “Rare” and “Frequent” tissue types
- ❖ Degree of compatibility
- ❖ Age
- ❖ Wait time
- ❖ Level of urgency
- ❖ Geographic proximity



❖ Optimizing for both kidney and plasma transplants



ALLIANCE
FOR PAIRED
KIDNEY
DONATION™

Thank you!

Questions?

HOW DO YOU BECOME AN
ORGAN DONOR?



Register as an organ donor at the DMV when you get or renew your driver's license.



Register online with your state: <http://bit.ly/StateRegistries>



Don't keep your decision a secret; share your stance on organ donation & encourage others to register, too.

**REGISTER AS AN ORGAN DONOR TODAY
TO SAVE LIVES!**