Incentivizing Participation of Compatible Pairs in Kidney Exchange Programs*

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Abstract

We simulate the impact of compatible pairs participating in a medium-sized kidney exchange program, where they engage in donor swaps only when recipients can obtain a kidney with a higher expected graft survival rate. Our results show that compatible pairs can indeed benefit from participation, and their involvement significantly increases the likelihood of finding matches for incompatible pairs, with a particularly pronounced effect for pairs that face the greatest challenges in finding compatible matches. This positive outcome is primarily driven by a shift in the pool's composition rather than an increase in its size. Moreover, we identify which compatible pairs, based on their observable characteristics, benefit the most from participating in the program.

Keywords: kidney paired donation, compatible pairs, kidney transplant

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1 Introduction

Kidney transplantation is the most effective treatment for most individuals with end-stage renal disease (ESRD), a condition where the kidneys can no longer function adequately. Patients with ESRD, who undergo transplantation, experience better outcomes than from any other treatment, improved quality of life, and are relieved from the time-consuming and onerous process of dialysis. However, the limited availability of organs results in higher patient mortality and a substantial gap between the demand for and supply of kidneys.

Living donor renal transplantation is the most promising solution for closing the gap between organ supply and demand, and grants a higher chance of success than organs from deceased donors. Yet, in some cases, a living donor's kidney may not be suitable for a recipient due to mismatches in blood (ABO incompatibility) or tissue types (HLA incompatibility) which can cause immediate graft rejection.

In such cases, a donor swap between two or more incompatible pairs can be arranged, creating a cycle of mutual donations that lead to successful transplants for all participating recipients. Kidney exchange programs (KEPs) work as clearing houses that periodically search for mutually compatible exchanges of donors in a pool of incompatible donor–patient pairs. Since the first application more than twenty years ago (see Delmonico [2004], Delmonico et al. [2004], Roth et al. [2004]), these programs have expanded all over the world, with more and more significant numbers.

Kidney exchange programs were historically established to circumvent ABO/HLA incompatibility, with the goal of maximizing the number of transplants of incompatible donor-recipient pairs, with considerations of match quality taking a secondary role to that of finding compatible matches.

However, as early as Roth et al. [2004], it was noted that these programs can also help recipients of compatible pairs find a better match. In fact, recent medical research (Jackson and Segev [2022]) supports the idea that kidney transplants from different living donors can

have substantially different outcomes. There is a broad range of donor factors known to impact recipient outcomes beyond ABO/HLA incompatibility, such as age and weight, and quantitative tools are now available to empirically compare potential living donors across many of these factors. Finding a suitable transplant, based on donor-recipient characteristics, results in longer graft survival that not only improves the recipient's welfare but also positively impacts future waiting lists by reducing the number of recipients who require a re-transplant.[1]

Despite the resulting suboptimal utilization of living donors, the kidney exchange systems in most European countries currently do not offer any incentives for compatible pairs to participate in exchanges. This shortcoming is the motivation of this paper.

We examine the impact of incentivized participation of compatible donor-patient pairs on the outcomes of kidney exchange programs. Our analysis is based on the principle that recipients in compatible pairs may benefit from participation by receiving a higher-quality kidney than their original donor could offer.

We estimate the potential benefits of compatible pair participation by simulating their impact on a medium-sized kidney exchange program, comprising 50 recipient-donor pairs per matching run—the average size of the Italian KPE. Most European KPEs, as well as some hospital- and region-based programs in the US, are of comparable or smaller scale. Notable exceptions include the UK and Spanish KPEs, which are significantly larger, enrolling approximately 250 and 100 recipient-donor pairs per matching run, respectively (see Biró et al. [2019])[2]. Additionally, we analyze which compatible pairs, based on their observable characteristics, may benefit the most from participating in the program.

[1]Median lifespan of a living- donor transplant kidney in US is less than 16 years, conditional on one year survival (Matas et al. [2015]). Around one-third of the patients who received a kidney transplant in Italy in 2023 had already undergone at least one previous transplant.

[2]Since the start of the program in June 2009 until the last matching run in September 2023, 883 recipients have been included in the Spanish KEP along with 906 donors. The mean number of participating donor-recipient pairs in the matching runs has been 98. Notably, only 21 donor-recipient pairs included were biologically compatible (ABO and HLA). The Spanish protocol does allow the inclusion of compatible pairs, but this option is unfrequently used by the transplant teams (Source: Organización Nacional de Transplantes, private communication).

The participation of compatible pairs offers several potential advantages.

Firstly, it can improve the quality of matches for compatible pairs by increasing graft survival rates.

Secondly, it may positively affect ABO/HLA incompatible pairs by improving the chances of incompatible pairs finding a match. Importantly, not every recipient has the same probability of finding a compatible donor. Blood-type O patients are less likely to find a compatible organ, because they can only receive a kidney from a donor with the same O blood-type. Recipients, who have donors with blood-type different than O, compete for a relatively scarce population of "overdemanded" blood-type $A/B/AB$ patients with blood-type O donors. This disparity is reflected in the distribution of recipient-donor pairs in traditional kidney exchange programs, where only incompatible pairs participate. These programs often show a high prevalence of blood-type O recipients paired with incompatible donors of other blood types, such as A, B, or AB. Therefore, the participation of compatible pairs can benefit incompatible pairs through changes in both the size and composition of the pool.

Thirdly, it may also reduce the need for desensitization - a medical procedure enabling recipients to accept organs from HLA or ABO-incompatible donors. Desensitization is a process that removes harmful antibodies from the blood stream. The procedure is both costly and often associated with suboptimal outcomes. Specifically, ABO-incompatible kidney transplants are linked to higher mortality rates and an increased risk of graft loss compared to ABO-compatible transplants within the first three years post-transplantation (Scurt et al. [2019]).

Although some compatible pairs may decide to participate in a kidney exchange program for altruistic reasons, it is also legitimate to acknowledge that the number of compatible pairs who may accept to participate can positively depend on the potential advantage that their participation may bring to them. Therefore, it is relevant to have a reliable measure of quality in kidney transplant. In order to measure this potential benefit we employ the Living Kidney Donor Profile Index (LKDPI) - a quality index recently developed in the medical

literature. Introduced by Massie et al. [2016], LKDPI is a scoring system used to evaluate the quality and potential outcomes associated with kidneys from living donors. This index is constructed for every donor-recipient pair and accounts for living donor characteristics (age, BMI, donor history of cigarette use, blood pressure, and others) and match characteristics (number of HLA mismatches, biological relation between donor and recipient, donation from a male recipient to a male donor, and others) associated with risk of all-cause graft loss after transplantation. A lower LKDPI score indicates a better predicted long-term kidney function after transplantation, while a higher score suggests a higher risk of graft failure.[3] To provide a more comprehensive evaluation, we translate this index into Expected Graft Survival (EGS) years, as described in Li et al. [2019]. This approach enables a more nuanced assessment of the potential benefits of kidney exchange programs, allowing for meaningful quantification of the expected advantages for the donors of participating pairs.

Our study simulates three scenarios to assess how the inclusion of compatible pairs could potentially improve outcomes within a medium-sized kidney exchange program using real data on donor-recipient pairs from the Kidney and Pancreas Transplant Center of the University of Padua. Scenario 1 involves a pool comprising 50 incompatible pairs and 20 compatible pairs. In this scenario, compatible pairs engage in donor swaps only if recipients experience an expected benefit. Scenario 2 represents a baseline configuration with a pool of 50 incompatible pairs. Scenario 3 involves a pool of 70 incompatible pairs, to evaluate outcomes in a larger, incompatible-only pool setting.

By comparing these scenarios, we aim to distinguish the effects resulting from changes in both the size and composition of the pool due to the participation of compatible pairs. Our findings show that recipients in compatible pairs have an average probability of around 31% of finding a better match. In terms of the average EGS we observe an improvement of approximately 1.5 years for these pairs.

The involvement of compatible pairs significantly enhances the probability of finding

[3] Although LKDPI is a practical tool for comparing and evaluating the quality of living donor transplants, it remains underutilized in current studies, with a few notable exceptions, such as Akbarpour et al. [2024].

matches for incompatible pairs, with a particularly strong effect for underdemanded pairs. This positive outcome is primarily driven by a change in the composition of the pool rather than an increase in its size. In comparing Scenario 1 with the other scenarios, we observe a notable increase in the fraction of incompatible pairs who have a probability greater than 25% of finding an exchange. Specifically, this fraction rises from approximately 20% in the other scenarios to about 45% in Scenario 1. However, when comparing Scenario 2 with Scenario 3, no significant differences emerge for incompatible pairs in terms of their probability to find an exchange, despite a 40% increase in the size of the pool.

For blood-type O patients with blood-type-incompatible donors, the fraction of these pairs with a probability to find an exchange greater than 25% increases significantly from nearly 0% in Scenarios 2 and 3 to around 25% in Scenario 1, meaning that most of the gains is driven by these pairs who are hard to match.

Additionally, we analyze which compatible pairs, based on their observable characteristics, benefit the most from participating in the program. We find that older donors, smoking donors, donors with higher systolic blood pressure, male recipients, and biologically related donor-recipient pairs are all characteristics with positive marginal effects on the probability of finding an exchange.

1.1 Literature Review

The introduction of Kidney Exchange Programs as a market-design challenge is credited to Roth et al. [2004]. They were the first to consider a wider system of exchanges among incompatible living donors and initial recipients[4]. They considered how three-way and larger scale exchanges among incompatible pairs, as well as indirect exchanges, could be arranged efficiently and incentive compatibly, within constraints of the social and legal environment. This

[4]In 2000, the United Network for Organ Sharing initiated pilot testing of living kidney donations by using kidneys from living incompatible donors through an exchange arrangement between two pairs. Many transplant centers have also started pilot indirect exchange programs (Ross and Woodle [2000]), where a potential donor who is incompatible with his intended recipient donates his kidney to the cadaveric waiting list, and his paired recipient receives priority for the next compatible cadaveric kidney.

analysis laid the groundwork for KEPs and spurred efforts to improve matching mechanisms and address equity and efficiency.

Both the practice of kidney exchange and theoretical contributions to market design have primarily focused on fostering participation of incompatible pairs in kidney exchanges and maximizing the total number of transplants more than improving the expected quality of transplants. While the inclusion of compatible pairs within KEPs was first proposed by Ross and Woodle [2000], most theoretical studies following this work assumed that recipients have dichotomous preferences over compatible organs from living donors (i.e. are indifferent between compatible kidneys and simply prefer compatible kidneys to incompatible ones), and therefore there is no room for an improvement for a compatible pair, at least in a static model of kidney exchanges (e.g., Roth et al. [2005], Roth et al. [2007], Sönmez and Ünver [2014], and more recently Cheng and Yang [2021]). Notably, a few theoretical papers stray away from the assumption of dichotomous preferences over compatible organs and consider heterogeneous quality in compatible living donor kidney organs. For instance, Andersson and Kratz [2019] argue that desensitization motivates an extension of the preference domain, allowing patients to distinguish between compatible donors and half-compatible donors (i.e. blood group incompatible donors who become compatible after desensitization). They show that number of transplants in pairwise kidney exchange programs can be substantially increased by providing an incentive for patients with "half-compatible" donors to participate in kidney exchange programs. Nicolò and Rodríguez-Álvarez [2012] proposed a model that implicitly incorporates the additional component of transplant quality decisions and patients' preferences to the mechanism design approach introduced by Roth et al. [2004]. Nicolò and Rodríguez-Álvarez [2017] consider a model in which patients' preferences are such that they prefer kidneys from compatible younger donors to kidneys from older ones.

In theoretical studies and in practice, participation of compatible pairs is often motivated by altruism. Recent studies that utilize the idea that quality of a transplant matters, on the contrary, try to incentivize compatible pairs' participation in an exchange by offering benefits

to them. For instance, Sönmez et al. [2020] consider a dynamic setting where compatible pairs participation can be rewarded by promising a future benefit in case their recipient needs a re-transplant (priority in a deceased donor waiting list). This approach yields benefits in terms of enhanced access to living donor transplants and decreased competition for deceased donor transplants. Our approach complements theirs by considering the direct and immediate benefits of higher transplant quality for compatible pairs. Some existing programs utilize compatible pairs with unfavorable donor-recipient characteristics. Bingaman et al. [2012] documents a program where compatible pairs with donors over fifty years old were advised to participate in an exchange for the opportunity to find a younger compatible donor, while Basu et al. [2020] analyzed results from kidney exchange programs, where compatible pairs participate for altruistic reasons or due to particular combinations of medical characteristics such as age and weight. Recipients of these pairs received kidneys from donors with lower LKDPI scores than their actual donor.

This paper argues that diverse types of compatible pairs can benefit from kidney exchanges, but it is important to assess which types have higher chances to benefit from participation in these programs. Accurately quantifying these benefits is essential for creating effective incentives for compatible pairs to participate, as well as for successfully implementing such programs.

A few studies have investigated the factors influencing compatible pairs' willingness to participate in KEPs, especially in countries like the US and UK, where some compatible pairs are already participating. Fortin et al. [2021] identified through surveys and qualitative interviews that these factors include the possibility of finding a better kidney, policies prioritizing repeat transplantation, and facilitating additional transplants. Similarly, Chipman et al. [2022], reports, based on data from the National Kidney Register, that actual donors were younger, had a higher BMI, were less likely to have blood type O, and had higher glomelar filtration rate than original donors.

Regarding the benefits of compatible pairs' participation for incompatible pairs, Gentry

et al. [2007] shows that compatible pairs help to balance blood group distributions in incompatible pools. In their approach, Li et al. [2019] introduced a model incorporating both compatible and incompatible agents to study the advantages of compatible pairs inclusion. Their findings show significant potential, nearly doubling the number of transplants for incompatible pairs and improving match quality for recipients in compatible pairs, increasing expected graft survival by 1 to 2 years. Although related, our methodology diverges from theirs. We consider a pool of incompatible pairs that remain in the mechanism until matched and an impatient pool of compatible pairs. In contrast to the continuous-time setting, where compatible pairs arrive and are matched sequentially, our model utilizes multiple matching runs where the remaining incompatible pairs persist in the pool, and new sets of incompatible and compatible pairs arrive with each round. Compatible pairs, however, can only participate in one matching run before exiting the pool.

While existing studies emphasize the impact of compatible pairs' participation on the overall pool and particularly on outcomes for incompatible pairs, our interest lies as well in the probability of compatible pairs finding an exchange within a mechanism that accommodates their participation. Our paper is the first one to show that compatible pairs can benefit directly from KEPs, using the LKDPI to quantify these gains. Additionally, we identify specific characteristics that may enhance the likelihood of compatible pairs successfully engaging in exchanges.

2 Institutional Settings

In 2024, approximately 5,800 patients are waiting for a kidney transplant in Italy, with an average waiting time of over three years.[5] In 2023, a total of 1,898 kidney transplants from deceased donors and 346 from living donors were performed. Among these, only 15 transplants were conducted through the kidney exchange program. The Italian kidney exchange program has been in effect since 2005; however, it remains underdeveloped, with an average

[5]Source CNT https://trapianti.sanita.it/statistiche/liste_attesa_1.aspx

of fewer than 10 transplants conducted per year in the last decade.[6] The Italian kidney exchange program only allows 2 or 3-size cycles and matching runs are performed at a quarterly basis. Only incompatible pairs are enrolled in the program, and over the last decade, the average size of the pool has been approximately 52 pairs, with a slight increase observed in the past three years. In the past year 2023, 35 new pairs enrolled in the program, and 15 pairs underwent transplantation within the kidney exchange program. Additionally, 30 pairs exited the program: 16 pairs because the recipient received an organ from a different program (primarily from a deceased donor), and 14 pairs because the recipient was deemed ineligible for a transplant.

In addition to the standard kidney paired donation program, there are some active international agreements. Moreover, since 2019, in Italy pairs who participate to the kidney exchange program may also enroll in the DEC-K (Deceased Kidney Paired Exchange) program in which a recipient of an incompatible pair can obtain absolute priority on the deceased donor list if the intended donor is willing to donate their organ to a recipient of another incompatible pair creating a chain of donation initiated by a deceased donor organ (see Furian et al. [2019] and Furian et al. [2020]). These programs complement the standard kidney exchange program. In the current study, we compare only the effect of introducing some compatible pairs on the standard program.

3 Simulations

We consider three possible scenarios to analyze how the participation of compatible pairs could affect the outcomes of a medium-sized kidney exchange program like the one in Italy, which these scenarios closely mirror. In our benchmark scenario (Scenario 2), the pool consists of 50 incompatible pairs.

In Scenario 1— our primary focus— the pool is composed of 50 incompatible pairs and

[6] Although Italian legislation allows for chains of donations initiated by samaritan donors, there have been no such chains since 2019, with an average of only 1.5 Samaritan donors during the previous five-year period. See CNT Report 2023.

20 compatible pairs, representing a conservative approach with a 40% increase in the size of the pool. The 20 pairs account for approximately 5% of the number of compatible pairs transplanted each year in Italy.

In Scenario 3 the pool is composed by 70 incompatible pairs.

It is important to emphasize that our goal is not to estimate how many compatible pairs would be willing to participate in an incentivized kidney exchange, but rather to assess the effect of this modification to the pool.

Comparing Scenario 2 to Scenario 1 allows us to estimate the effects of changes in both the size and composition of the pool, while comparing Scenario 2 to Scenario 3—where only the size has increased—will enable us to disentangle the effects of composition from size.

To ensure conservative results, we impose specific constraints on the exchanges permitted in our simulations. First, mirroring most of the existing KPE programs, including the current Italian program, we restrict exchanges to 2-cycle and 3-cycle arrangements. Second, a compatible pair is allowed to participate in an exchange cycle only if it directly benefits the recipient. While altruistic participation of compatible pairs in kidney exchange programs is commendable, this conservative approach ensures that the simulation reflects realistic and implementable policies. Specifically, we impose that a compatible pair should participate in an exchange only if the expected quality of the transplant is superior to the transplant with their original donor.

An exchange is considered welfare improving for a compatible pair only if it entails a minimum 20-point reduction in LKDPI compared to the LKDPI of the transplant with the original intended donor.[7]

In our simulations, the observation of interest is a recipient/donor pair. For each observation of interest, we run 1000 repetitions (experiments), randomly drawing a matching pool with the specified size and composition characteristics, and measure the average outcome of

[7]The average LKDPI for compatible pairs in our data set is 21.5. According to Li et al. [2019] reducing the LKDPI from 20 points to 0 corresponds to an estimated increase of approximately two years in the survival time of the transplanted organ.

these experiments.

The simulation procedure involves several components:

1) A kidney exchange solver. It receives a problem instance defined as a pool of pairs who want to exchange donors among themselves. It outputs a solution that maximizes the number of exchanges among the pairs.

2) A scheduling simulator. It organizes the pairs on a timeline to enter the kidney exchange chronologically. Specifically, every experiment consists of three matching runs, where the observation of interest is only included in the third matching run. Incompatible pairs that are not matched in a matching run participate in the next consecutive matching run, while all compatible pairs, whether matched or not, are redrawn after every matching run. This approach simulates a historical formation of the pool, as pairs entering the pool are more likely to encounter hard-to-match pairs that have already participated in previous matching runs.

The kidney exchange solver translates the problem instance into a mathematical integer linear programming (ILP) problem. For this purpose a classical cycle formulation is used (for a review of the different optimization methods see Péter Biró [2021]. The ILP problem is solved using the Gurobi solver (Gurobi Optimisation).

For illustration purposes, an experiment using Scenario 1 and a compatible pair i can be outlined as follows.

Draw a random sample of 50 incompatible pairs (ICPs) and 20 compatible pairs (CPs) from the dataset.

Let $t = \{1, 2, 3\}$ denote the matching run index.

- Let K_{ic}^t denote the set of incompatible pairs that successfully find an exchange in matching run t and let $k_{ic}^t = |K_{ic}^t|$ denote the cardinality of the set, representing the number of incompatible pairs that successfully find an exchange in matching run t.

1. **First Matching Run (MR1)**: Conduct the first matching run with this sample. After the first matching run: Remove the K_{ic}^1 incompatible pairs that successfully

participated in an exchange. Remove all 20 compatible pairs, regardless of whether they participated in an exchange.

2. **Second Matching Run (MR2)**: Introduce k_{ic}^1 new ICPs and 20 new CPs from the data into the pool, combining them with the leftover ICPs after MR1. Perform a second matching run with this pool. Remove the K_{ic}^2 incompatible pairs that successfully participated in an exchange. Remove all 20 compatible pairs, regardless of whether they participated in an exchange.

3. **Third Matching Run (with Pair i)**: Add the compatible pair i (the observation of interest), along with 19 new CPs and k_{ic}^2 new ICPs to the remaining ICPs after MR2. Form a new pool with these pairs and conduct a third matching run, recording the matching outcome specifically for pair i.

The outcome of the experiment contains information on whether the observation of interest (pair i) has found an exchange and, if so, the LKDPI of the transplant. Knowing these results for each pair i, each scenario, and all experiments, we then calculate the probability of finding an exchange in the kidney exchange as the average number of successes (exchanges) out of 1000 repetitions. Additionally, we calculate the average LKDPI in cases of success by dividing the total sum of the LKDPIs in case of success by the number of successes.

4 Data Set

Data used for this project contain information on donor-recipient pairs of all living transplants performed in the decade 2010-2019 at the Kidney and Pancreas Transplant center of the University of Padua, the largest center in Italy for living donor kidney transplants, as well as pairs that were incompatible and later registered for the national exchange program.[8]

[8]In 2023, the Kidney and Pancreas Transplant Unit of the University of Padua performed 46 transplants from living donors. The number of transplants from living donors that have been conducted at the Kidney and Pancreas Transplant center of the University of Padua represents approximately 17.3% of all such transplants performed in Italy.

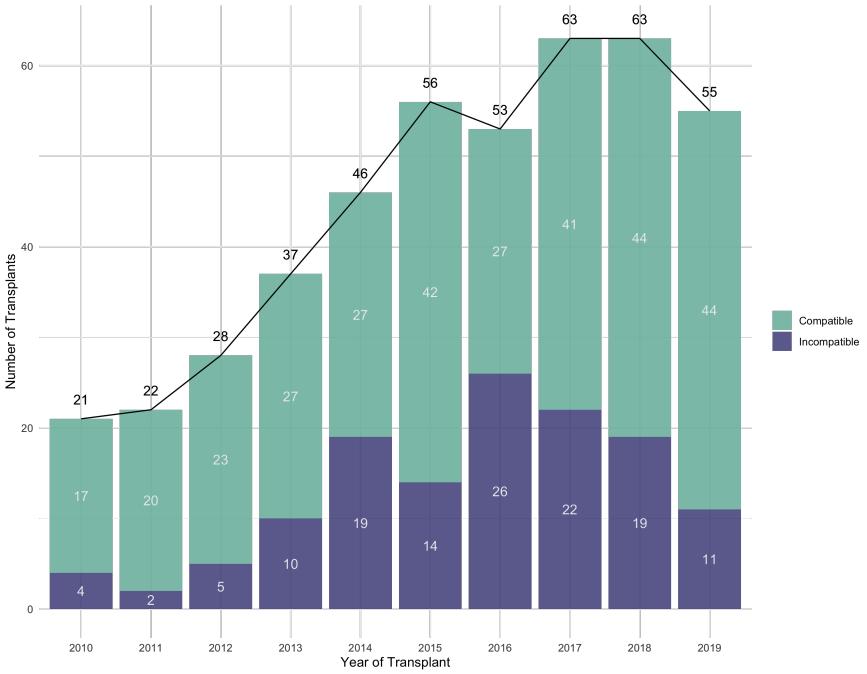

Figure 1: Number of transplants conducted in the largest transplant centre in Italy per year.

Figure 1 summarizes transplant activity from 2010 to 2019 at the Kidney and Pancreas Transplant Center of the University of Padua. The number of compatible pairs that were transplanted with their original donors raises annually, while the number of incompatible pairs that were transplanted in the centre with the means of desensitisation tends to vary unevenly from year to year.

Prior to COVID, all donor-recipient pairs enrolled in the center were divided into three categories based on their compatibility status: compatible pairs, incompatible pairs, and those pairs whose recipient needs to undergo a desensitization procedure to overcome the (ABO/HLA) incompatibility barrier.

A pair was deemed incompatible if there is a ABO mismatch between the donor and recipient, if the donor has HLA that are prohibited for the recipient or if both conditions apply. Pairs whose recipients could undergo a desensitization procedure to overcome the ABO/HLA incompatibility barrier were typically transplanted. All (fully) compatible pairs were transplanted with their original donors.

We simulated a kidney exchange program with two types or donor/recipient pairs, compatible and incompatible ones, the latter including those previously deemed unsuitable or subjected to desensitization. This approach aligns with post-COVID trends and physician recommendations to reduce desensitization and direct such pairs to KEP program.

The whole set of pairs consists of 312 initially compatible pairs, 105 pairs that underwent desensitization, and 27 fully incompatible pairs. This results in a total of 312 compatible pairs and 132 incompatible pairs used in our analysis, representing 70% and 30% of the dataset, respectively.

	Donors		**Recipients**	
	Male	Female	Male	Female
n	124 (16.23 %)	320 (83.72 %)	285 (47.26 %)	159 (52.74 %)
Mean values				
Age (y.o.)	53	53	45	42
Weight (kg)	80.96	64.64	74.59	59
Height (cm)	175.1	162.2	173.8	162.7
BMI*	25.98	24.55	24.64	21.89
eGFR†	94.44	93.55	9.2	9.8
SBP‡	126.85	123.18		
Frequency (%)				
Diabetes			3.86	1.26
Hepatitis			1.75	3.14
Desensitisations			23.16	16.42
Hypertension	21.77	18.13		
Smoking	50	36.56		
Race: Caucasian	96.8	97.2	99.3	96.2
Blood group: A	41.9	33.1	38.9	42.8
Blood group: B	12.1	12.2	13	10.7
Blood group: AB	1.6	5.6	3.2	5
Blood group: O	44.4	49.1	44.9	41.5
—N— = 444				

Notes: *according to WHO recommendations BMI in $[18.5; 24.9]$ denotes Normal weight; †eGFR ≥ 90 is in the normal range, and eGFR < 15 means kidney failure; ‡SBP assumed to be elevated if within $[120; 129]$, and normal if below 120).

Table 1: Donors' and recipients' characteristics.

The dataset includes a comprehensive set of donor and recipient characteristics, some of which are summarized in Table 1. For every pair, we observe recipient and donor factors (age, gender, race, weight, height, body mass index (BMI), blood group, their biological relationship, list of human leukocyte antigens (HLA)), recipient medical history (primary cause of kidney failure, presence of comorbidities [hepatitis, diabetes], creatinine clearance, list of prohibited antigens), treatments received (dialysis type, dialysis duration (months), nephrectomy), donor characteristics (hypertension, presence of any comorbidities, systolic blood pressure (SBP), smoking status), transplant factors (date of transplant, ABO compatibility, time of cold and hot ischemia, desensitisation and its reason [ABO, HLA, or both], rejection features (cause and date of graft loss and death), and graft function (creatinine level and its clearance, estimated glomerular filtration rate (eGFR)). This unique dataset allows us to calculate the exact LKDPI for every potential transplant between any recipient and donor included in it.

5 Results

5.1 Expected gains for Incompatible Pairs

To assess the impact of introducing compatible pairs into the matching pool on the likelihood that incompatible pairs may find an exchange, we can analyze the inverse cumulative probability of finding an exchange for the incompatible pairs. Figure 2 illustrates these inverse probabilities for the three scenarios. The interpretation of this inverse cumulative is straightforward: for example, in Scenario 1 (with the introduction of compatible pairs), approximately 30% of incompatible pairs have a probability strictly greater than 50% of finding an exchange.[9]

A key observation is that Scenarios 2 and 3 are quite similar, indicating that simply

[9] Approximately 83% of pairs in Scenario 1 have a probability strictly greater than 0%, corresponding to the 110 pairs with a non-zero probability of finding an exchange.

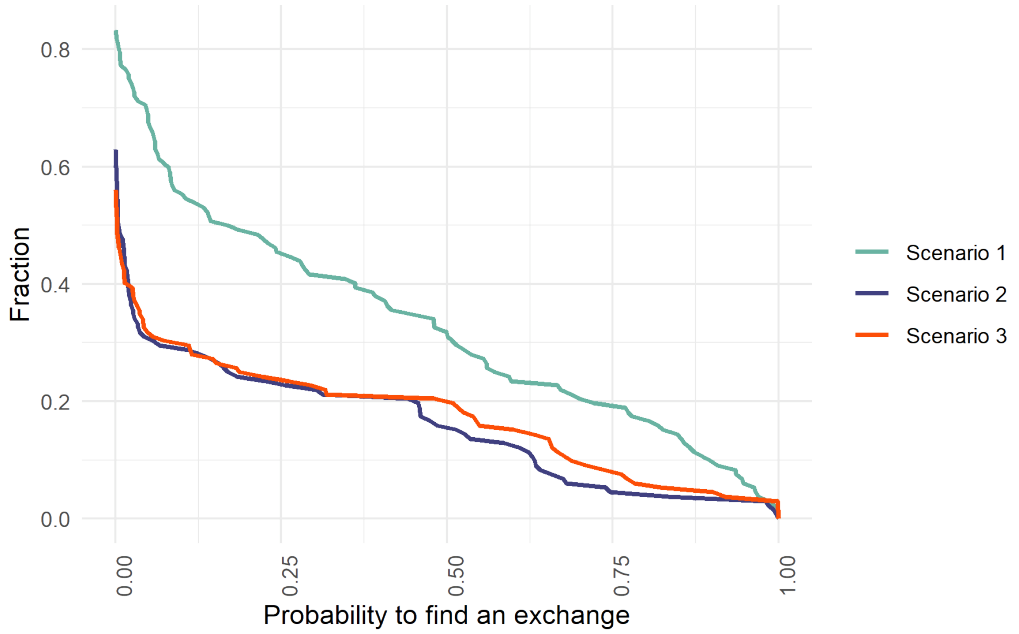

Figure 2: Inverse of the cumulative probability ($\mathbb{P}(X > t)$) to find an exchange for incompatible pairs.
Note: Scenario 1): 20 CPs and 50 ICPs, Scenario 2): 50 ICPs, Scenario 3): 70 ICPs.

increasing the size of the incompatible pair pool by 40% (from 50 to 70 pairs) does not significantly impact the probability of finding an exchange. However, changing the composition of the pool (Scenario 1 compared to Scenario 3) has a notable effect on the probability of finding an exchange. For instance, the fraction of pairs with a probability strictly higher than 25% to find an exchange increases from around 20% to approximately 45% with the participation of compatible pairs.

More specifically, in Table 2, we see that out of a total of 132 incompatible pairs, 110 pairs have a non-zero probability of finding an exchange in Scenario 1, versus 83 pairs in Scenario 2 and 74 pairs in Scenario 3. Put differently, the average probability of finding an exchange increases from 16% in Scenario 2 and 18% in Scenario 3 to 33% in Scenario 1.

It is important to note the trade-off between the quantity and quality of transplants for incompatible pairs. An increase in the number of transplants is associated with a decrease in the expected quality of transplants among incompatible pairs with a non-zero probability

	Scenario (1) *20CP + 50 ICP*		Scenario (2) *50 ICP*	Scenario (3) *70 ICP*
	(1) CP	(2) ICP	(3) ICP	(4) ICP
Num. pairs with nonzero Pr(exchange)	267	110	83	74
(%)	(85.58)	(83.33)	(62.88)	(56.06)
Average Pr(exchange) among pairs - all	0.308	0.331	0.161	0.177
(s.d.)	(0.324)	(0.346)	(0.278)	(0.302)
Average Pr(exchange) among pairs - nonzero	0.360	0.397	0.256	0.316
(s.d.)	(0.322)	(0.343)	(0.315)	(0.346)
Expected quality of a transplant among pairs with nonzero Pr(exchange)				
in LKDPI units (Average)	-4.690 (25.72)*	27.16	15.19	14.35
max	32.72	57.30	51.05	55.68
min	-35.02	-7.078	-19.1	-19.26
in years of graft survival (Average)	15.92 (11.02)*	10.66	12.45	12.62
max	22.81	16.13	18.73	18.76
min	9.854	7.267	7.852	7.414

Notes: *average quality of initial transplants for CP with nonzero Pr(exchange) is in brackets; total number of ICP in the data: 132; total number of CP in the data: 312.

Table 2: Probabilities of participating in an exchange according to the three scenarios

of finding an exchange (keeping in mind that the alternative for these pairs is to have no exchange). The average LKDPI for incompatible pairs is 27 points in Scenario 1, while it equals to 15 and 14 points in Scenarios 2 and 3, respectively.

5.1.1 Expected gains for "underdemanded" incompatible pairs

A living donor's kidney may not be suitable for a recipient due to mismatches in blood (ABO incompatibility) or tissue types (HLA incompatibility), with the first cause of incompatibility being three times more likely than the second one. Blood-type O patients are particularly disadvantaged by these biological barriers, as they can only receive organs from blood-type O donors. Conversely, blood-type A patients can receive transplants from both blood-type A and O donors, blood-type B patients from types B and O, and blood-type AB patients from all blood types.[10] This disparity impacts blood-type O patients' likelihood of benefiting from kidney paired donation. For instance, a blood-type O patient with a blood-type-incompatible A donor might exchange with a blood-type A patient who has an O donor. However, because the blood-type A patient and O donor are naturally compatible, they are less likely to enter an exchange program unless they face tissue-type incompatibility. This results in a large pool of "underdemanded" blood-type O patients with recipients who have blood-type different than O, or blood-type A or B patients with recipients who have a blood-type AB. This pool of "underdemanded" are competing for the group of "demanded" pairs, which includes the following types[11] (Ünver [2010], Sönmez and Ünver [2014]): "overdemanded", "self-demanded", and "reciprocally" demanded. The "overdemanded" type refers to pairs with non-O blood-type recipients and O donors but with HLA incompatibility. The "self-demanded" type refers to pairs with the same blood-group type for the recipient and donor but with HLA incompatibility. The "reciprocally" type refers to pairs with blood-type A

[10] In Italy around 47% of the population has blood-type O and 42% blood type A.

[11] Another common measure to identify recipients who have lower probability to find a compatible donor is the Panel Reactive Antibody (PRA) level. The percent PRA value is a measure of a patient's level of sensitization to HLA antigens. The PRA reflects the percentage of the general population that a potential recipient makes antibodies (is sensitized) against. For example, a patient with a PRA of 75% will be incompatible with 75% percent of potential donors. Unfortunately, our dataset does not include such information.

recipients and B donors and vice versa. This categories can be summarized as (Donor-Recipient pairs):

$$\textit{Underdemanded} \quad \mathcal{P}^U = \{\text{A}-\text{O}, \text{B}-\text{O}, \text{AB}-\text{O}, \text{AB}-\text{A}, \text{AB}-\text{B}\}$$

$$\textit{Demanded} \begin{cases} \mathcal{P}^O = \{\text{O}-\text{A}, \text{O}-\text{B}, \text{O}-\text{AB}, \text{A}-\text{AB}, \text{B}-\text{AB}\} \\ \mathcal{P}^S = \{\text{O}-\text{O}, \text{A}-\text{A}, \text{B}-\text{B}, \text{AB}-\text{AB}\} \\ \mathcal{P}^R = \{\text{A}-\text{B}, \text{B}-\text{A}\} \end{cases}$$

Given the disparity, it is not surprising then that the participation of compatible pairs could significantly benefit underdemanded pairs. Figure 3 shows the inverse cumulative distribution for underdemanded pairs and for demanded pairs across three scenarios.

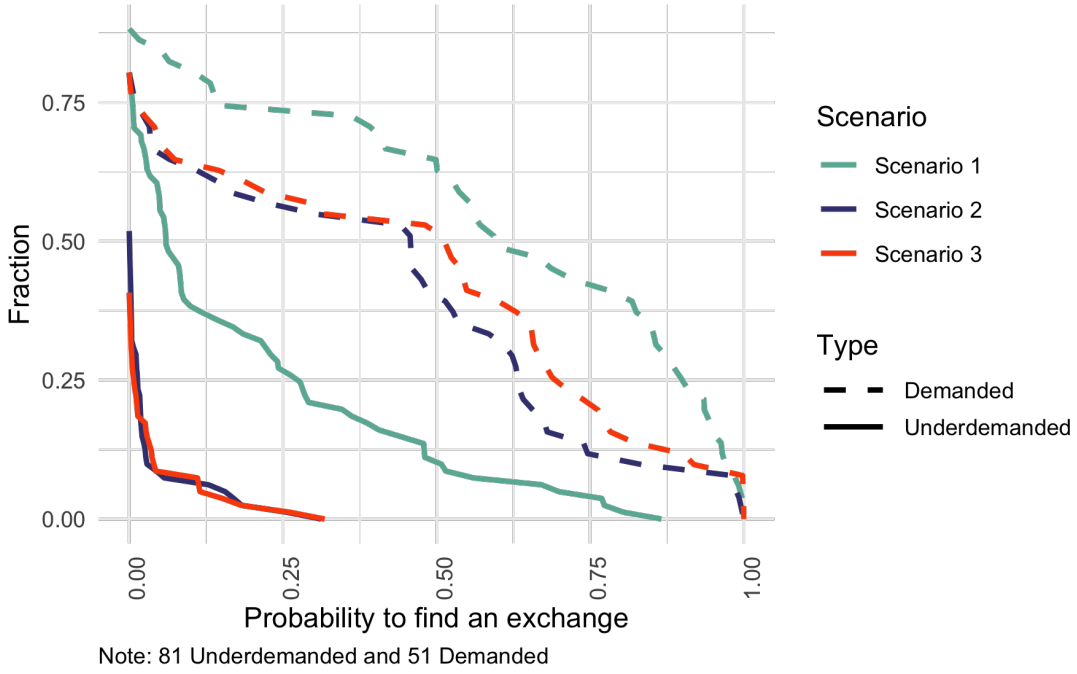

Figure 3: Inverse of the cumulative probability ($\mathbb{P}(X > t)$) to find an exchange for underdemanded and demanded pairs.
Note: Scenario 1): 20 CP and 50 ICP, Scenario 2): 50 ICP, Scenario 3): 70 ICP.

Scenarios 2 and 3 are quite similar for both underdemanded and demanded pairs, indicating that merely increasing the pool size (from 50 to 70 incompatible pairs) has minimal effect. It is clear that introducing compatible pairs (Scenario 1) has a greater impact on

underdemanded, even though the probability of finding an exchange is always higher for demanded pairs. For example, for underdemanded pairs, the fraction with a probability higher than 25% to find an exchange increases from nearly 0% in Scenarios 2 and 3 to around 25% in Scenario 1. In contrast, for demanded pairs, this fraction increases from about 60% to almost 75%.

5.2 Expected gains for compatible pairs

Scenario 1 involves the participation of compatible pairs in a kidney exchange program. Compatible pairs only exchange their donors if the recipients' LKDPI score decreases by at least 20 points compared to the score of the initial transplant. According to Table 2, the average probability of finding a better match through this exchange is 31%. Moreover, out of the 312 pairs analyzed, only 45 pairs have a 0% probability of finding a better match. This indicates that the vast majority of pairs have some potential for improving their match through the KEP.

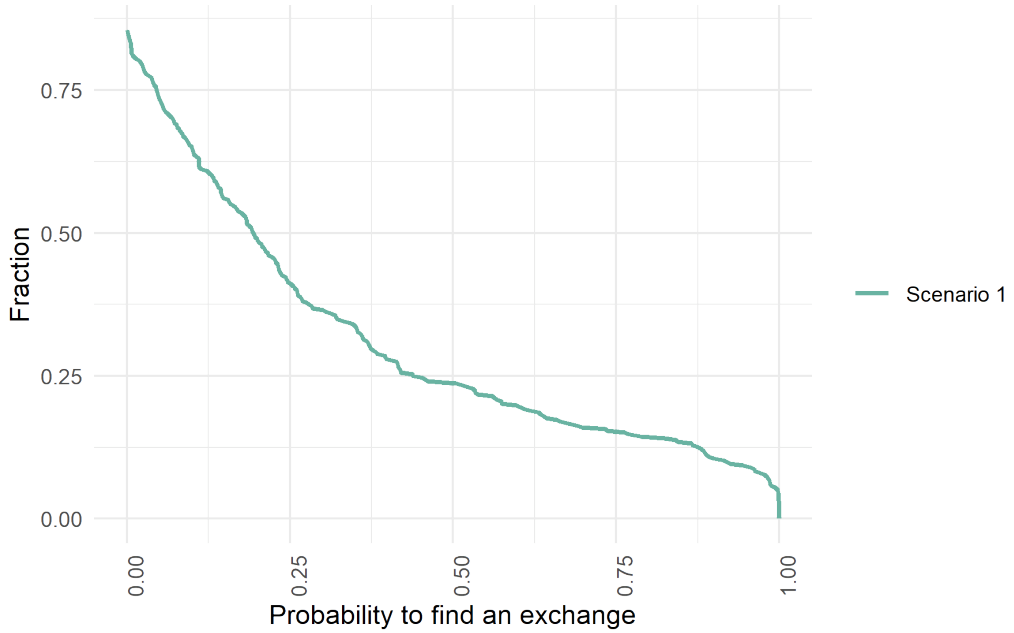

Figure 4: Inverse of the cumulative probability ($\mathbb{P}(X > t)$) to find a better match for compatible (N=312) pairs.

The inverse cumulative probability of finding a better match for these compatible pairs is depicted in Figure 4. This figure demonstrates that half of the compatible pairs have a probability greater than 20% of finding a better match. This significant finding suggests that participating in the kidney exchange program could be beneficial for a substantial portion of compatible pairs, offering them a meaningful chance of securing a better match and thereby potentially improving transplant outcomes.

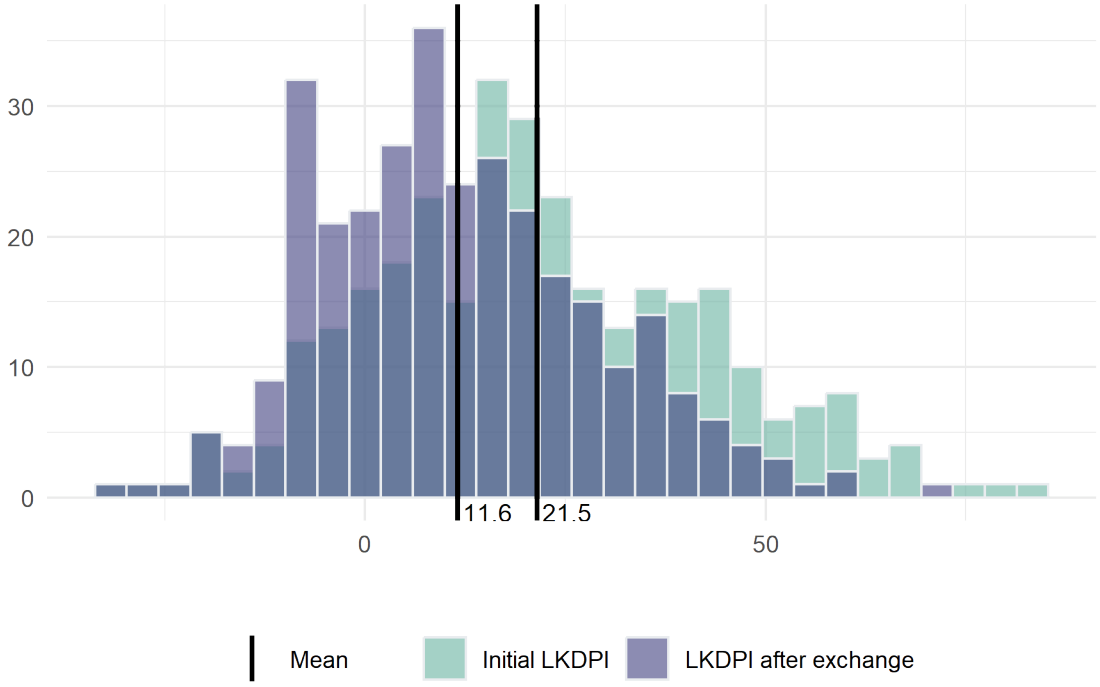

Figure 5: Distribution for compatible (N = 312) pairs of the initial LKDPI versus the LKDPI in the simulation.

On average, compatible pairs are enhancing the expected quality of a transplant. Figure 5 illustrates that, on average, the expected quality in Scenario 1 is equal to a score of 11.6 points according to the LKDPI, compared to an initial average score of 21.5 points.[12] The LKDPI scores can be further translated into years of expected graft survival following Li et al. [2019]. Since LKDPI is computed based on a survival Cox model, it can be translated

[12]If a pair has a zero probability of finding a better match, its LKDPI remains the same as the initial LKDPI.

to a model of the survival time of the transplanted organ in the donor. Especially, they have found that the graft survival half-life (or EGS) is a function of LKDPI following an exponential curve. Translating this average LKDPI score into expected graft survival (Figure 7 in the Appendix), we observe an improvement of approximately 1.5 years in expected graft survival for compatible pairs.

5.3 Assessing the likelihood of finding a better match for compatible pairs

A key aspect of any kidney exchange program designed to encourage compatible pairs' participation is identifying which pairs are most likely to benefit. Participation can involve psychological costs and potential delays in transplantation. Additionally, significant time and effort may be required from medical professionals to thoroughly explain the expected costs and benefits of kidney exchange program participation to compatible pairs. Therefore, analyzing which compatible pairs are more likely to benefit is essential. Assessing the likelihood of finding a better match is critical in enabling compatible pairs to make well-informed decisions about participating.

To evaluate which compatible pairs have a greater likelihood of finding a more favorable match, we examine the simulations in Scenario 1. Here, compatible pairs participate in the kidney exchange program and may find an exchange with an improved match quality relative to their initial LKDPI score. We set a threshold of at least a 20-point decrease compared to the score for a transplant with their intended donor as the minimum benefit required for participating in an exchange. This probability of finding a better exchange can be computed in each simulation scenario as the number of exchanges divided by the number of simulations. We then empirically estimate which observable characteristics of the pair determine this probability with a fractional probit regression model, in which the

conditional probability that pair i successfully finds an exchange is specified as:

$$\mathbb{P}(Y_i|X_i) = \Phi(\beta_0 + X_i\beta + u_i), \tag{1}$$

where X_i is a vector of covariates (donor and recipient characteristics), $\Phi()$ the standard normal cumulative density function, and u_i is the individual unobserved heterogeneity (assumed to be independent of covariates). We consider a set of donor's and recipient's characteristics such as age, gender, and health characteristics, as well as the interaction between some of them. Namely, our controls include the following set of characteristics for every compatible pair i:

$$X_i = (\ d_{age}, r_{age}, d_{age} \times r_{age}, d_{egfr}, d_{smoke}, d_{sbp}, d_{male}, d_{smoke} \times d_{male}, r_{male}, d_{male} \times r_{male},$$
$$d_{r\_bio\_related}, total_{hla\_mism}, d_{weight}, r_{weight}, d_{weight} \times r_{weight}, r_{blood\_group}, d_{blood\_group}),$$

where d_k and r_k refer to donor's and recipient's characteristic k correspondingly.

In what follows we estimate three specifications, each including a set of donor-recipient characteristics. The first specification controls for the same parameters that are used to calculate the LKDPI of a pair. Then we run a specification with more controls for the recipient and some interaction terms such as donor's and recipient's age. Inclusion of this interaction term might be relevant in cases when the age difference between donor and recipient is measured in decades. While the LKDPI formula separates HLA mismatches according to their class (i.e. HLA-B and HLA-DR), we look at the total number of HLA mimatches in this and the next specifications as the effect of different types of mismatches was not significant. Finally, we also include interaction term that accounts for a female smoking donor - the two conditions that are known to (separately) lower the transplant quality. All specifications are estimated on the sample of compatible pairs. Table 3 displays the results for the model presented above for all three specifications reported in columns (1), (2), and (3) correspondingly. We report marginal effects to interpret the influence of

each covariate on the probability of finding an exchange for compatible pairs. For the age, gender, and smoking status variables, the average marginal effects are calculated from the joint inclusion of the linear and the interaction terms to account for non-linear effects.

We find that older donors, smoking donors, donors with higher systolic blood pressure, male recipients, and biologically related donor-recipient pairs are all characteristics with positive marginal effects on the probability of finding an exchange. Conversely, characteristics such as donors with a better functioning kidney (higher glomerular filtration rates) and male donors have negative marginal effects on the probability of finding an exchange. Additionally, we find that the combination of donor and recipient genders, as well as their blood group compatibility, also have significant positive marginal effects on the probability of finding an exchange, which is in line with the blood group correspondence discussed in Section 5.1.1.

5.3.1 Which compatible pairs have larger expected gains from participation?

Specification (3) regression coefficients are used to compute the probability of finding a better exchange for compatible pairs with particular fixed characteristics. Exploiting these full model results, we have put up a calculator to compute this probability with donor and recipient characteristics as inputs (the calculator based on the dataset used in this study can be found here).

Table 4 summarizes characteristics used in the analysis of compatible pairs, while full list of blood group combinations of donors and recipients of these pairs can be found in Table 6 in the Appendix. To provide intuition behind the impact of different characteristics of a pair on the probability of finding a better exchange , one can vary the characteristics of interest, holding all other characteristics fixed. We performed this exercise for the blood group, the number of HLA mismatches, the smoking status of the donor, the biological relationship between the donor and the recipient, the weight of the donor and the recipient, the age of the donor and the recipient, and the GFR of the donor; continuous variables are fixed to

Dep: Pr_exchange	(1) ME	(2) ME	(3) ME
d_age	0.008***	0.006***	0.006***
	(0.0020)	(0.0014)	(0.0014)
r_age		0.003**	0.003***
		(0.0011)	(0.0011)
d_GFR	-0.005***	-0.003***	-0.003***
	(0.0014)	(0.0008)	(0.0008)
d_smokes	0.117***	0.155***	0.152***
	(0.0332)	(0.0206)	(0.0202)
d_SBP	0.004***	0.003***	0.002***
	(0.0014)	(0.0008)	(0.0008)
both_male	-0.123**		
	(0.0554)		
d_male		-0.088***	-0.091***
		(0.0232)	(0.0227)
r_male		0.071***	0.071***
		(0.0236)	(0.0235)
d_r_bio_related	0.006	0.159***	0.163***
	(0.0470)	(0.0280)	(0.0287)
d_weight	-0.002*	-0.001	-0.001
	(0.0013)	(0.0008)	(0.0008)
r_weight	0.002*	0.000	0.000
	(0.0012)	(0.0008)	(0.0008)
d_blood_groupA		-0.397***	-0.397***
		(0.0210)	(0.0214)
d_blood_groupAB		-0.526***	-0.527***
		(0.0157)	(0.0161)
d_blood_groupB		-0.432***	-0.439***
		(0.0233)	(0.0230)
r_blood_groupA		0.378***	0.377***
		(0.0218)	(0.0222)
r_blood_groupAB		0.598***	0.604***
		(0.0446)	(0.0448)
r_blood_groupB		0.271***	0.275***
		(0.0301)	(0.0292)
total_hla_mism1		0.120***	0.121***
		(0.0377)	(0.0399)
total_hla_mism2		0.213***	0.210***
		(0.0349)	(0.0367)
total_hla_mism3		0.249***	0.248***
		(0.0440)	(0.0458)
total_hla_mism4		0.403***	0.396***
		(0.0464)	(0.0484)
HLA-B & HLA-DR mismatches	Yes		
(d_i male) × (r_i male)		Yes	Yes
(d_i age) × (r_i age)		Yes	Yes
(d_i smokes) × (d_i female)			Yes
Observations	312	312	312

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: eGFR ≥ 90 is in the normal range, and eGFR < 15 means kidney failure; SBP assumed to be elevated if within $[120; 129]$, and normal if below 120.

Table 3: Marginal Effects of different characteristics on the probability of finding an exchange for compatible pairs

N = 312	**Donors**	**Recipients**
Mean values		
Age (y.o.)	53.0	43.5
Weight (kg)	67.7	68.7
eGFR	93.8	
SBP	124	
Frequency (%)		
Sex: Female	73.0	35.3
Sex: Male	26.9	64.7
Smoking	39.2	
Biologically Related	59.9	59.9
Blood group: A	32.4	46.8
Blood group: B	6.73	10.9
Blood group: AB	0.64	4.81
Blood group: O	65.1	37.5
Number of HLA mismatches: 0		5.77
Number of HLA mismatches: 1		10.3
Number of HLA mismatches: 2		46.5
Number of HLA mismatches: 3		12.5
Number of HLA mismatches: 4		25.0

Table 4: Characteristics of donors and recipients of compatible pairs.

their mean and discrete variables are fixed to the level of the most observations.

Figure 6 and Table 5 below present the relation between the probability of finding an exchange and donor's age for the three most common blood group combinations of donors and recipients ($O-O$, $O-A$, and $A-A$) depending on donor's smoking status. We find that the predicted probability of finding a better graft increases with donor's age and is higher for pairs with a smoking donor. For example, in the case of an O-A blood group with a smoking donor, the probability rises from 55% for a 20-year-old donor to 90% for a 70-year-old donor. Additional results can be found in Figures 8 - 13 in the Appendix.

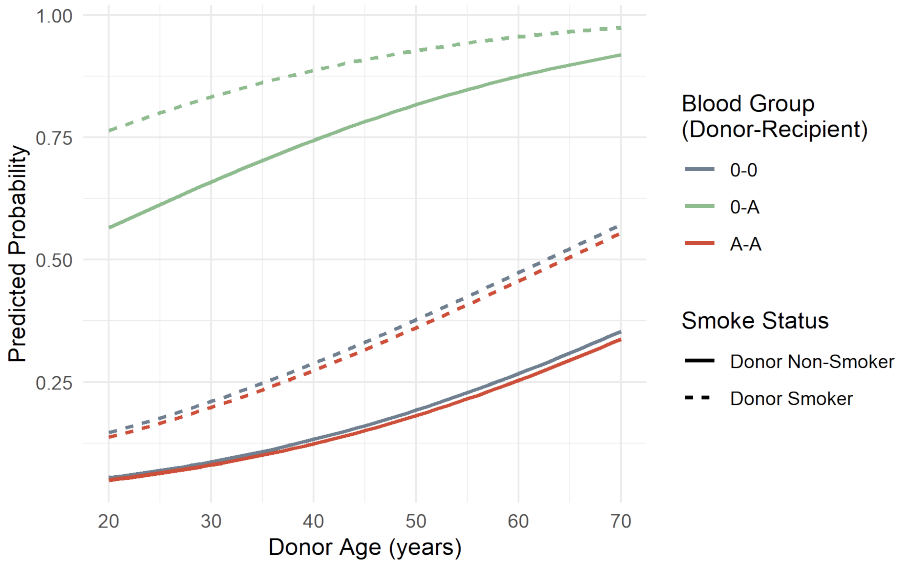

Figure 6: Predicted probability of finding an exchange based on different donor age for compatible pairs depending on donor's smoking status.
Note: Estimated probabilities are presented for the pairs, where donor and recipient are relatives; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.

(a) Donor does not smoke

	Recipient			
Donor	0	A	AB	B
0	0.214	0.836	0.975	0.713
A		0.202	0.558	
B			0.434	0.059

(b) Donor smokes

	Recipient			
Donor	0	A	AB	B
0	0.406	0.937	0.994	0.868
A		0.389	0.758	
B			0.651	0.157

Table 5: Predicted probability to find an exchange for compatible pairs depending on donor's smoking status..
Note: Estimated probabilities are presented for the pairs, where donor and recipient are relatives; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.

6 Conclusion

Our study provides a preliminary yet innovative assessment of the potential benefits of compatible pairs participation in a medium-sized kidney exchange programs, such as the Italian program. We demonstrate that compatible pairs can indeed gain advantages from their involvement. More importantly, their participation significantly improves the likelihood

of finding matches for incompatible pairs, with particularly pronounced benefits for those facing the greatest challenges in securing compatible matches. This positive effect arises primarily from changes in the pool's composition rather than its size. Additionally, we identify several donor and recipient characteristics that positively influence the likelihood of compatible pairs finding an exchange. These include older donors, smoking donors, donors with higher systolic blood pressure, male recipients, and biologically related donor-recipient pairs.

Our study demonstrates that medium-sized KPE programs could benefit from the participation of (some) compatible pairs. Moreover, the finding that changes in the composition of the pool, rather than its size, play the most critical role in improving the chances of incompatible pairs finding an exchange suggests that the benefits of compatible pair participation could be substantial for large-sized programs, too. Indeed, compatible pairs are likely to have even greater opportunities to achieve better matches in larger programs.

Looking ahead, our study could be further enhanced by addressing several key areas. First, it would be valuable to replicate our analysis using datasets from other countries.

Second, we simulate a program in which compatible pairs seek better exchanges during a single matching run to minimize transplant delays. However, compatible pairs might remain in a kidney exchange program longer, waiting for an optimal match before opting out. In this scenario, it would be crucial to evaluate the trade-offs between the potential benefits of participation and the costs of delays. Estimating each compatible pair's willingness to wait for a better outcome would provide valuable insights, as there is evidence of heterogeneity in patients' time and risk preferences while awaiting kidney transplants (see Genie et al. [2020]).

Third, while we employed the LKDPI to evaluate the expected quality of transplants, consistent with extensive yet debated medical literature, alternative measures could also be considered for this purpose. Nevertheless, our study makes a methodological contribution by introducing a framework to calculate the expected benefits arising from modifications

to kidney exchange programs, independent of the specific index used to assess transplant quality.

References

Mohammad Akbarpour, Julien Combe, Yinghua He, Victor Hiller, Robert Shimer, and Olivier Tercieux. Unpaired kidney exchange: Overcoming double coincidence of wants without money. *The Review of Economic Studies*, 2024. URL https://doi.org/10.1093/restud/rdae081.

Tommy Andersson and Jörgen Kratz. Pairwise Kidney Exchange over the Blood Group Barrier. *The Review of Economic Studies*, 87(3):1091–1133, 2019.

Arpita Basu, Mikel Prieto, Catherine Kosberg, Martin L. Mai, Hasan A. Khamash, Caroline C. Jadlowiec, Naim S. Issa, Patrick G. Dean, Elizabeth C. Lorenz, Mark D. Stegall, and Carrie A. Schinstock. Ten Years of Kidney Paired Donation at Mayo Clinic: The Benefits of Incorporating ABO/HLA Compatible Pairs. *Transplantation*, 104(6):1229–1238, 2020.

A W Bingaman, F H Jr Wright, M Kapturczak, L Shen, S Vick, and C L Murphey. Single-center kidney paired donation: the Methodist San Antonio experience. *American Journal of Transplantation*, 12(8):2125–2132, 2012.

Péter Biró, Bernadette Haase-Kromwijk, Tommy Andersson, Eyjólfur Ingi Ásgeirsson, Tatiana Baltesová, Ioannis Boletis, Catarina Bolotinha, Gregor Bond, Georg Böhmig, Lisa Burnapp, Katarína Cechlárová, Paola Di Ciaccio, Jiri Fronek, Karine Hadaya, Aline Hemke, Christian Jacquelinet, Rachel Johnson, Rafal Kieszek, Dirk R Kuypers, Ruthanne Leishman, Marie-Alice Macher, David Manlove, Georgia Menoudakou, Mikko Salonen, Bart Smeulders, Vito Sparacino, Frits C R Spieksma, María Oliva Valentín, Nic Wilson, and Joris van der Klundert. Building kidney exchange programmes in europe —an overview of exchange practice and activities. *Transplantation*, 103(7):1514–1522, 2019.

Yao Cheng and Zaifu Yang. Efficient kidney exchange with dichotomous preferences. *Journal of Health Economics*, 80:102536, 2021.

Valerie Chipman, Matthew Cooper, Alvin Thomas, Matthew Ronin, Brian Lee, Stuart Flechner, David Leeser, Dorry Segev, Didier Mandelbrot, Tyler Lunow-Luke, Shareef Syed, Garet Hil, Chris Freise, Amy Waterman, and Garrett Roll. Motivations and outcomes of compatible living donor-recipient pairs in paired exchange. *American Journal of Transplantation*, 22(1):266–273, 2022.

Francis Delmonico. Exchanging kidneys — advances in living-donor transplantation. *The New England Journal of Medicine*, 350:1812–4, 05 2004.

Francis L. Delmonico, Paul E. Morrissey, George S. Lipkowitz, Jeffrey S. Stoff, Jonathan Himmelfarb, William Harmon, Martha Pavlakis, Helen Mah, Jane Goguen, Richard Luskin, Edgar Milford, Giacomo Basadonna, Michael Chobanian, Beth Bouthot, Marc Lorber, and Richard J. Rohrer. Donor kidney exchanges. *American Journal of Transplantation*, 4(10):1628–34, 2004.

Marie-Claude Fortin, Jagbir Gill, Johanne Allard, Fernando Ballesteros Gallego, and Jagbir Gill. Compatible donor and recipient pairs' perspectives on participation in kidney paired donation programs: A mixed-methods study. *Can J Kidney Health Dis*, 8, 2021.

Lucrezia Furian, Cristina Cornelio, Cristina Silvestre, Flavia Neri, Francesca Rossi, Paolo Rigotti, Emanuele Cozzi, and Antonio Nicolò. Deceased-donor-initiated chains: first report of a successful deliberate case and its ethical implications. *Transplantation*, 103(10):2196–2200, 2019.

Lucrezia Furian, Antonio Nicolò, Caterina Di Bella, Massimo Cardillo, Emanuele Cozzi, and Paolo Rigotti. Kidney exchange strategies: new aspects and applications with a focus on deceased donor-initiated chains. *Transplant International*, 33(10):1177–1184, 2020.

M.G. Genie, A. Nicolò, and G. Pasini. The role of heterogeneity of patients' preferences in kidney transplantation. *Journal of Health Economics*, 72(10):102331, 2020.

S.E Gentry, D.L Segev, M. Simmerling, and R.A Montgomery. Expanding kidney paired donation through participation by compatible pairs. *American Journal of Transplantation*, 7(10):2361–2370, 2007.

Gurobi Optimisation. Solve Complex Problems, Fast. URL https://www.gurobi.com/.

Kyle R. Jackson and Dorry L. Segev. Rethinking incompatibility in kidney transplantation. *American Journal of Transplantation*, 22(4):1031–1036, 2022.

Zhuoshu Li, Kelsey Lieberman, William Macke, Sofia Carrillo, Chien-Ju Ho, Jason Wellen, and Sanmay Das. Incorporating compatible pairs in kidney exchange a dynamic weighted matching model. *In Proceedings of the 2019 ACM Conference on Economics and Computation*, pages 349 – 367, 2019.

A B Massie, J Leanza, L M Fahmy, E K Chow, N M Desai, X Luo, E A King, M G Bowring, and D L Segev. A risk index for living donor kidney transplantation. *American Journal of Transplantation*, 16(7):2077–84, 2016.

A.J. Matas, J.M. Smith, M.A. Skeans, B. Thompson, S.K. Gustafson, D.E. Stewart, W.S. Cherikh, J.L. Wainright, G. Boyle, J.J. Snyder, A.K. Israni, and B.L. Kasiske. Optn/srtr 2013 annual data report: Kidney. *American Journal of Transplantation*, 15:1–34, 2015. Special Issue: OPTN/SRTR 2013 Annual Data Report.

A Nicolò and C Rodríguez-Álvarez. Transplant quality and patients' preferences in paired kidney exchange. *Games and Economic Behavior*, 74:299 – 310, 2012.

A Nicolò and C Rodríguez-Álvarez. Age-based preferences in paired kidney exchange. *Games and Economic Behavior*, 102:508 – 524, 2017.

David Manlove William Pettersson Tommy Andersson Lisa Burnapp Pavel Chromy Pablo Delgado Piotr Dworczak Bernadette Haase Aline Hemke Rachel Johnson Xenia Klimentova Dirk Kuypers Alessandro Nanni Costa Bart Smeulders Frits Spieksma María O Valentín Ana Viana Közzétételi Péter Biró, Joris Van de Klundert. Modelling and optimisation in european kidney exchange programmes. *European Journal of Operational Research*, 291 (2):447–456, 2021.

Lainie Friedman Ross and E Steve Woodle. Ethical Issues in Increasing Living Kidney Paired Exchange Programs. *Transplantation*, 69(8):1539–1543, 2000.

Alvin. E. Roth, Tayfun. Sönmez, and M. Utku Ünver. Kidney exchange. *The Quarterly Journal of Economics*, 119(2):457 – 488, 2004.

Alvin E. Roth, Tayfun Sönmez, and M. Utku Ünver. Pairwise kidney exchange. *Journal of Economic Theory*, 125(2):151–188, 2005.

Alvin. E Roth, Tayfun. Sönmez, and M. Utku Ünver. Efficient kidney exchange: coincidence of wants in markets with compatibility-based preferences. *American Economic Review*, 97:828–851, 2007.

Florian G Scurt, Lara Ewert, Peter R Mertens, Hermann Haller, Bernhard M W Schmidt, and Christos Chatzikyrkou. Clinical outcomes after abo-incompatible renal transplantation: a systematic review and meta-analysis. *The Lancet*, 393:2059–2072, 2019.

Tayfun Sönmez, M. Utku Ünver, and M. Bumin Yenmez. Incentivized kidney exchange. *American Economic Review*, 110(7):2198–2224, 2020.

Tayfun Sönmez and M. Utku Ünver. Altruistically unbalanced kidney exchange. *Journal of Economic Theory*, 152:105–129, 2014.

M. Utku Ünver. Dynamic kidney exchange. *The Review of Economic Studies*, 77(1):372–414, 2010.

Appendix

Additional Tables and Figures

Figure 7 below shows how the average LKDPI for compatible pairs in our dataset changes as the results of their participation in a kidney exchange program. Corresponding years of EGS are calculated following Li et al. [2019].

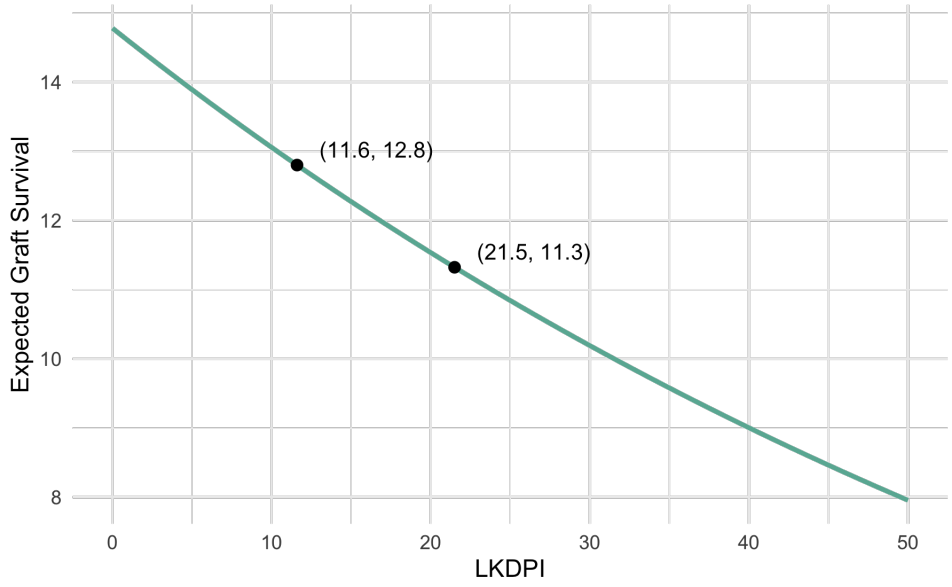

Figure 7: Graft survival half-life as a function of LKDPI where the function is an exponential curve ($f(x) = 14.78e^{-0.01239x}$).

Table 6 presents the blood group combinations for compatible pairs in our data set.

The following figures provide additional insights into how the characteristics of both the donor and the recipient influence the predicted probability of finding a welfare-improving exchange for compatible pairs. Older recipients (Figure 8) and higher donor systolic blood pressure (SBP) (Figure 9) contribute to a higher probability of finding an exchange. However, donor's age has a more significant impact on the probability than recipient's age. (Figures 6 vs. 8). Depicted on Figure 10, the total number of HLA mismatches negatively impacts the quality of the match with the intended recipient. Additionally, we observe that when

Donor-Recipient	Number of Observations
0-0	117
0-A	53
0-AB	3
0-B	15
A-A	93
A-AB	8
AB-AB	2
B-AB	2
B-B	19
	N = 312

Table 6: Blood group combinations for compatible pairs.

the donor and recipient are biologically related, the probability of finding an exchange is significantly higher (Figures 11 - 13).

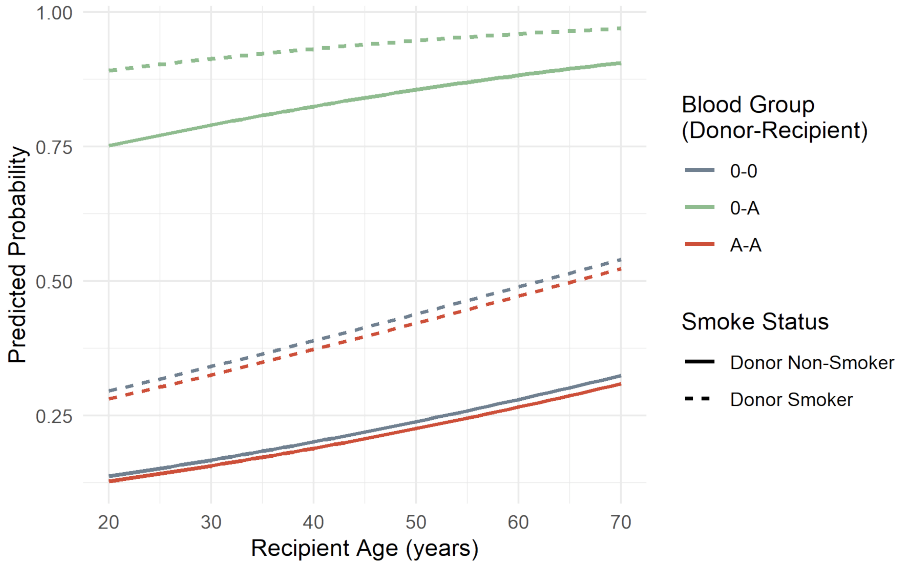

Figure 8: Predicted probability of finding an exchange based on different recipient age for compatible pairs.
Note: Estimated probabilities are presented for the pairs, where donor and recipient are relatives; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.

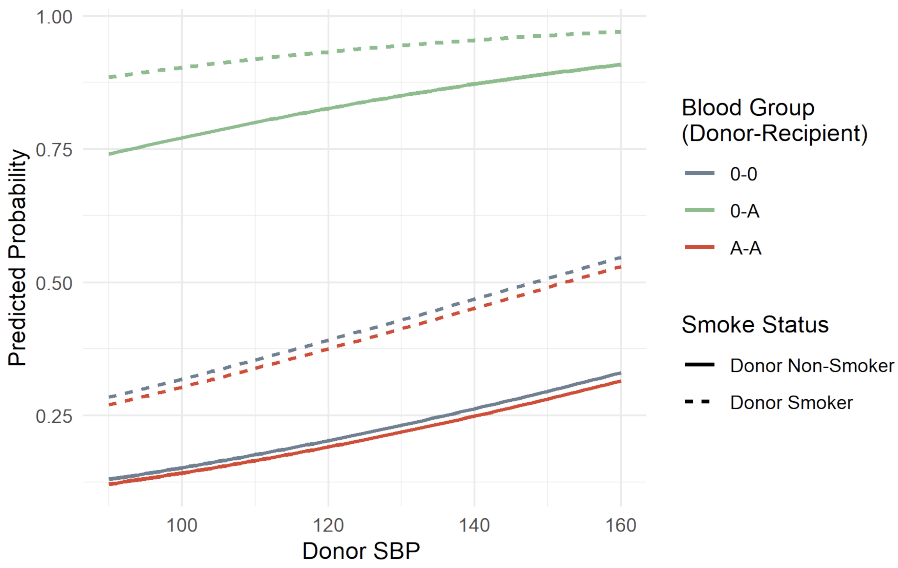

Figure 9: Predicted probability of finding an exchange based on different donor SBP for compatible pairs.

Note: Estimated probabilities are presented for the pairs, where donor and recipient are relatives; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.

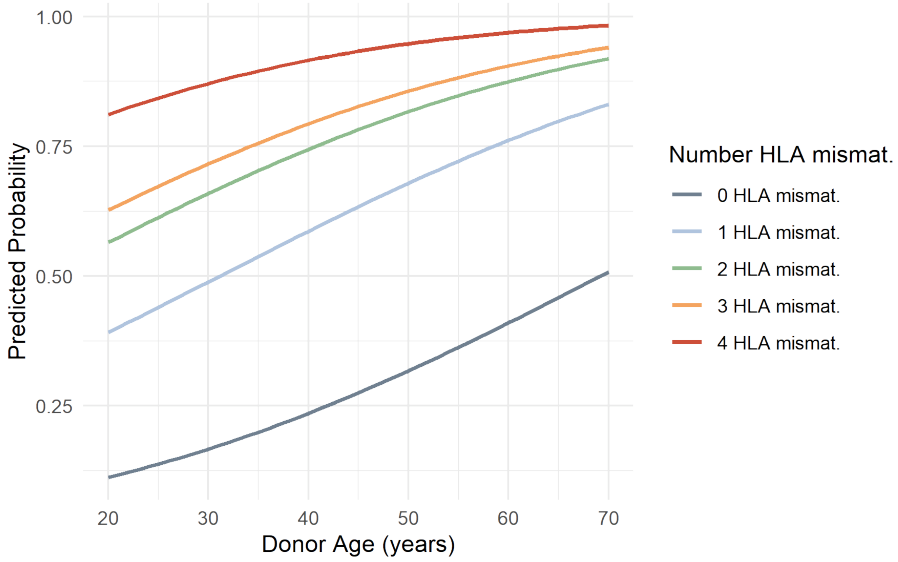

Figure 10: Predicted probability of finding an exchange based on the number of HLA mismatches with the intended donor.

Note: Estimated probabilities are presented for the pairs, where donor does not smoke; donor is blood group O and recipient A; recipient is male; donor is a female; and all continuous variables are taken at mean values.

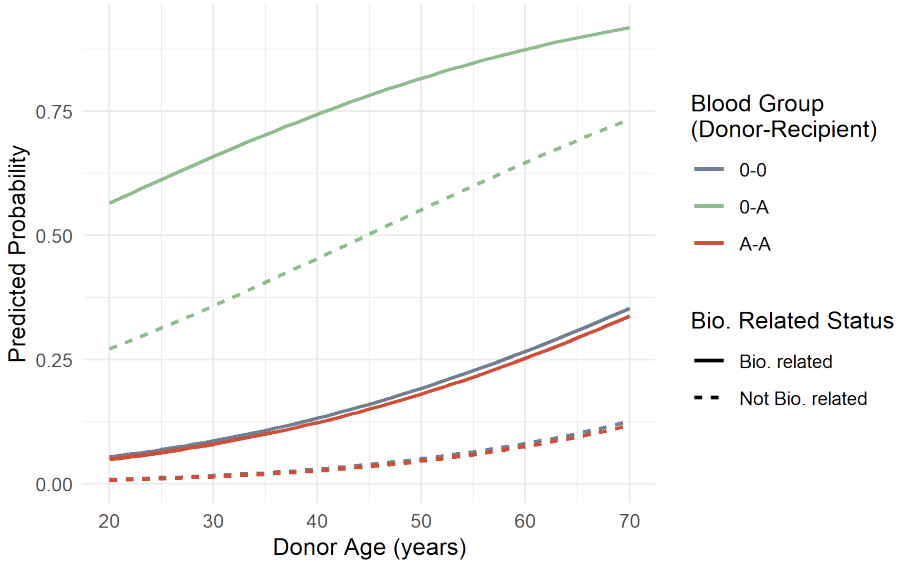

Figure 11: Predicted probability of finding an exchange based on different donor age for compatible pairs.
Note: Estimated probabilities are presented for the pairs, where donor does not smoke; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.

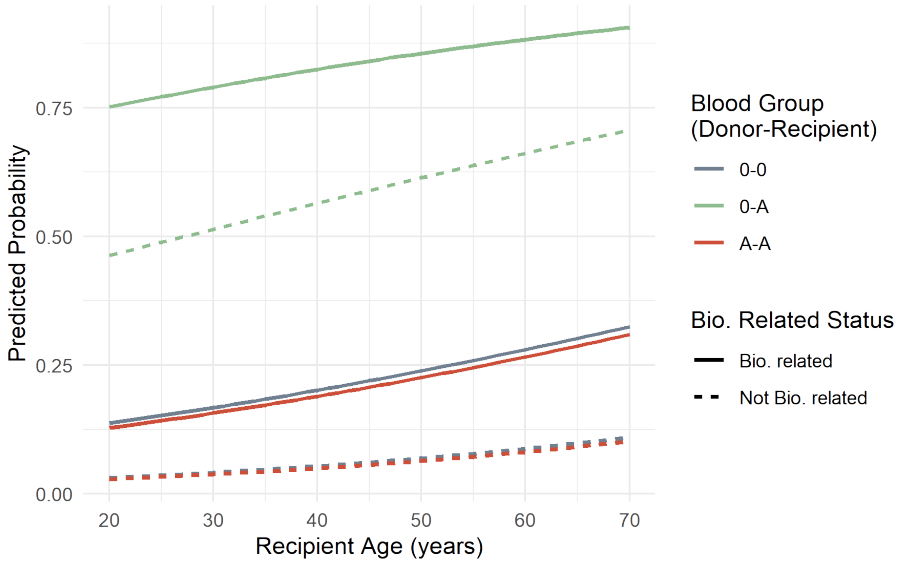

Figure 12: Predicted probability of finding an exchange based on different recipient age for compatible pairs.
Note: Estimated probabilities are presented for the pairs, where donor does not smoke; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.

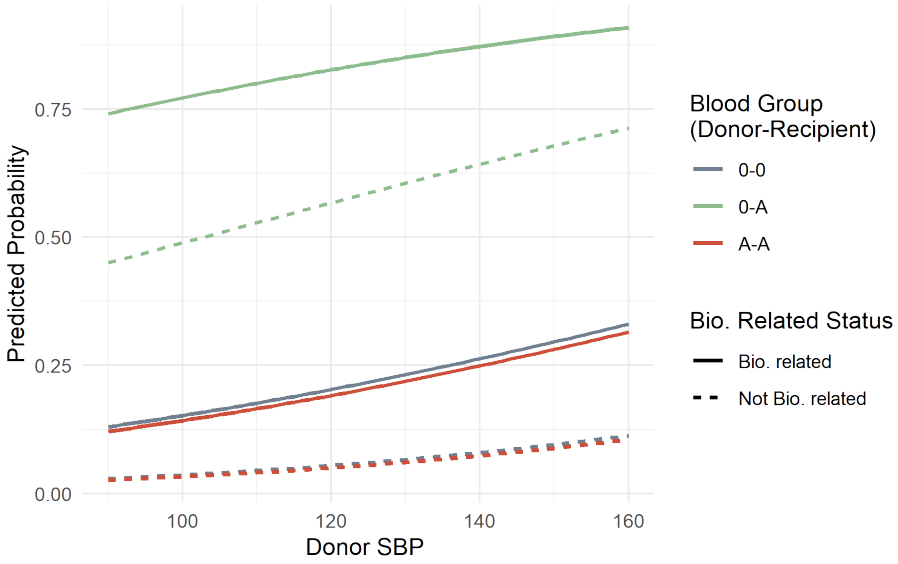

Figure 13: Predicted probability of finding an exchange based on different donor SBP for compatible pairs.

Note: Estimated probabilities are presented for the pairs,where donor does not smoke; they have 2 HLA mismatches; recipient is male; donor is a female; and all continuous variables are taken at mean values.