Assessing the Potential Impact of a Kidney Exchange Program in Mexico

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Abstract

In Mexico, around 16,527 patients are waiting for a kidney transplant. Since the national brain-death donation rate (3.4 per million inhabitants) is too slow to offset this number of people, a strategy to increase the number of kidney transplants is to consider the available, but usually incompatible, living donors related to some recipients through a kidney paired donation. Several countries have implemented successful kidney exchange programs, where all donors and recipients are evaluated to obtain the best compatibility match among them. While this is a reality in other countries, in Mexico there is not such a program at a national level. In this work, we simulate and evaluate the impact of implementing a Mexican kidney exchange program. The proposed simulation considers an optimization procedure to maximize the number of compatible matchings from a patient-donor pair pool. Results obtained from simulation estimate an increment of 80% in the number of living-donor transplants and a much less accelerated increase in the number of recipients on the waiting list with respect the data provided by the Mexican healthcare sector in 2022. This is clearly a positive result of the impact of establishing such a program in the country.

Keywords: Kidney disease; Kidney exchange program; Simulation; Optimization.

1 Introduction

Many patients who need a kidney transplant can identify a living donor. A Living Donor Kidney Transplantation (LDKT) is considered the best treatment choice for patients with end-stage renal disease (ESRD) as it provides greater long-term survival rates, better quality of life, and a better response to undergo preoperative desensitization in case of ABO blood type or human leukocyte antigens (HLA) incompatibilities [11]. However, one of the main concerns about kidney transplantation is to find compatible donors for patients in order to reduce the risk of a graft rejection. When direct living donors, who are commonly relatives of the recipients, are not compatible with their patient; then, a kidney exchange transplantation is usually recommended.

A Kidney Exchange Program (KEP) has been a good alternative implemented in several countries to collect information on incompatible donor-recipient pairs in order to match them for a kidney exchange transplantation [14]. Although KEPs have provided successful results in different countries, in Mexico there is not exist such a program at a national level, only some isolated efforts have been developed. In this work, we analyze the impact of implementing a KEP in Mexico by simulating this situation using several blood type distributions obtained from the Mexican population.

1.1 Kidney transplantation in Mexico

In Mexico, the first organ transplant was performed in 1963 with no pre-existing legislation. The first regulation was created in the Código Sanitario de los Estados Unidos Mexicanos in 1973. Since then, several legislations, modifications, and collaborations have been carried out to improve and regulate the organ transplantation system in the country. Currently, the Centro Nacional de Trasplantes (CENATRA) is the responsible for promoting and coordinating the processes from donation to transplantation of organs, tissues and cells [2].

Although CENATRA is a relatively recent organization that began in 2000, the objectives it aims to achieve include planning a series of initiatives to increase the rates of organ donation and transplantation in Mexico by optimizing existing resources and infrastructure for better coordination between donors and transplant centers. The organization also seeks to design new strategies to encourage altruistic donations, improve educational programs and public awareness campaigns to foster a culture of donating organs, and enhance the skills of the involved healthcare professionals, as well as working on evaluating innovative approaches to identify potential ESRD patients, among other initiatives.

According to [2], in Mexico, there are 20,607 people who require an organ transplantation, of whom 16,527 are waiting for a kidney transplant, having a wait of 35.3 months (on average) since their registration on the waiting list. The kidney waiting list has shown a significant increase of 6,484 new cases in the last ten years and only 17.5% (2700) of the ESRD patients have received a transplant in 2022, where

1513 were living donors and 506 were deceased donors. In addition, the deceased donation rate is 3.4 donors per million inhabitants (441 in total) by 2022, a low rate compared to the US which had a rate of 44.5 deceased donors per million inhabitants (about 14,769 donors) in 2022 [15, 1, 10].

To increase the number of kidney transplants, optimization models and algorithms can be used. In Mexico, there are some algorithms that have been independently applied by some healthcare institutions; however, these have been isolated efforts, which are not part of a national kidney exchange program. Nevertheless, they have had successful results during their implementation [16, 17, 18]. This alternative is still a non-affordable option to the whole Mexican population.

Contribution of the paper. In this work, we assessed the potential impact of a kidney exchange program in Mexico. For this, we proposed a simulation-optimization process aimed to: (a) determine if a kidney exchange program is a suitable alternative according to the information of the Mexican population, (b) estimate the potential number of incompatible pairs that can originate during a specific time period, (c) determine the expected number of incompatible pairs that are eligible to belong to a kidney exchange program and its potential benefit.

This work is organized as follows. First, in Section 2, the simulation-optimization process is described. Second, in Section 3, the results of the proposed approach and a sensitivity analysis performed to evaluate the impact of creating a national kidney exchange program, are presented. Finally, some conclusions and future research lines are provided in Section 4.

2 Materials and methods

In this section, the proposed simulation-optimization process used to assess the impact of implementing a KEP, is described. First, we explain the complete simulation process and the distributions we have used to estimate the data. Then, we briefly describe the optimization problem we solve to find the optimal matching for each set of incompatible pairs generated during the simulation.

2.1 Simulation

We simulate the number of incompatible donor-patient pairs that would arise during a year, according to certain distributions of the Mexican population. For this simulation, steps S1–S4 described below are considered (Figure 1).

S1. **Age assignment.** The first step is to assign the age for each patients considering three age groups: *Youths, Adults, and Older adults.* Second, for each group a donor-patient is assigned based on the age distribution provided by the [15]. Table 1 summarizes this information into 6 categories for donors and 3 for patients. The "Sibling" category contains the direct *Biological* categories from the OPTN report, while the *Other* category contains the "Biological, blood-related Other

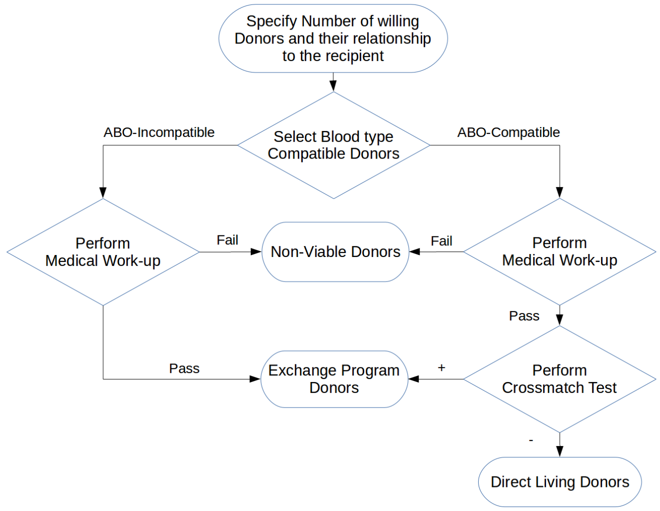


Figure 1: Decision tree model [19] for the simulation-optimization KEP process.

Relative", "Non-Biological, Life Partner" and "Non-Biological, Other Unrelated Directed". The "Not reported" and the "Unknown" categories from the report are not considered in this study. Finally, two donors from the donor candidate pool are selected randomly.

Table 1: US Transplants: January 1, 1988 - May 31, 2017 (OPTN, June 19, 2017)

Patient age / Donor relation (%)	Youths <17	Adults 18-49	Older adults 50+	Total
Parent	7,064 (75.2%)	11,317 (15.7%)	102 (0.2%)	18,483 (14.0%)
Child	0 (0.0%)	3,251 (4.5%)	18,936 (37.6%)	22,187 (16.8%)
Sibling	668 (7.1%)	31,970 (44.3%)	9,704 (19.3%)	42,342 (32.1%)
Spouse	0 (0.0%)	7,784 (10.8%)	7,426 (14.7%)	15,210 (11.5%)
Other	1,666 (17.7%)	17,854 (24.7%)	14,239 (28.3%)	33,759 (25.6%)
Total	9,398 (100%)	72,176 (100%)	50,407 (100%)	131,981 (100%)
Age distribution	7.1%	54.7%	38.2%	100%

S2. **ABO group assignment.** An ABO blood group is assigned to patients and their potential donors according to the Mexican population blood type distribution obtained from [3]. According to the frequency of each ABO group, the blood type O is the most common group with 65% of the population, followed by type A (25%), B (8.6%), and AB (1.4%), respectively. In case of children's blood types, it is required to know parents' genotypes. The child's genotype will be a combination of two random selected alleles (one for each parent) determined by using the Hardy-Weinberg principle [13] (see Tables 2-3). First, a random genotype is assigned to the parents, spouse, and others, according to the distribution in Table 2. Second, the genotypes of the patient and the siblings randomly inherit an allele from each parent (Table 3). Finally, the genotypes of children are determined and, with this, their blood type.

Table 2: Genotype frequencies of Mexican population.

Genotype	%
AA	2.03
AO	22.97
AB	1.46
BB	0.26
BO	8.27
OO	65

Table 3: Allele frequencies of Mexican population.

Allele	Frequency
A	0.14
B	0.05
O	0.81

S3. **ABO and work-up tests.** For determining the ABO compatibility, an ABO blood test for each donor-recipient pair is carried out. Depending on the obtained results, a specific medical work-up is performed to assess the health and the decision to donate of donors. For this purpose, we discard 25% of spousal donors and 56.7% of other donors [9, 19], according to several reasons for not accepting them [8]. For those ABO-compatible donors who passed the work-up, a crossmatch test is performed (S4). On the other hand, if a donor is ABO incompatible but passes the medical work-up, **the pair joins the exchange program pool**. In any other case, donors are non-viable and are not considered in the simulation.

S4. **Crossmatch test.** First, the sex of the patient is randomly assigned according to the OPTN data from 1988 to 2017 [15], with 40% of patients being female. A Panel-Reactive Antibody (PRA) group is then assigned to the patient.The positive crossmatch rate varies depending on whether the patient is the wife or the mother of the donor, since they are more likely to be sensitized to their husbands' and children's antigens, respectively [see 9, for overall weighted distribution and rates].

Possible outcomes of the simulation are the following:

- **Direct donation**: ABO compatible donor who passed both medical work-up and crossmatch test.
- **Exchange program**: ABO incompatible donors who passed the medical work-up; or ABO compatible donors who passed medical work-up but failed the crossmatch test. The pool formed with this output is introduced to the optimization phase explained in Section 2.2 to find the maximum number of compatible kidney exchange.
- **Non-viable donor**: Donors who failed the medical work-up.

Some assumptions are considered for the simulation:

- Except for the spouse, other candidates (sibling, child, parent, other) could be selected twice.
- Patient is a *mother* when female and has a child as a donor.
- Patient is a *wife* when female and has a spouse as a donor.
- If none of the donors pass the medical workup, the patient will have no donor and joins the waiting list.
- If both potential donors pass the medical work-up and the crossmatch test, only one of them is randomly selected as the final direct donor.
- If both donors pass the medical work-up but are incompatible with the patient (i.e. fail the blood test or crossmatch), only one of them is randomly selected to join the exchange program.
- If both donors pass the medical work-up, and only one of them is compatible with the patient (blood-type/crossmatch tests), the compatible donor is considered for a direct transplant. The incompatible one is removed from the simulation.
- Each donor/patient can donate/receive at most only one kidney.

2.2 Optimization of incompatible pairs

When kidneys from a given donor are not compatible due to a given blood type or a positive crossmatch result, an *Incompatible Patient-Donor Pair* (PDP) is formed (Figure 2). A group of them is called a Kidney Exchange pool [12], which can be interpreted as a directed compatibility graph by associating one vertex Px to each PDP (see Figure 3a). A directed arc from one vertex Px to another Py, where x and y represent two different PDPs, is added only if a donor Dx of the first pair is compatible (and it is able to donate) with the patient Ry of Py. This arc may have a specific weight determined by a committee of healthcare professionals. Finally, a *cycle* in the graph represents a possible kidney swap of k PDPs, with k as the maximum number of transplants that can be carried out simultaneously, forming a k-way exchange (a cycle that contains k pairs).

Cycles are usually constrained in length as they involve $2k$ simultaneous surgeries, certain materials and human resources, as well as considering some important logistics aspects. The solution (compatibility cycles) obtained after optimizing the pool (Figure 3b), represent the maximum number of transplants that can be potentially performed.

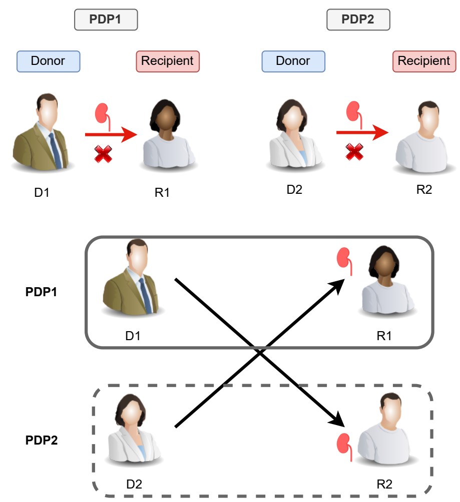
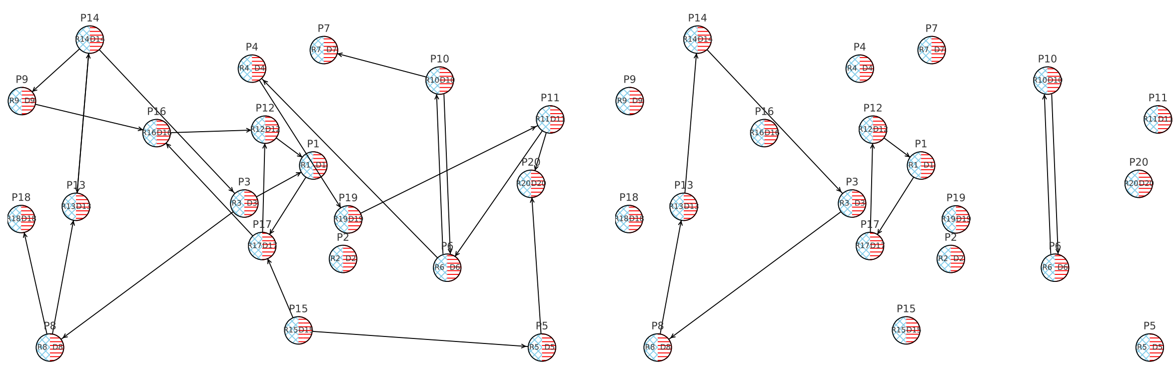


Figure 2: 2-way kidney exchange



(a) Kidney exchange pool (b) Associated optimal solution

Figure 3: A kidney exchange pool and its solution.

Mathematically, the *Kidney Exchange problem* can be seen as a combinatorial optimization problem that can be defined on a directed graph. The goal is to find cycles of maximum total cardinality (or a weighted maximum cardinality). We used the algorithm proposed by Dickerson et al. [4] to maximize the number of **compatible** patient-donor pairs obtained from the PDPs pool.

3 Results and discussion

In this section, we will first estimate the number of incompatible pairs that can be generated annually. Second, the corresponding pool of incompatible pairs is created using the simulator. Third, the optimization algorithm is applied to the given pool to find the optimal match between incompatible pairs. Finally, we analyze all the information obtained in the previous steps to determine the potential impact of implementing a kidney exchange program.

3.1 Estimation of incompatible pairs

To estimate the number of incompatible pairs in a year, we run the proposed simulation until 2,126 direct transplants are obtained. This is the number of living donor kidney transplants (LDKTs) performed in Mexico in 2017. Once this number of transplants is reached, we can estimate the number of expected incompatible pairs that would eventually join in a hypothetical kidney exchange program in a year. The average values, from a sample of 30 replications, are shown and compared in Table 4. For comparison purposes, we also run the simulation for US population using the blood type frequencies from Zenios et al. [19] determined for the *Caucasians* group. The simulation stops when 2,126 direct transplants are obtained.

Table 4: Predicted number of incompatible pairs in Mexico in a year

	Mexico		**US**	
	#Pairs	**(%)**	**#Pairs**	**(%)**
Generated patients	**3,121**	**100.0**	**3,336**	**100.0**
Pairs for direct transplant	2,126	68.1	2,126	63.7
Pairs for the KE program	995	31.9	1,210	36.3
- ABO incompatibility	500	50.2	709	58.6
- Crossmatch test failure	495	49.8	501	41.4

Results show that, in the case of Mexico, the simulation estimates an average of 995 incompatible pairs in a year, which is 31.9% of the total number of generated pairs. We can observed that, for incompatible pairs, an average of 50.2% joined the exchange program due to a blood type incompatibility; while 49.8% joined the program due to an unsatisfactory cross-match test. On the other hand, for the US results, an average of 1,210 are obtained; 58.6% of the incompatible pairs are due to blood type incompatibility.

3.2 Pool of incompatible pairs

Once we have predicted the annual number of incompatible pairs, we proceed to establish a pool of that size (995 incompatible pairs for both countries) considering the probability distributions provided in Section 2.1. The outcomes are based on the average value computed across 30 repetitions.

Age and blood type distribution. Table 5 shows that, for both Mexico and US, the largest proportion of patients falls within the Adult and Older Adult age groups; just about 7% of them fall within the Young category. On the other hand, Table 6 shows the resulting blood type distribution for both pools, where most of the recipients are blood type O, 74.1% for Mexico while 60.6% for US. This is due to the fact that recipients with blood type O can only accept blood from like-typed donors. Therefore, a large proportion result in mismatched pairs.

Table 5: Patient age distribution for Mexican and US pools

	Mexico		**US**	
Age category	Count	Proportion (%)	Count	Proportion (%)
Young	66	6.6	70	7.0
Adult	499	50.2	516	51.9
Older adult	430	43.2	409	41.1
Total	995	100.0	995	100.0

Table 6: Blood type distribution of donor/recipient pairs in Mexican and US pools

	Mexico					**US**				
Pairs	dO	dA	dB	dAB	**Total**	dO	dA	dB	dAB	**Total**
rO	29.8%	32.2%	10.9%	1.2%	**74.1%**	15.5%	33.9%	9.4%	1.8%	**60.6%**
rA	6.7%	6.3%	3.2%	1.0%	**17.2%**	7.0%	12.2%	5.6%	3.0%	**27.8%**
rB	2.8%	2.6%	1.7%	0.8%	**7.9%**	0.4%	5.1%	1.8%	2.6%	**9.9%**
rAB	0.2%	0.4%	0.1%	0.1%	**0.8%**	0.3%	0.7%	0.3%	0.3%	**1.6%**
Total	**39.5%**	**41.5%**	**15.9%**	**3.1%**	**100.0%**	**23.2%**	**51.9%**	**17.1%**	**7.7%**	**100.0%**

[1] dX and rX denote donor and recipient blood types, respectively.

3.3 Optimal matching

Next, with the created pools, we will focus on optimizing them with the aim to maximize the number of matched pairs, which represents the potential number of transplants to be carried out. For this, we used the solution algorithm mentioned in Section 2, allowing only cycles of length $k = 2$. Results showed that, for the Mexican pool, an optimal matching of 624 pairs was obtained. While for the US pool, the algorithm found 562 matched pairs. The prevalence of donors with O blood type partially contributes to a higher rate of successful matches in the Mexican pool. The detailed results of this optimization are described below.

Matched pairs. Table 7 shows that almost half of the matched pairs in the Mexican pool (47.4%, 294) are pairs where both recipient and donor belong to the blood group O whereas, for the US, matched pairs are more balanced between blood types A and O.

Unmatched pairs. Table 8 shows that, for the Mexican pool, most of the unmatched pairs have a recipient with blood type O (93.3%). This is reasonable since they can only receive blood from a donor of the same ABO group. On the other hand, there is only one unmatched pair, where the donor is blood type O (due to the fact that donors with this blood type can donate to anyone). For the US pool, there is not any unmatched pair when donor is blood type O, and most of the unmatched pairs have a recipient with blood type O (85.9%).

Table 7: Matched pairs % found for Mexican and US pools

	Mexico[1]					US[2]				
Pairs	**dO**	**dA**	**dB**	**dAB**	**Total**	**dO**	**dA**	**dB**	**dAB**	**Total**
rO	47.4%	10.7%	4.5%	0.0%	**62.7%**	27.4%	12.6%	0.9%	0.2%	**41.1%**
rA	10.6%	9.9%	4.8%	0.2%	**25.5%**	12.5%	21.4%	9.4%	0.7%	**44.0%**
rB	4.5%	4.2%	1.9%	0.2%	**10.7%**	0.7%	9.1%	2.3%	0.2%	**12.3%**
rAB	0.3%	0.6%	0.2%	0.0%	**1.1%**	0.5%	1.2%	0.5%	0.4%	**2.7%**
Total	**62.8%**	**25.4%**	**11.4%**	**0.4%**	**100.0%**	**41.1%**	**44.3%**	**13.1%**	**1.5%**	**100.0%**

[1] According to 624 matched pairs
[2] According to 562 matched pairs

Table 8: Unmatched pairs in Mexican and US pools

	Mexico					US				
Pairs	**dO**	**dA**	**dB**	**dAB**	**Total**	**dO**	**dA**	**dB**	**dAB**	**Total**
rO	0.3%	68.2%	21.6%	3.2%	**93.3%**	0.0%	61.4%	20.6%	3.9%	**85.9%**
rA	0.0%	0.3%	0.5%	2.4%	**3.2%**	0.0%	0.2%	0.7%	6.0%	**7.0%**
rB	0.0%	0.0%	1.3%	1.9%	**3.2%**	0.0%	0.0%	1.2%	5.8%	**6.9%**
rAB	0.0%	0.0%	0.0%	0.3%	**0.3%**	0.0%	0.0%	0.0%	0.2%	**0.2%**
Total	**0.3%**	**68.5%**	**23.4%**	**7.8%**	**100.0%**	**0.0%**	**61.6%**	**22.5%**	**15.9%**	**100.0%**

Table 9: Matching rates for Mexican and US pools.

	Mexico					US				
Pairs	**dO**	**dA**	**dB**	**dAB**	**Total**	**dO**	**dA**	**dB**	**dAB**	**Total**
rO	99.7%	20.9%	25.9%	0.0%	**53.1%**	100.0%	21.1%	5.3%	5.6%	**38.3%**
rA	100.0%	98.4%	93.8%	10.0%	**93.0%**	100.0%	99.2%	94.6%	13.3%	**89.2%**
rB	100.0%	100.0%	70.6%	12.5%	**84.8%**	100.0%	100.0%	72.2%	3.8%	**69.7%**
rAB	100.0%	100.0%	100.0%	0.0%	**87.5%**	100.0%	100.0%	100.0%	66.7%	**93.8%**
Total	**99.7%**	**38.5%**	**44.9%**	**6.5%**		**100.0%**	**48.3%**	**43.3%**	**10.4%**	

Matching rates. Matching rates are used to measure the likelihood of finding a compatible kidney transplant for a patient and donor with a specific blood type combination. These values are calculated dividing the total number of matched pairs by the total number of pairs. Table 9 shows the matching rates for different blood type combinations. Notice that, for the Mexican pool, the matching rate is higher when the donor is blood type O (99.7%) and recipients have blood type AB (87.5%). On the other hand, the lowest matching rate is for AB donors (6.5%) since they can only donate to recipients with AB. A similar behavior is shown for the US pool.

3.4 Incompatible pairs in waiting list

Having the simulated data for the number of new incompatible pairs that can be generated annually, now the number of incompatible patient-donor pairs in the Mexican waiting list is estimated using the proposed simulator. The simulator randomly generates pairs until the sum of the number of pairs who join to the exchange program plus the number of patients without a donor is equal to the number of

Table 10: Estimation of the number of incompatible pairs in the Mexican waiting list.

	#Cases	**Proportion (%)**
Patients in waiting list	13,313	100.0
Patients without donor	7,351.5	55.2
Pairs in the KE program	5,961.5	44.8
- ABO incompatibility	2,996	50.3
- Crossmatch test failure	2,965.5	49.7

patients in the waiting list (13,313 as of July, 2017, [2]). This process was replicated 30 times, and the average results are shown in Table 10. It can be observed that 44.8% of the patients in the waiting list have an incompatible donor. The implementation of a kidney exchange program in Mexico presents an opportunity to identify compatible kidney transplants for these patients. Considering all the information provided above, we simulate the impact of creating a kidney exchange program in Mexico, in terms of the number of potential transplants that might be carried out.

3.5 Impact of a kidney exchange program in Mexico

To determine the potential impact of a kidney exchange program in Mexico, we simulate a hypothetical program starting from 2018. The following assumptions were made:

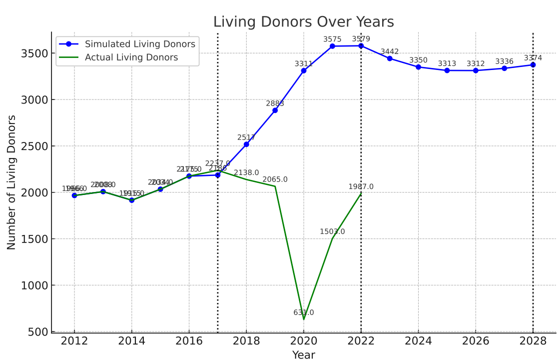
- Percentage of potential incompatible pairs that could annually enroll in the program (WL/New, from waiting list/new patient-donor pairs) .
  - 2018: 10% WL, 50% New.
  - 2019: 20% WL, 60% New.
  - 2020: 40% WL, 70% New.
  - 2021: 60% Wl, 80% New.
  - 2022+: 80% WL, 80% New.
- Percentage of potential incompatible pairs who would leave the program after admission.
  - 20% of unmatched incompatible pairs leave the kidney exchange program every year.
  - 60% of recommended matches do not proceed to transplant.

The basis for the assumptions made is that in the early years of the program, only a few incompatible patient-donor pairs will join it since the program is new and people might be unaware of the advantages it offers. As the program evolves and gains wider acceptance, more incompatible pairs will join it. Also, we consider that some of the recommended matches might not proceed to transplantation due to other factors such as variations in levels of sensitization between patients and donors, illness, uncertainty in medical knowledge, logistical issues, or patients obtaining another opportunity of a kidney transplant [5].

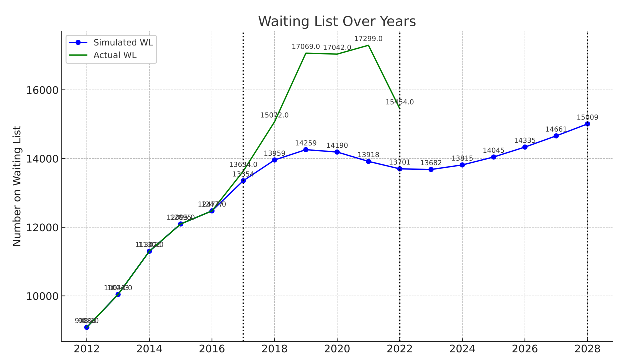
Table 11: Estimation of incompatible pairs joined to a kidney exchange program from 2018 to 2028.

Year	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
New Incompatible Pairs	497	597	696	796	796	796	796	796	796	796	796
Incompatible Pairs from WL	596	1,072	1,716	1,545	824	164	32	6	1	0	0
Total pairs	1,093	2,327	3,813	4,635	4,408	3,613	3,002	2,608	2,366	2,220	2,131
Matched	678	1,443	2,364	2,873	2,733	2,240	1861	1,617	1,467	1,376	1,321
Transplanted	271	577	945	1,149	1,093	896	744	647	586	550	528
Remaining in pool	822	1,750	2,867	3,485	3,315	2,717	2,257	1,961	1,779	1,669	1,603
Remaining in WL	5,364	4,291	2,575	1,030	206	41	8	1	0	0	0

We simulate a pool for each year and optimize them to find the maximum number of matches. We predicted 995 incompatible pairs at the end of 2018 (Table 4) and 5,961 incompatible pairs in the waiting list (see Table 11). Every year, 995 new incompatible cases arise; however, only a percentage of them would join the kidney exchange program (according to the assumptions mentioned above). Concerning the waiting list, the number of incompatible pairs aligns with predictions. These pairs will remain in the pool until they either find a compatible match or leave the kidney exchange program. Table 11 presents the results obtained for each year, where incompatible pairs are denoted as "IP" and patients who remain in waiting list as "WL". The total number of pairs per year corresponds to the sum of the new incompatible pairs plus those who already belong to the waiting list, and the 80% of unmatched pairs for the last year (as 20% of them are supposed to leave the pool). Once a pool is completed for each year, it is optimized to find the maximum number of matches taking into account that only 40% of them will proceed to transplant.



(a) Living-donor kidney transplants.



(b) Patients in waiting list.

Figure 4: Estimations from 2012 to 2028: : simulated vs real.

Figure 4 presents a comparative analysis of two key metrics: the estimated number of Living Donor Kidney Transplants (LDKTs) and the number of registered patients on the waiting list. The data covers from 2012 to 2028 and it is compared with current statistics provided by CENATRA for the years 2012 to 2022 [1]. Figure 4 is divided in three different time periods:

- 2012-2016: This period displays actual data from CENATRA for both LDKTs and the waiting list.
- 2017-2022: During this period, the figure shows estimated values against real-world data from

CENATRA.

- 2023-2028: The figure shows only estimated data obtained by the proposed simulation.

This analysis aims to understand the long-term behavior and potential impact of the kidney exchange program in further years.

In Figure 4a, we can observe an important increase in the number of transplants involving living donors (blue line with dots), especially when compared to actual data (solid green line). This increase shows the impact of the hypothetical implementation of a kidney exchange program. This trajectory continues until 2021, where it stabilizes. Notice in actual data that, in 2020, there was an important decrease on the number of LDKTs attributed to the COVID-19 pandemic. In any case, the estimated data provided by the simulator indicates that a kidney exchange program would substantially benefit a large number of patients. On the other hand, in Figure 4b, it is observed how the number of registered patients on the waiting list increases constantly in the actual data. However, with the potential implementation of a kidney exchange program in 2018, the increment is more stable due to the opportunity of finding a match to carry out a transplantation. Since patients may undergo transplantation or leave the pool, the pool becomes smaller, so the waiting list still increases but at a slower rate (see Table 11).

3.6 Sensitivity analysis

A last experiment was performed to analyze the impact of implementing the program considering two new scenarios: **Pessimistic** and **Optimistic** cases. The assumptions taken for each of them are shown in Table 12.

In the **Pessimistic** case, an initial low percentage of pairs who enter (%New, %WL) and a high number of them who leave the program (**%L**-Leave, **NP**-No proceed) are considered. The last criterion was selected according to a study carried out to UNOS data [5], where at least 90% of the transplants were not performed for several reasons. On the other hand, in the **Optimistic** case, a high percentage of both entering and remaining pairs in the program are taken into account. The proposed scenarios are compared with the hypothetical case (**Main**) mentioned in Section 3.5 to analyze the impact of these considerations in the success of the program.

Figures 5a-5e show the comparison among scenarios for several criteria considered in Table 12. In Figure 5a it is observed that, for the **Pessimistic** scenario, it takes about five years to achieve the participation of incompatible pairs in the program with respect the other two scenarios. Also, it can be noticed in Figure 5b that as sooner the incompatible pairs from waiting list are included in the program, the faster the list reduces its size. Since all those pairs, the incompatible ones from waiting list plus the new ones (Total Pairs, Figure 5c), are considered for the pool to be optimized; therefore, the number of matched pairs that proceed can be identified earlier (considering a rate of $\lfloor 624/995 \rfloor \times 100\% = 62\%$ of the total number of pairs) and transplants can be performed in the early years of the program (Figures 5d-5e).

Table 12: Assumptions for **Pessimistic** and **Optimistic** scenarios.

Years	%New	%WL	%L/%NP
Pessimistic			
2018-2024	(10-70)*	(5-70)*	40/90
2025+	80	80	
Optimistic			
2018	70	50	0/30
2019	80	60	
2020	80	70	
2021+	80	80	

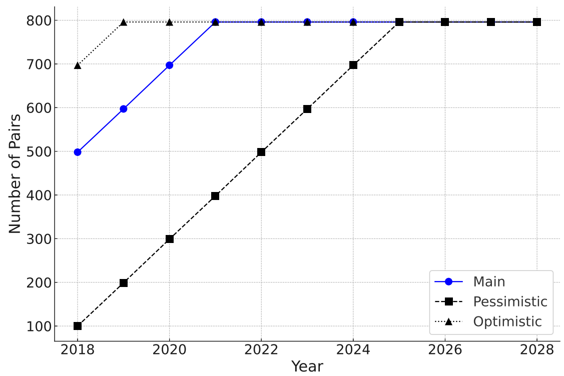
* +10% increase per year.

On the other hand, it is important to notice that, for the **Pessimistic** scenario, since the number of matches is low and because of a high percentage of these does not proceed (90%), a low number of transplants per year is estimated, which indicates that it is of vital importance to create strategies to increase the interest of recipients and their donors to participate in this program since the beginning, and strategies to identify how to reduce the causes of transplants that do not proceed.

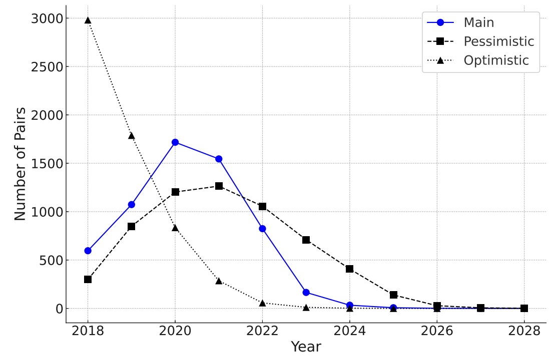
4 Conclusions

The waiting list for kidney transplants in Mexico has steadily increased every year. This situation, along with the low donation rate, has led to serious health issues to many people diagnosed with terminal renal disease. A kidney exchange program may provide a positive impact since it considers the incompatible donor-patient pairs to increase the number of potential transplants. Although some kidney exchange strategies have already been successfully performed in Mexico, they have been carried out in an isolated manner by some healthcare institutions. In this work, the impact of implementing a national kidney exchange program in Mexico is simulated and assessed. We estimate an average of 995 incompatible pairs that might arise in Mexico each year. Also, 5,961 patients in the waiting list (44.8%) would have an incompatible donor. Fortunately, due to the Mexican blood type distribution, the probability of finding a match is higher compared to other countries. Results show that program can provide a significant increase of living donor kidney transplants in the subsequent years after its implementation. Finally, this study was based on several assumptions related to the number of pairs that enter and leave the program; then, a sensitivity analysis was carried out to determine how a change of scenario impacts the expected success of the program. The comparison showed the importance of generating strategies to increase the interest in belonging to the program during the first years, as well as strategies to avoid the increase of potential transplants that cannot be performed for other reasons.

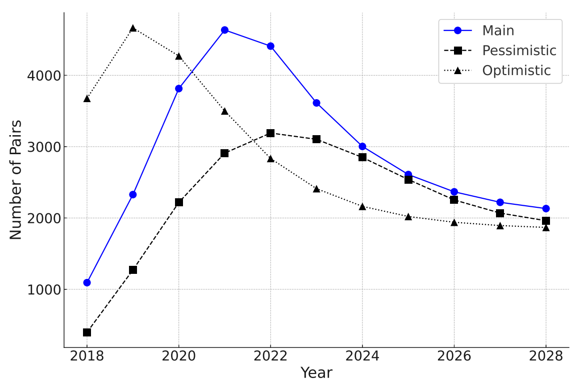
As future research lines, since our simulation only considers two potential donors per patient, it is pos-



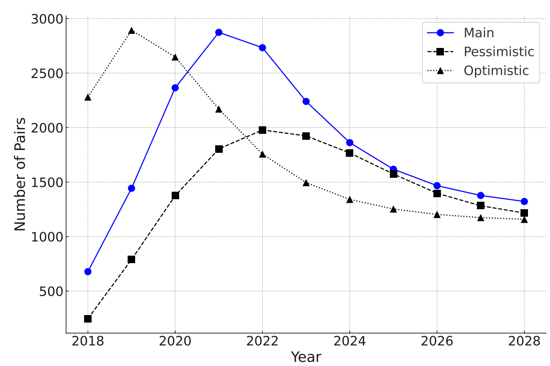
(a) New Incompatible Pairs



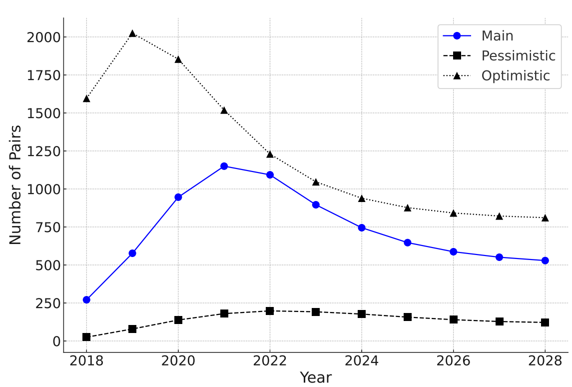
(b) Incompatible pairs from WL



(c) Total Pairs



(d) Matched



(e) Transplanted

Figure 5: Comparison among scenarios (Pessimistic, Main, Optimistic) from 2018 to 2028

sible to figure out this distribution. Second, medical work-up and cross-match tests probabilities should be estimated for the Mexican population (in this work, we considered the data for the US population since it is not directly available from the Mexican databases). Finally, it should be interesting to consider new policies or transplant mechanisms as it has been done in Domínguez et al. [6, 7].

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