33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Computerized Decision Support System for Kidney Paired Donation Program

Yanhua Chen and Peter X.-K. Song

Abstract— **In order to assist physicians and other health professionals for health care improvement, clinical decision support systems, through interactive computerized software, become very popular in clinical practice. The crisis associated with kidney organ shortage has triggered an innovative strategy, termed as Kidney Paired Donation (KPD) program, to address a rapidly expanding demand for donor kidneys. KPD program involves how to making optimal decision for allowing patients with incompatible living donors to receive compatible organs by best matching donors. Although some computerized optimization tools are being used in the current KPD program, there still lacks a general decision support system which enables us to evaluate and compare different kidney allocation strategies and effects of policy. In this paper, we discuss a general computer-based KPD decision model that appropriately reflects the real world clinical application. Also, the whole decision process is to be visualized by our Graphical User Interface (GUI) software, which offers a user friendly platform not only to provide a convenient interface for clinicians but also to assess different kidney exchange strategies of clinical importance.**

I. INTRODUCTION

In order to assist physicians and other health professionals for health care improvement, clinical decision support system built upon an interactive decision support software, become very popular in many practical clinical applications. In the case of kidney organ transplantation, the demand for kidney donors far exceeds the supply-more than $90,000$ patients on the waiting list for transplantations at the end of May 2010 in the United States [1]. Although deceased donation and living donation are the two resources for kidney transplantation, living-donor transplantation got increased recently since it has a higher chance of post-transplant survival rate. Unfortunately, about one-third of patients with willing live donors will be excluded from kidney transplantation because of biological incompatibility, such as ABO blood type or human leukocyte antigen (HLA) mismatch [2]. Therefore, kidney paired donation (KPD) program is established to provide a solution to this dilemma by swapping organs between two incompatible pairs, thus facilitating the chance of transplantation involving the two willing donors' kidneys.

The key question in the KPD program is how to make an optimal decision of kidney exchanges that benefit patients the best. In the current kidney optimal decision literature, the most widely used strategy of matching incompatible donor-recipient pairs is to maximize the number of transplants by solving an Integer Programming (IP) problem [3], [4], [5], [6], [7]. This method determines the optimal two-way and three-way cycle exchanges through the means of graphic optimality. In order to improve both quantity and quality of life after transplantations, a probability-based algorithm is proposed in [8], taking account of the medical-outcome-based utility (e.g., the life years gained from real transplants (LYFT) [9]) as well as the probability of successful actual transplants, to optimize the overall expected utility of exchanges. More recently, KPD program begins to include chains triggered by altruistic donors (ADs) because chains not only relax the reciprocality and simultaneity requirements of KPD but also tend to save more lives than ones achieved by only pairs donation [10], [11]. Refer to [12] for a comprehensive review of KPD program.

In summary, all the aforementioned KPD program research primarily focuses on exploring different kidney allocation strategies which specific computer programs are developed using their own algorithms. However, there lacks a general model which enables us to evaluate and compare different allocation strategies and effects of policy. Also, a user friendly platform that permits easy communications between clinicians and computer tools is very important for the practicality of KPD program. Thus, there is an urgent need for adequate software related to this program to facilitate convenience in the clinical research. In this paper, we propose a general KPD decision support system that appropriately reflects the needs of real world clinical applications and enables effective evaluation of different kidney donor allocation strategies. In addition, the graph user interface (GUI) is developed to model, visualize, and monitor the real world KPD program. The remainder of the paper is organized as follows. We first present the mathematical background and decision support model of KPD program in details in Section II. Then, a thorough description of KPD software is demonstrated in Section III. Finally, we give conclusion and discuss some future work in Section IV.

II. DECISION MODEL

A. Mathematical Background

A KPD problem can be represented as a directed graph network $N = (P, L)$. Let $|P|$ be the number of nodes and $|L|$ be the number of links in the network, where $|.|$ denotes cardinality. Figure 1 shows an example. Each node in the network N represents an incompatible donor-recipient pair (e.g., node 2) or an altruistic donor (e.g., node 1). Each link from node i to j indicates that the donor kidney in ndoe i is compatible with the recipient in node j (e.g., $1 \rightarrow 2$).

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In the network N, the directed links are established for compatibility of ABO blood type and HLA sensitization. For example, in [8], each link is assigned a weight representing the *link utility* l_{ij} of the kidney transplant from the donor in node i to the recipient in node j. In addition, each link associated with an *link probability* π_{ij} indicates that the possibility of successful kidney transplant from i to j.

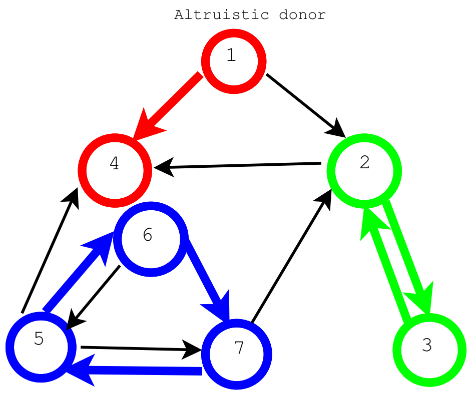

Fig. 1. A toy of KPD program including six incompatible pairs and an altruistic donor. It contains 3 two-way cycles ({2,3}, {5,6}, {5,7}), 1 three-way cycle ({5,6,7}) and 4 chains beginning with an altruistic donor ({1,4}, {1,2}, {1,2,4}, {1,2,3}).

The goal of KPD program is to find a collection of mutually disjoint rings (cycles and/or chains) that have the maximum overall matches of N. This decision task can be formulated as an optimization problem on graph network N by the following setup of an IP,

$$\max \sum_{r \in R} x_r f_r, \quad (1)$$

$$\text{s.t.} \quad \begin{array}{c} x_r \in \{0,1\}, \forall r \in R, \\ \sum_{r \in R(i)} x_r \leq 1, 1 \leq i \leq |P|. \end{array}$$

where R is the class of all rings of length 2 and/or 3 in network N, $R(i)$ is the exchange set of rings in R that contain node i and x_r is a vector of indicators representing if a ring c is to be executed for transplant ($x_r = 1$) or not ($x_r = 0$). Notice that f_r is derived from medical-outcome-based utility [8] or some existing KPD scoring system [3] depending on different allocation decision strategies. Then, plugging f_r into Equation (1), for example, we use IP approach in [7] to find the optimal matches showed in Figure 1: $1 \rightarrow 4$, $2 \rightarrow 3 \rightarrow 2$, $5 \rightarrow 6 \rightarrow 7 \rightarrow 5$.

B. Decision Support Model

In order to compare and evaluate different KPD allocation algorithms, we proposed a general computer-based KPD decision support system based on a micro-simulation model developed in [8]. This system is illustrated as a flow diagram in Figure 2. In detail, the system defines three basic kinds of components:

1) **Data Input**: The system can deal with an integrated collection of data records and files from different sources of input, such as the existing KPD database, user's input data and simulated data from trained statistical models.
2) **Micro-simulation Model**:
   - *KPD database generation*: According to different input data of donors and patients, the system generates the experimental incompatible donor-recipient pairs and ADs depending on the relationship between blood type mismatch or HLA incompatibility.
   - *KPD graph generation*: Users assign and confirm input parameters from the system, such as the range of value for link utility and link probability either following uniform random distributions [8] or from expert score system [3], then the system generates a directed graph network N for the KPD program.
   - *Computer server makes optimization decision*: The system launches computation engine (e.g., Gurobi optimization software [13]) as an independent process. The computation engine, in turn, reads the saved KPD graph, chooses the kidney allocation methods, executes the user-defined KPD decision algorithms, runs the mathematical optimizations on the computer server, and outputs the optimal virtual matches.
   - *Real lab match run*: The system determines the optimal successful kidney transplants using fallback plan or not in the real lab match run [8].
3) **Output results**: The system produces, displays and visualizes the final successful transplants by texts, tables and graphs.

III. Software

A. Configuration

We also developed a software for the KPD program. The KPD software consists of a comprehensive frontend GUI in Qt development environment [14] and a backend computation engine powered by optimization integer programming, such as Gurobi. In particular, the system includes two main components: Computation engine and GUI. Computation engine serves as the core of the KPD program and applies optimization functions and algorithms to output matching results. GUI receives and processes data from users, selects parameters, and then outputs results in easily accessible environments. KPD's computation engine, an optimization model, is written entirely in C++ and compiled into a binary executable code. The GUI is also developed in C++ language and compiled into a separate executable program. Communication between the computation engine and the GUI is accomplished through input and output data or files.

This GUI software framework is flexible enough to accommodate multiple KPD program strategies in cross-platform so that it has the following capabilities: (1) the ability to create the experimental data from original KPD files or database, (2) the ability to define input parameters and choose KPD allocation algorithms, (3) the ability to perform computer

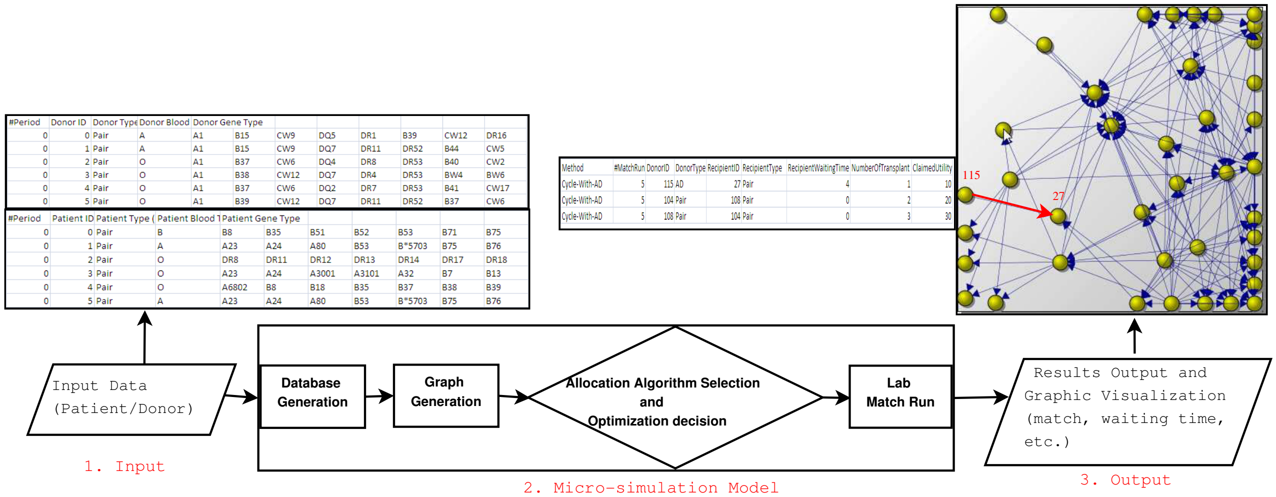

Fig. 2. A flow diagram of a general computer-based KPD decision support system

optimization match run and the real lab match run for decision, (4) and the ability to analyze and compare the output results for different KPD organ allocation algorithms.

B. GUI Functions and Comparison Results

The current GUI offers a range of functions to create a user friendly interface to support communications between inputs and outputs in the KPD program. In the current version, four allocation algorithms can be compared. They are: (1) *Cycle-Without-AD-Base* [7]: a traditional method that only considers the optimization on the number of transplants; (2) *Cycle-Without-AD-EU* [8]: a method uses the expected utility into the optimization process and considers fallback plan option into the real lab match run; (3) *Cycle-With-AD-Base*: a method integrates ADs into the KPD program and carries out the algorithm of [7] into the optimization process; and (4) *Cycle-With-AD-EU*: a method integrates ADs into the KPD program and carries out the algorithm of [8] into the optimization process.

Figure 3 shows a slapshot of GUI software of the KPD program by the *Cycle-With-AD-EU* method. The center big window of Figure 3 displays the output results by every step of operation. A clock-wise flowchart, composed of a series of small windows around the center window of Figure 3, denotes the input data or parameters by pop-up dialogs and boxes. First, when choose "Open File" menu, the system can read donors and recipients data from user-specific files. Second, if one clicks "Data Generation" and sets the parameters, such as the initial number of people, arrival rate, percentage of ADs and the total number of match runs, the windows of *Recipients* and *Donors* of Figure 3 show the randomly drawn kidney experimental data, including period (i.e., number of match run), unique ID, type of nodes (i.e., pair or AD), blood type (i.e., A, B, AB, O), or HLA type. If ID number is the same between recipient candidate and donor, it indicates a pair of originally incompatible donor-candidate, otherwise it denotes an AD. Based on these data sets, the GUI provides several additional options for users to further explore the data. For instance, on the click of "Graph Generation", a user can assign the link utility and link probability value, then the corresponding directed graph network is created in the *Graph Build* window. Then, a user can select the optimization algorithms by clicking the "Optimization Run" button and choose one optimization method and math run number index from input boxes: *Cycle-Without-AD-Base*, *Cycle-Without-AD-EU*, *Cycle-With-AD-Base*, and *Cycle-With-AD-EU* to obtain the optimal virtual matches. After that, when clicking "Lab Match Run", the upper part of center window will generate a report of optimal successful matches between donors and recipients, including donor ID, donor type, recipient ID, recipient type, recipient waiting time, number of transplants and utility for each match run. In addition, a summarized result of total match runs are calculated and showed in the bottom of center window.

Finally, the results of optimal matches for different allocation strategies are saved for comparison and analysis. For instance, Figure 4 demonstrates the cumulative number of transplants versus the number of match runs (months) between four allocation algorithms. The KPD data pool is generated by specifying three input parameters: the initial number of pairs is 200, the percentage of ADs is 5%, and new pairs entering into the pool following a Poisson process with an arrival rate is 10. In addition, the graph network is created by assigning two parameters: link utility is fixed as 10 and link probability follows a uniform random distribution on interval $[0.1, 0.5]$. Then four kidney allocation decision strategies are selected to obtain four different actual transplants using our computerized system. These results indicate that the expected-utility based methods, such as *Cycle-Without-AD-EU* and *Cycle-With-AD-EU*, are clearly advantageous to save more patients' lives since they provide higher number of transplants than that of the corresponding methods, such as *Cycle-Without-AD-Base* and *Cycle-With-AD-Base*. In addition, the methods without using ADs (i.e., *Cycle-Without-AD-Base* and *Cycle-Without-AD-EU*) are

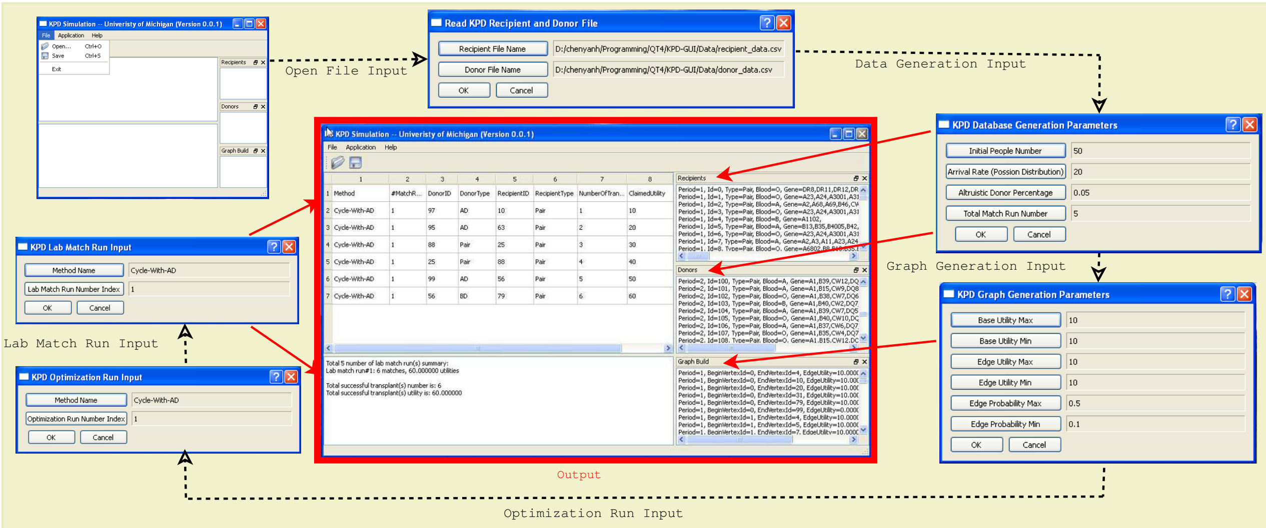

Fig. 3. A GUI for KPD program

consistently outperformed by the methods using ADs (i.e., *Cycle-With-AD-Base* and *Cycle-With-AD-EU*) over all match runs. In short, the GUI provides a very powerful tool to help clinicians, donors and patients more easily analyze and assess the KPD program.

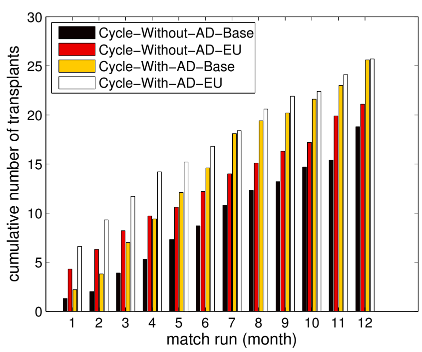

Fig. 4. Comparison of cumulative number of transplants versus month (number of match run) for *Cycle-Without-AD-Base*, *Cycle-Without-AD-EU*, *Cycle-With-AD-Base* and *Cycle-With-AD-EU* methods.

IV. Conclusions and Future Work

In this paper, we propose a general decision support system that closely matches the real clinical application to maximize the mutual benefits for KPD program. The system discussed in this paper has been partially developed into a GUI software package, which is released publicly through the necessary Institutional Review Board (IRB) regulations. In the future, we plan to pursue incorporating more allocation algorithms comparison, accommodation for different input data and graphic visualization of output data into our system for its maximum flexibility of clinical practice.

V. Acknowledgments

We thank Dr. John D. Kalbfleisch, Yijiang Li and Yan Zhou of Department of Biostatistics, for their support and discussion on details of the project. This research was funded by U. S. NSF (National Science Foundation), CRA (Computing Research Association) and CCC (Computing Community Consortium) under sub-award CIF (Computing Innovation Fellows)-B-66 (2010-2011).

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