American Journal of Transplantation 2012; 12: 2115–2124
Wiley Periodicals Inc.

doi: 10.1111/j.1600-6143.2012.04141.x

Equal Opportunity Supplemented by Fair Innings: Equity and Efficiency in Allocating Deceased Donor Kidneys

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For 7 years, the Kidney Transplantation Committee of the United Network for Organ Sharing/Organ Procurement Transplantation Network has attempted to revise the kidney allocation algorithm for adults (≥18 years) in end-stage renal disease awaiting deceased donor kidney transplants. Changes to the kidney allocation system must conform to the 1984 National Organ Transplant Act (NOTA) which clearly states that allocation must take into account both efficiency (graft and person survival) and equity (fair distribution). In this article, we evaluate three allocation models: the current system, age-matching and a two-step model that we call "Equal Opportunity Supplemented by Fair Innings (EOFI)". We discuss the different conceptions of efficiency and equity employed by each model and evaluate whether EOFI could actually achieve the NOTA criteria of balancing equity and efficiency given current conditions of growing scarcity and donor-candidate age mismatch.

Key words: Age-matching, efficiency, equal opportunity, equity, ethics, fair innings, kidney transplantation, lifespan equity, organ allocation, public policy, utility

Abbreviations: CAG, candidate age group; DAR, donor age range; DD, deceased donor; DDKT, deceased donor kidney transplant; DHHS, Department of Health and Human Services; ECD, expanded criteria donor; EOFI, Equal Opportunity Supplemented by Fair Innings; EPTS, estimated posttransplant survival; ESRD, end-stage renal disease; KDPI, kidney donor profile index; KTC, Kidney Transplantation Committee; NOTA, National Organ Transplant Act; OPO, Organ Procurement Organization; OPTN, Organ Procurement Transplantation Network; PRA, panel reactive antibody; SCD, standard criteria donor; UNOS, United Network for Organ Sharing; WLC, waitlist candidates.

Received 29 November 2011, revised 07 March 2012 and accepted for publication 09 March 2012

Introduction

For 7 years, the United Network for Organ Sharing (UNOS)/Organ Procurement Transplantation Network (OPTN) Kidney Transplantation Committee (KTC) has been revising the deceased donor (DD) kidney allocation algorithm for adults (≥18 years) in end-stage renal disease (ESRD) awaiting deceased donor kidney transplant (DDKT). Any change must conform to the 1984 National Organ Transplant Act (NOTA) which clearly states that allocation must take into account both efficiency (graft and person survival) and equity (fair distribution) (1). In its most recent proposal, "Concepts for Kidney Allocation" published online in February 2011, the KTC proposed a 20/80 plan in which the top 20% of DD kidneys as determined by a kidney donor profile index (KDPI) would be allocated to the top 20% of waitlist candidates (WLC) defined as the candidates with the highest estimated posttransplant survival (EPTS) (2). The remaining 80% of DD kidneys would be allocated to the remaining 80% of WLC using an "age-matching" formula (2). The KTC proposed a window of 30 years (donor age ±15 years). For example, a 50-year-old DD kidney would be allocated to an individual between 35 and 65 years of age. The KTC specifically rejected an allocation algorithm based on age-matching alone even though it offered similar gains in person and graft survival as the 20/80 proposal (2).

We (and others) have previously pointed out that implementation of the 20/80 proposal would fail to meet the NOTA equity requirements because (1) The KTC Concept Paper focused exclusively on the algorithm's impact on efficiency (number of years gained in person and graft survival) and failed to address its impact on equity (3); (2) the method used to create the top quintile does not have the statistical power to segregate the top 20% from the

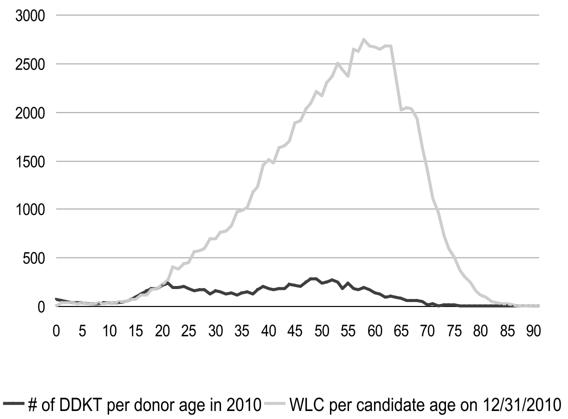

Figure 1: Deceased donor kidney transplants by donor age and waitlist candidates by candidate age. Discrepancy between age of deceased donors versus age of candidates. Annual number of deceased donor kidney grafts are fairly constant between the ages of 18 and 55 years with slight peak at approximately 21 years due to trauma and at approximately age 50 due to cerebrovascular disease. However, there are far fewer young adult candidates (18–35 years) than older candidates (>35 years) up to age 70 years. Thus allocating younger DD kidneys to younger candidates—such as proposed by the algorithms in the Kidney Concept Paper—without correcting for the mismatch in age distribution of donors and candidates is age discriminatory because it disproportionately allocates DD kidneys to young candidates.

next 20%; and therefore discriminates arbitrarily (4,5,6) and (3) gains in life years over a pure age-matching algorithm are negligible (4). Whether a pure age-matching algorithm would have been acceptable was not evaluated although doubtful given concerns of age discrimination.

In August 2011, the Department of Health and Human Services (DHHS) Office of General Counsel and DHHS Office of Civil Rights expressed concern that the use of a ±15-year age-matching algorithm as described in the KTC Concept proposal (either as the sole algorithm or in combination with the 20/80 proposal) did not meet the requirements of the Age Discrimination Act of 1975. While age may be legitimately used as a proxy for medical variables, the government was concerned that a ±15-year age-matching algorithm appeared to be arbitrary (7), a criticism bolstered by the KTC's decision not to examine the impact of its proposals on equity. The failure to evaluate equity in the new algorithms is particularly troubling because the waitlist is expanding rapidly, particularly for those over 50 years of age, and because there is a mismatch between the ages of DDs and WLC (see Figure 1) which has significant distributive implications for any proposal that incorporates an age-matching algorithm.

In this article, we describe three allocation models for adults, leaving "Share 35" as the algorithm for allocating kidneys to minors. They are: (1) the current system, (2) age-matching (as a sole algorithm and not as part of the 20/80 proposal) and (3) a two-step multiprincipled model that we call "Equal Opportunity Supplemented by Fair Innings" (EOFI). We then evaluate the different conceptions of equity and efficiency employed by each. Although the first two models cannot achieve the NOTA criteria of balancing equity and efficiency, we show that EOFI can because it uses a framework incorporating various equity and efficiency principles sequentially. Such a proposal was presaged by Persad et al. in 2009 who evaluated the principles of allocation of scarce medical interventions and concluded that "To achieve a just allocation of scarce medical interventions, society must embrace the challenge of implementing a coherent multi-principle framework rather than relying on simple principles or retreating to the status quo" (8).

Three Algorithm Proposals

(1) The current allocation system incorporates both efficiency (points for tissue-typing, with special priority to 0-antigen mismatches) and equity (points for waiting time and sensitization). With ~90 000 individuals in ESRD awaiting DD kidneys (9), and fewer than 11 000 DD kidneys available annually, waiting time points have become the primary allocation factor. Kidneys are allocated as either standard criteria donor (SCD) or expanded criteria donor (ECD) kidneys (9). WLC elect whether to be listed for both ECD and SCD kidneys, or only for SCD kidneys. The waitlist for ECD kidneys is much shorter, but both short- and long-term results are worse. Thus, the decision to list for ECD must be shared between transplant programs and candidates (10), based on candidate age, comorbidities, sensitization, dialysis experience and life-expectancy (11).

(2) The crux of age-matching in the current KTC proposal is to increase efficiency by both (i) allocating better DD kidneys (using donor age as a proxy for expected graft survival) to WLC who have longer life expectancy after transplantation (using candidate age as a proxy for EPTS; and (ii) allocating more DD kidneys to younger adult WLC due to the mismatch between donor and candidate ages (Figure 1). Both the KTC 20/80 and age-matching proposals do not use strict age-matching algorithms (i.e. offering only 30-year-old kidneys to 30-year-old candidates), but rather, they propose allocating kidneys within a ±15-year window (2).

(3) We propose a two-step algorithm, lexically constrained (meaning that order matters), that we call Equal Opportunity Supplemented by Fair Innings. The first step (Equal Opportunity) maintains that individuals of all ages should have an equal chance of getting a kidney. The algorithm is designed to give WLC of age X the same chance of getting an organ in any given year compared with WLC of age Y (where X and Y are ages ≥18 years). In order to deal with local

allocation realities where few WLC of any one particular age may exist, WLC are grouped into candidate age groups (CAGs). For demonstration, we use data from 2010, and to facilitate comparisons, we use the following four CAGs (18−34; 35−49; 50−64 years and >65+) to mirror the candidate groups chosen in the KTC Concept paper. Each CAG receives enough kidneys to hold the ratio of DDKT to WLC constant for each CAG: $^{\#\text{DDKT per CAG}}/_{\#\text{ WLC per CAG}}$ = constant. In 2010, there were 9713 adult DDKT (excluding multiorgan transplants) and on December 31, 2010, there were 95 674 adult WLC which means that the constant is 0.102 DDKT/WLC.

The second step (Fair Innings) maintains that those developing ESRD at younger ages are worse off than those developing ESRD when older because they have had fewer healthy life years (12,13), and directs the better DD kidneys (using donor age as a proxy for better) to younger WLC regardless of comorbidities. In EOFI, we create donor age ranges (DARs) to create DD kidney groups of the same general quality. For this demonstration of EOFI, we construct five DARs: (1) DAR 0–10 [which are treated as 50-year-old kidneys as their graft survival is more similar to 50-year-old kidneys than other younger kidneys (14)]; (2) DAR 11–34 (which are the kidneys that are considered optimal by share 35); (3) DAR 35–49-year-old kidneys (kidneys which are all judged to be SCD under current policies and practices); (4) DAR 50–59-year-old kidneys (which are a mixture of SCD and ECD by current policies and practices) and (5) DAR >60 years (which are all ECD by current policies and practices). In step 2, kidneys from the youngest DAR (with the exception of organs from donors ≤10 years) are assigned to the youngest CAG within the constraints of step 1 which limits the number of kidneys given to each CAG. Knowing the number of kidneys that are distributed into each CAG, we sequentially assign kidneys starting with the youngest CAG to oldest CAG starting from youngest DAR to oldest DAR. Most DARs are split between two CAGs. This means that when EOFI is operating in real time, kidneys are assigned to a CAG probabilistically. To demonstrate this process, consider CAG [18–34] which contained 10 645 WLC on January 1, 2010. To achieve equity using 2010 data, 10.2% (1081) of WLC in this CAG would receive a DDKT. The WLC in CAG [18–34 years] would receive all of their DD kidneys from DAR [11–34]. However, only 32% of DD kidneys from DAR [11–34] would be probabilistically distributed to WLC in CAG [18–34 years], the remainder (68%) distributed to WLC in CAG [35–49 years]. Once an organ is allocated to a CAG, the organ would be offered to a particular individual using dialysis time (and other factors including ABO compatibility) as the tiebreaker. EOFI repeats this process for all DDKT (described more fully in the Appendix). Overall, the result (see Figure 2B) is that younger kidneys would be consistently distributed to younger WLC in our model, whereas wide variability of donor ages for each CAG exists

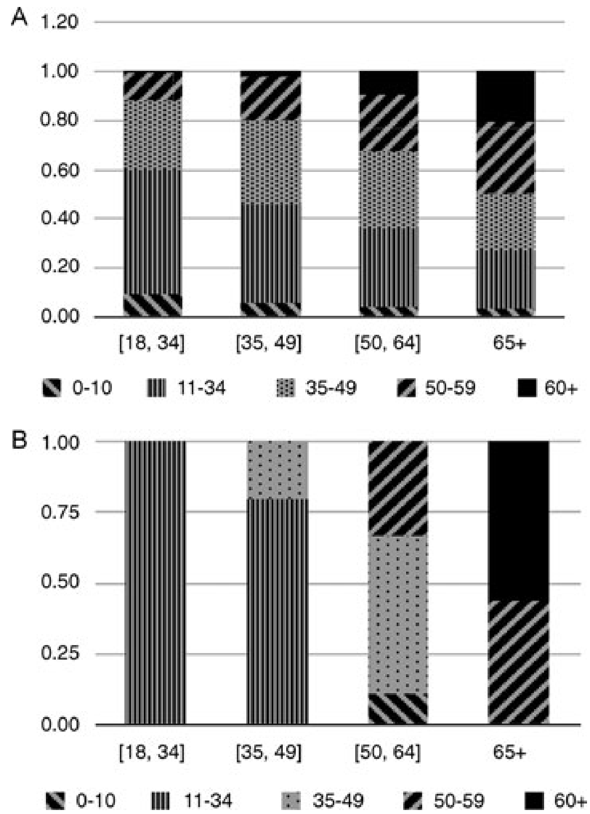

Figure 2: Percent DDKT by donor age under two allocation schemes. This figure demonstrates the age distribution of deceased donor kidneys to each of the candidate age groups for the year 2010 under two distinct allocation methods. (A) shows how organs were actually allocated in 2010 using UNOS STAR data. Note that kidneys of all ages are allocated to WLC of all ages. In contrast, (B) demonstrates that Equal Opportunity Fair Innings methodology assigns DD kidneys based on their Donor Age Range (DAR). In the EOFI 2010 projection, all candidates between the ages of 18–34 would have received a DD kidney from a donor younger than 35 years (equivalent to DD kidneys that are allocated under Share 35), and candidates over the age of 65 would have received all of their DD kidneys from donors over the age of 50 years. Note that even for candidates >65 years, 45% would come from donors 50–59 such that the average donor age for all kidneys allocated to candidates >65 years would be 59.7 years.

in the current system in which every WLC is eligible for every SCD kidney (kidneys <50 years; see Figure 2A).

Equity and Efficiency in the Three Models

NOTA requires allocation balancing equity and efficiency, but does not specify which conceptions of equity and efficiency. The three models all define efficiency as promoting graft and patient survival but use various conceptions of equity.

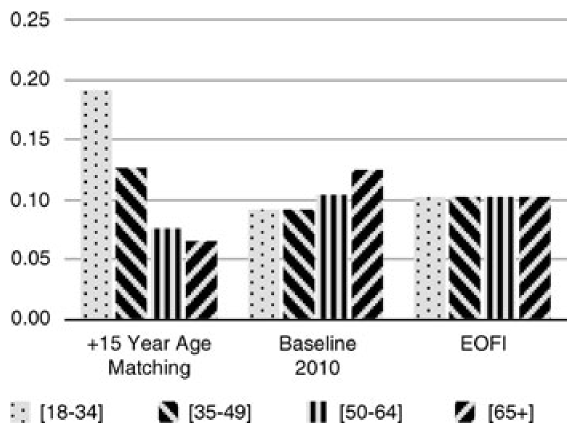

Figure 3: Measurement of equity based on DDKT/WLC ratio for three allocation models across candidate age. Using data from UNOS and from the Kidney Transplant Committee report, we calculate the equal opportunity principle (DDKT/WLC) for each of the three protocols considered in this manuscript: baseline, age-matching and EOFI for each candidate age group ([18,34], [35,49], [50,64], [65+]). The data show that the baseline algorithm advantages the older candidate age groups and age-matching is biased toward the younger candidate age groups whereas EOFI is designed to keep DDKT/WLC constant for all candidate age groups (providing equal opportunity).

(1) The current allocation system mainly conceives of equity as queuing (first-come, first served). It also incorporates a component of lottery in the sense that when a candidate reaches the top of the queue, the quality of the kidney that he or she is offered is random within either the category of DD kidneys that the WLC has agreed to accept. It is criticized for its inefficiency (it does not attempt to provide more or better kidneys to young adult WLC) (8,15). Although queuing and lottery are often described as equitable, the current system can actually be challenged on equity concerns. First, it uses waitlist time despite compelling data of racial and socioeconomic disparities in getting listed for transplant (16,17). Critics propose changing to dialysis time as a more equitable basis for the queue (2,18). Second, and more problematic, the proportion of kidneys transplanted into WLC of each age group is not equitable: WLC from different age groups have disparate likelihoods of receiving transplants. Currently, WLC >50 years receive more kidneys per WLC than WLC <50 years (see Figure 3). The greater number of transplants in older WLC can be explained mainly by the fact that they are more willing to accept ECD kidneys, but are also eligible for SCD, a problem predicted by Veatch (19).

(2) Although age-matching has been proposed multiple times, the arguments have been based solely on efficiency (20–22), without consideration of equity. An algorithm using age-matching, whether the 20/80 rule or pure age-matching, can be partly justified using arguments from prudential lifespan equity (it treats persons the same over the lifespan) (23). That is, prudential lifespan equity justifies providing less ideal (older) kidneys to 60-year-old WLC and better (younger) kidneys to 30-year olds because that is what one would have naturally. Treating persons of different ages differently is not inequitable because each person is treated equally to all others at each stage of life. It also incorporates a lottery component because all kidneys of the same age are not equal. Age-matching as an allocation strategy, then, has an equity explanation and is not unethical *a priori*. But age-matching fails as a solitary algorithm (and as an algorithm complemented by the 20/80 rule) because of the mismatch between donor and candidate age distributions (see Figure 1). This mismatch leads to skewed (and unfair) allocations (see Figure 3) which are left uncorrected in the ±15-year algorithm and exacerbated in the 20/80 model because the 20% best recipients and best donors will be categorized as "best" in large part based on age.

(3) The first step of the EOFI model embodies respect for the equal worth of each WLC by allocating kidneys to each CAG proportional to the number of WLC within that CAG such that WLC in each age group receive an equal number of kidneys in any given year. We believe this first step addresses the federal government's equity concern about age discrimination because it requires that all individuals, regardless of age, have an equal chance for a DDKT (the equity principle of equal opportunity). We eliminate the arbitrary inequity imposed by mismatch in donor and candidate age distribution that is present in current age-matching algorithms because step one equalizes the number of organs allocated to each CAG ensuring equal opportunity for WLC in all CAGs. Selection between WLC within the same CAG is determined by another equity principle, queuing. But in contrast with the current system, our queuing system would use dialysis time to overcome racial/ethnic, socioeconomic and educational barriers that lead to inequities in time to listing (16,17).

The second step of the EOFI algorithm is justified by fair innings, an argument which begins by assuming that "there is some span of years that we consider a reasonable span of life, a fair innings" (24, p. 91). Harris argues that such a strategy is morally defensible on equity grounds because it gives priority to the "worst off"—those who have not yet attained a reasonable lifespan (24). It is also efficient because it would allocate kidneys preferentially to young individuals in ESRD. We believe that a fair innings algorithm (step 2) that results in older WLC receiving older DD kidneys is a nondiscriminatory use of age, provided that the number of kidneys allocated to each age group is held constant (step 1) because it treats individuals equally at different life stages [prudential lifespan equity (23)]. In our proposal, then, all kidneys are allocated based on age without distinguishing between SCD and ECD. In application, this means that most WLC over age 65 will only be offered what are defined by the current system as ECD kidneys. By grouping DD kidneys into DARs that are consistent with current policies and practices, the DARs are large enough to permit some degree of lottery. This is especially important for the older WLCs to ensure that they have some probability of getting an SCD or SCD-like quality kidney. In our 2010 demonstration, 44% of candidates over the age of 65 would receive a DD kidney from a donor aged 50–59.

To determine whether a model fulfills the NOTA requirement to balance efficiency and equity, one must measure efficiency and equity. Like the KTC, we would measure efficiency in terms of graft and patient survival. Age-matching and EOFI are more efficient than the current model (baseline) because they either allocate more organs to younger people and/or allocate the younger DD kidneys to younger people. Although the efficiency gains achieved by EOFI will require further simulation, Figures 2(A) and (B) show that EOFI systematically promotes a younger to younger allocation compared to the baseline which increases efficiency (for more details, see the Appendix).

EOFI employs multiple conceptions of equity: equal opportunity, fair innings, prudential lifespan equity, queuing and to a certain extent lottery. The first principle, equal opportunity, can be quantitatively measured. The ratio: $^{\#\text{ DDKT per CAG}}/_{\#\text{ WLC per CAG}}$, expresses the likelihood that individuals within a CAG will get transplanted. The degree to which each model achieves equal opportunity is shown graphically in Figure 3. Under EOFI, 10% of WLC of every age group would have had a DDKT in 2010. In contrast, age-matching has been accused of being age-biased because older WLC are allocated disproportionately fewer organs, whereas the current algorithm disproportionately allocates more organs to older WLC. The lack of equal opportunity in both age-matching and the current algorithm is unethical because it fails to "take seriously the idea of the importance and dignity of each individual" (13,24). Thus, EOFI is the only one of the algorithms to fulfill NOTA's requirement to balance equity (specifically equal opportunity for WLC of all ages) with efficiency (providing better kidneys to younger WLC).

Unintended Consequences

As stated previously, the inefficiency of the current allocation system is the main impetus for reform. While the KTC simulations show that age-matching (whether as part of the 20/80 system or under a pure age-matching algorithm) is much more efficient than the current system, the simulations do not consider possible unintended consequences. The first is that any policy that gives priority to the young must acknowledge that adolescents and young adults are more likely to be noncompliant than other age groups (25), and thus greater allocation to young adults may not achieve the full expected gains in life years.

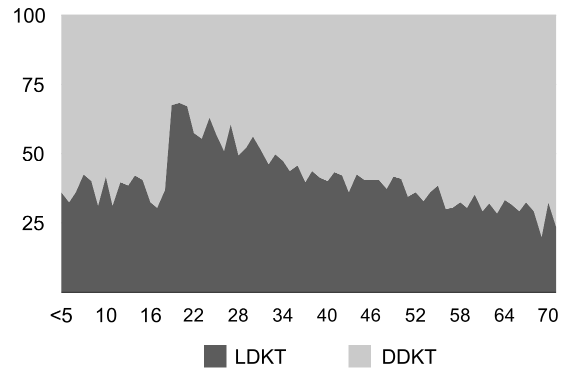

Figure 4: Percent of living and deceased donor kidney transplants by recipient age. Young adults (18–35 years) have the highest percentage of living donors since implementation of Share 35. The percentage of living donors to pediatric candidates is similar to candidates aged 36–50. Individuals older than 50 have the lowest rate of living donor kidney transplants.

A second possible unintended consequence may arise because DD kidney allocation only accounts for 60% of all transplanted kidneys and does not consider what impact a new allocation system will have on living donation rates and distribution. Currently, younger adult candidates are more likely to receive a higher proportion of living donors than others (4). Given that organs from living donors have longer graft survival, it would be inefficient to shift living donation from younger to older candidates. The impact of any allocation change on living donation may adversely affect efficiency if living donations to young candidates decrease and/or are shifted to older candidates, or even worse, living donations decrease overall. Given that living donors account for over one-half of all kidneys given to young adults in ESRD (see Figure 4) and that living donor grafts have a longer expected life years than a DD kidney, any decrease in living donors to this population may lead to an overall decrease in life years gained from total kidney transplantation.

The concern is not hypothetical. When UNOS implemented the "Share 35" rule which gives children on dialysis priority for the best DD kidneys in 2005, an unintended consequence was a significant decrease in the number of parents serving as living donors for their children (26). This pattern persists as can be seen in the lower rate of living donor transplantation for those <18 compared to those 18–25 years (see Figure 4) using 2010 data. Age-matching would greatly increase the likelihood that a younger recipient will get a DDKT (Figure 3), and may unintentionally disincentivize younger WLC from seeking living donors.

The unintended disincentives would be minimized under EOFI because the equal opportunity step of our model only slightly increases the number of DD kidneys allocated to younger WLC compared to the current model (see Figure 3) based on the principle of equal opportunity rather than any efficiency considerations. Rather, the main efficiency benefit of our model is not allocating more than an equal share of kidneys to younger WLC, but allocating better kidneys (using age as a proxy for quality) to the younger WLC to maximize EPTS and delay the need for retransplant. Because our model results in only a minimal change in the number of DD kidneys being allocated to young adults with ESRD, the likelihood that they will receive an organ remains relatively unchanged from current waitlist times. Thus, the new model should have minimal effect on the number of young adult WLC seeking living donors (in contrast with the impact of "Share 35" on living donation to pediatric WLC). Of course, the final decision whether to accept a particular kidney and whether to seek a living donor should be made between the WLC and the transplant team reflecting both patient values and clinical judgment (10).

One potential unintended consequence of EOFI is that older WLC who previously bypassed the long SCD waitlist by signing up for an ECD kidney will no longer have that option. Rather, their waiting time will be equivalent to all other WLCs despite the fact that they will be offered older kidneys. This may increase the likelihood that they seek a living donor.

Next Steps

Our model is incomplete. First, for the purpose of this article, we defined the WLC for each year as the number of individuals on the UNOS waitlist on the last day of the year, using a static "snapshot" that does not include the dynamics of WLC enrolling and disenrolling. This "snapshot" includes those who may be on the waitlist temporarily while awaiting living donor transplants and those who are status 7 and unable to accept a DD kidney if offered. Neither of these groups is distributed randomly in the waitlist population. Including those waiting for living donors in the WLC denominator may actually slightly overestimate the number of young adult WLC, whereas including those who are status 7 may overinflate the number of kidneys to be allocated to those between 50 and 64 which is the CAG with the largest percentage of inactive WLC (27). Before an EOFI algorithm can be implemented, the transplant community will need to develop a consensus definition of who is an "actual" WLC to determine the true size of the denominator for each CAG. We discuss this further in the Appendix.

Second, selection within a CAG using dialysis time rather than waitlist time will reduce socioeconomic and racial disparities that occur due to the longer delay from the development of ESRD to placement on the waitlist for minorities, those of lower socioeconomic status, and those of low educational attainment (2,18,28). This will also exclude preemptive DD transplantation, which may also reduce socioeconomic disparities given that individuals who are listed preemptively are not random but tend to be better educated and have private health insurance (29). However, equalizing the starting point for DD organ eligibility should not be interpreted to deny the benefit of preemptive transplantation and candidates should be educated about the option of preemptive living donor transplantation as a way to reduce dialysis-induced morbidities (29).

Finally, at least three important implementation details are not addressed in our concept proposal. First, our model does not address highly sensitized patients; i.e., those with high panel reactive antigens (PRA). If WLC with high PRA only have access to a single age range of potential kidneys, they may never be offered a suitable organ. Thus, WLC with high PRA would need to have access to larger CAGs, larger geographic groups or both to give them a fair chance of receiving an organ. Second, further exploration is needed about how to allocate DD kidneys from donors aged 0–10 years. Data exist to suggest that these DD kidneys, on average, are more similar to 50-year-old DD kidneys than other younger kidneys in terms of graft survival (14), and so that is how we allocated them for this demonstration. Third, although we discuss EOFI using 15-year windows for CAGs and create DARs that mimic current policies and practices, simulations are needed to determine if different sizes would be better (on equity and/or efficiency grounds). While we (and others) have argued elsewhere against the inequities imposed by local allocation (4,30), if local allocation is retained, each organ procurement organization (OPO) would need to run EOFI with the local DD kidney distribution and WLC distribution. Different sized OPOs also may need to use different size CAGs and DARs. These issues can be easily accommodated by our model without affecting the basic tenet which is that DDKT/WLC remains constant.

Conclusion

The newest KTC allocation algorithms fail to fulfill the NOTA requirement to balance equity and efficiency. In this article, we propose a two-step allocation model, lexically constrained: equal opportunity followed by a fair innings strategy. This model balances efficiency (providing better kidneys to younger WLCs) with multiple conceptions of equity: equal chances for all recipients independent of age (equal opportunity), advantaging the young because they are "worst off" (fair innings) to achieve equal treatment of individuals at all life stages (prudential lifespan equity), retaining some degree of randomness in age distribution (lottery) and employing dialysis time as a tiebreaker (equity by queuing). It uses transparent rules, an easily modifiable algorithm, and is consistent with the Age Discrimination Act and NOTA. We urge UNOS to consider EOFI for further evaluation.

Acknowledgments

We thank Walter Glannon, PhD for his thoughtful comments on an earlier draft of this article. We also thank David Blair, MD/PhD candidate for his assistance with building the EOFI algorithm.

Funding: W.P. was funded in part by a University of Chicago Fentress Award for senior students at the Pritzker School of Medicine.

Disclosure

The authors of this manuscript have conflicts of interest to disclose as described by the *American Journal of Transplantation*. Dr. Veatch is currently a member of the United Network of Organ Sharing (UNOS) Ethics Committee. The views expressed are his own and do not represent UNOS.

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Appendix: Implementing Equal Opportunity Supplemented by Fair Innings

Introduction

In the main article, we proposed a two-step allocation scheme that we called "Equal Opportunity supplemented by Fair Innings (EOFI) for the allocation of deceased donor (DD) kidneys. EOFI accepts four inputs:

(1) Candidate age distribution at the time of allocation start (# of Candidates per Candidate Age, Figure 1);
(2) Deceased donor kidney transplants (DDKTs) by donor age distribution from a chosen time period prior to allocation start (Figure 1);
(3) A list of candidate age groups (CAG);
(4) A list of donor age ranges (DARs).

Using these four inputs in the manner described later, the EOFI algorithm creates a "Hypothetical" Allocation Matrix, how allocation "should have" gone in the year being considered if EOFI were upheld. We then use this information to generate an Assignment Matrix, which would determine the allocation method for the following year. This Assignment Matrix would allocate DD kidneys based on donor age to a particular CAG. This often requires a probabilistic allocation of DD kidneys.

The time period over which CAGs and DDKT are evaluated and the age range of CAGs and DARs are adjustable parameters. Below we demonstrate our model using data from 2010 to demonstrate how DD kidneys would have been allocated in 2011 under EOFI. Thus, although our model is static like the algorithms described in the Kidney Concept Proposal, the model can be recalculated at intervals agreed upon or by criteria determined by the wider transplant community.

All data for this demonstration are gathered from the UNOS Standard Transplant Analysis and Research (STAR) Files data set (31). We use 2010 data and consider only kidney transplants to adults and exclude kidneys that were part of multiorgan transplants. We count only those DD kidneys that were successfully transplanted and count two kidneys transplanted en bloc as a single organ. We select waitlist candidates (WLC) by selecting those registrations placed on the list before December 31, 2010 (INIT_DATE variable prior to December 31, 2010) and remained on the list into 2011 (END_DATE variable date after December 31, 2010). Since SHARE 35 remains for allocation to candidates younger than 18 years, we remove all of the kidneys allocated to minors from our analysis.

For our demonstration, we use the following inputs: (1) the candidate age distribution on December 31, 2010; (2) a 1-year allocation period; (3) assign candidates to four age groups: [18–34], [35–49], [50–64], [65+] and (4) group donors into five age groups: [0–10], [11–34], [35–49], [50–59], [60+].

Equal Opportunity (Step 1)

We first determine how many DD kidneys each CAG should receive so that the ratio of transplants per age group to number of candidates per age group is the same for all age groups. In 2010, there were 9713 adult DDKT and on December 31, 2010, there were 95 674 adult WLC, so this ratio is 0.102 DDKT/WLC.

Table A1: Number of WLC and number of DDKT required by equal opportunity for each CAG

CAG	No. of WLC	No. of DDKT required by by equal opportunity
[18—34]	10 645	1081
[35—49]	28 355	2877
[50—64]	40 747	4139
[65+]	15 927	1616

We propose that each CAG be allocated the same proportion of DD kidneys such that ${}^{\#\, DDKT\ per\ CAG}/_{\#\ \mathrm{WLC\ per\ CAG}}$ = constant for all CAGs. For example, in the 18–34-year-old candidate age group (CAG 1), there were 10 645 WLCs on December 31, 2010. Therefore, the number of DDKT the 18–34-year olds "should" receive is 1081 ($DDKT_1$). The results of performing this calculation for all CAGs are displayed in Table A1.

Fair Innings (Step 2)

Suppose that all the DD kidneys could be collected over the course of a year an allocated on 1 day (in our example, December 31, 2010). Starting at the youngest CAG, we would allocate organs from the youngest DAR until the CAG has been allocated the appropriate number of kidneys to satisfy Equal Opportunity. For example, the CAG [18–34] would need 1081 DD kidneys ($DDKT_1$) to satisfy Equal Opportunity. Therefore, beginning with the DAR [11–34], we allocate 1081 DD kidneys to the [18–34] CAG, "using" 1081 of the 3,366 DD kidneys from the DAR [11–34]. After this process is completed, the algorithm moves on to the CAG [35–49] allocating it the 2285 DD kidneys ($DDKT_2$) required from the youngest available DAR (so 2285 from [11–34] and 592 from [35–49]). This process is continued for the remaining CAGs. One exception to the "youngest DAR available" process is organs from donors aged 0–10 which we have chosen to treat as 50-year-old kidneys as their graft survival is more similar to 50-year-old kidneys than other younger kidneys (14). The results of this process can be represented as a EOFI "Hypothetical" Allocation Matrix (see Table A2), with columns representing DAR and rows representing CAGs.

This matrix represents how we would have allocated DD kidneys in 2010 to uphold Equal Opportunity and Fair Innings. We propose that we use this information to allocate DD kidneys in real time for the next year based on this information. Specifically, we call for a system where DD kidneys are allocated based on the age of the donor according to an Assignment Matrix. This Assignment Matrix allocates DD kidneys based on DARs, and this allocation is usually probabilistic involving more than one CAG. If the donor distribution (number of donors per DAR) changes little, then allocating DD kidneys according to the EOFI Assignment Matrix (see Table A3) will be consistent with both Equal Opportunity and Fair Innings.

Consider two examples that help to clarify how our algorithm differs from the current baseline system. First, a 25-year-old dies and donates a DD kidney. This DD kidney would fall into the DAR [11–34], and be assigned to the CAG [18–34] with a 0.32 probability or to the CAG [35–49] with a 0.68 probability. The 25-year-old organ would have zero chance of being assigned to the CAG [50–64] or CAG [65+]. However, in the baseline system in 2010, this organ would go to a candidate over the age of 50 approximately 54% of the time, a result that would be impossible under EOFI (baseline data are shown graphically in the main article, Figure 2A).

Table A2: EOFI "hypothetical" allocation matrix

		[0–10] N (%)	Donor [11–34] N (%)	Age [35–49] N (%)	Range [50–59] N (%)	[60+] N (%)	SUM N (%)
Candidate	[18, 34]	0 (0)	1081 (11)	0 (0)	0 (0)	0 (0)	1081 (11)
Age	[35, 49]	0 (0)	2285 (24)	592 (6)	0 (0)	0 (0)	2877 (30)
Group	[50, 64]	425 (4)	0 (0)	2322 (24)	1392 (14)	0 (0)	4139 (38)
	65+	0 (0)	0 (0)	0 (0)	706 (7)	910 (9)	1616 (16)
	SUM	425 (4)	3366 (35)	2914 (30)	2098 (21)	910 (9)	9713 (100)

Table A3: EOFI probability assignment matrix

		[0–10]	Donor [11–34]	Age [35–49]	Range [50–59]	[60+]
Candidate	[18, 34]	0	0.32	0	0	0
Age	[35, 49]	0	0.68	0.20	0	0
Group	[50, 64]	1	0	0.80	0.66	0
	[65+]	0	0	0	0.34	1

Second, consider the case where a 51-year-old dies and donates a DD kidney. Under EOFI, this DD kidney would be assigned to the CAG [50–64] with a 0.66 probability or to the CAG [65+] with a 0.34 probability. If allocated by current practice and depending on whether it was classified as a standard criteria donor (SCD) or expanded criteria donar (ECD) kidney, it would be offered to all candidates independent of their age (SCD) or only those who have opted for ECD listing, respectively. In contrast, in EOFI, this distinction is not taken into consideration in the allocation algorithm nor is the kidney donor profile index (KDPI), a concept that has been developed to score the quality of kidneys as a continuous variable rather than a binary categorization. However, either the binary (ECD/SCD) or continuous (KDPI) characterization is envisioned to play a major role in patient choice as part of shared decision making within the EOFI allocation matrix with individual WLC being able to choose and have their preferences included in their waitlist profile.

In EOFI, once a DD kidney is assigned to a CAG, it will be allocated to a specific individual WLC in that CAG being determined by a modified version of the current point system, with queuing based on dialysis time rather than waitlist time (we discuss this in greater detail later). If that individual or transplant team refuses the organ, it would be offered to another individual in same CAG with the next highest point total.

Next Steps

This appendix outlines an allocation algorithm that would satisfy the principles of EOFI. If one accepts that the EOFI algorithm proposed in the main article achieves a fair balance between equity and efficiency, then simulation is necessary to choose values for parameters that will require modification and/or clarification to the simple two-step proposal that we have described. One question, already mentioned, is how to allocate kidneys from donors aged 0–10 years. Below we enumerate six other aspects of the algorithm for which different solutions will yield different equity and efficiency balances.

(1) We defined the CAGs (i.e. [18–34], [35–49], [50–64], [65+]) to match the candidate groups in the Age-matching simulations found in the Kidney Concept Paper in order to facilitate comparisons (2). The size of the CAGs can be modified. Narrower CAGs will better satisfy Fair Innings (Youngest to Youngest). However, it may be that, given local allocation, different sized Organ Procurement Organizations (OPOs) will need to choose to use different size CAGs. Simulations of EOFI with different size CAGs are also needed to quantify the efficiency gains (in life years gained after transplant or some other metric) of EOFI over the baseline system. While it is reasonable to assume giving younger DD kidneys to the youngest candidates will improve system efficiency, how much efficiency is generated needs to be determined and this may also impact the selection of the CAGs.

(2) Once an organ is assigned to a CAG, there needs to be a method to allocate the kidney within the CAG. We suggest using time from initiation of dialysis as the primary determining factor within the CAG, thus invoking queuing as the principle for equitable distribution. Other factors can be incorporated into the intra-CAG allocation, if desired by the transplant community such as points for DR matching similar to the current system.

(3) WLC who are highly sensitized (i.e. with high PRAs) may never be allocated a DD kidney if they are only eligible for DD kidneys within their DAR. Rather such candidates may need to be eligible a larger age range of DD kidney donors. To accommodate such candidates will require exceptions to restricting candidates to those organs within their DAR (both permitting them to be eligible for both older and younger organs).

(4) EOFI assumes that the age distribution of DD kidneys is relatively stationary, or unchanging in time. While this is true for the last several years (31), there have been distributional changes over time. For example, in the 1990s, the shortage of DD kidneys led to greater acceptance of older DD kidneys (32,33). Even if one assumed a constant donor distribution, it is not clear how frequently to recalculate the Assignment Matrix. The time frame must be long enough to properly sample the DD kidney by donor age distribution to ensure that each CAG is assigned the correct proportion of organs in real time. Moreover, the waitlist has been expanding rapidly, with over 20 000 new entrants annually since the late 1990s and now closer to 30 000 new entrants annually (31). The Assignment Matrix will need to be recalculated as the waitlist changes, even if the donor distribution remained constant. In our demonstration, we used a 1-year time frame although a different time frame might be preferable if significant changes in the number of DDKT or the number of WLC occurred.

(5) The actual denominator used in the EOFI calculations should be more nuanced than using the number of registrations on the UNOS waitlist. Currently in EOFI, we count WLC using specific variables found in the STAR data set. This includes counting more than once approximately 9000 candidates who are listed in more than one OPO. Approximately,

8000 candidates are also transiently listed annually while awaiting the work-up of a living donor. While many would accept a DD kidney if offered, the likelihood is low as they have minimal wait time accrued. In addition, approximately 30% of WLC are inactive at any given moment (34). Because it is critical to our equity measure to consider only candidates who would/could accept an organ if allocated to them, it may be reasonable to exclude all or most of these candidates from the denominator. This revised number of WLC may be better suited to serve as the denominator in our equity measure, since it better estimates the number of candidates who truly intend (or are capable of) accepting a DD kidney if one were allocated to them. In addition, making time from initiation of dialysis the allocation principle within a CAG would remove an advantage of listing candidates before their evaluations were complete or they were ready to actively receive a kidney transplant which would hopefully reduce the number of inactive candidates.

(6) Maintaining the Share 35 policy for kidney allocation to minors means that the number of DD kidneys transplanted into pediatric candidates must be removed from the DD kidneys available for EOFI. We assumed that the number of pediatric candidates remains relatively constant year to year, which is the case for the past decade (31), and we removed all DD kidneys that were transplanted into pediatric candidates from our analysis (465 transplants in 2010). If the number of pediatric recipients changes significantly, or the number of living donor transplants for pediatric candidates vary widely, some of the DD kidneys we assume will be available for adults will not be or some additional DD kidneys may be available for adult transplantation.

Conclusion

We propose EOFI for consideration as a modification to the current DD kidney allocation system. In this appendix, we show how the results in the article were generated. Actual simulations are needed to quantify the efficiency gains that can be expected and to ensure that equity can actually be achieved in a real-world setting. Parameters like CAG size and Allocation Matrix recalculation time will need to be determined through more complicated simulation before model implementation, and may vary between OPOs if organs continue to be allocated locally.