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ORIGINAL ARTICLE

Donor kidney volume measured by computed tomography is a strong predictor of recipient eGFR in living donor kidney transplantation

David P. Al-Adra[1,2,3] · Maria Lambadaris[1] · Andrew Barbas[1,2,3] · Yanhong Li[1] · Markus Selzner[1,2,3] · Sunita K. Singh[1,4,5] · Olusegun Famure[1] · S. Joseph Kim[1,4,5] · Anand Ghanekar[1,2,3,6]

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Abstract

Purpose The effect of living donor kidney allograft size on recipient outcomes is not well understood. In this study, we sought to investigate the relationship between preoperatively measured donor kidney volume and recipient estimated glomerular filtration rate (eGFR) in living donor kidney transplantation (LDKT).

Methods We studied computed tomography (CT) donor kidney volumes and recipient outcomes for 438 LDKTs at the Toronto General Hospital between 2007 and 2016. Estimated glomerular filtration rate (eGFR) was calculated at 1, 3, and 6 months and a multivariable linear regression model was fitted to study the effect of donor kidney volume on recipient eGFR.

Results The mean volume and weight of the donated kidneys were 157.3 (±32.3) cc and 186.7 (±48.7) g, respectively. Kidney volume was significantly associated with eGFR on multivariable analysis ($P < 0.001$). Specifically, for every 10 cc increase in kidney volume, there was a 1.68 mL/min, 1.25 mL/min and 0.97 mL/min rise in recipient eGFR at 1, 3, and 6 months, respectively.

Conclusions Donor kidney volume is a strong independent predictor of recipient eGFR in LDKT, and therefore, may be a valuable addition to predictive models of eGFR after transplant. Further research may determine if the inclusion of donor kidney volume in matching algorithms can improve recipient outcomes.

Keywords Living donor kidney · Kidney volume · Computed tomography · eGFR prediction · Outcomes

Abbreviations

BMI	Body mass index
CKD-EPI	Chronic kidney disease epidemiology collaboration formula
CNI	Calcineurin inhibitor
CT	Computed tomography
eGFR	Estimated glomerular filtration rate
LDKT	Living donor kidney transplantation
MSE	Mean squared error
PRA	Pannel reactive antibody

David P. Al-Adra and Maria Lambadaris contributed equally to this work.

S. Joseph Kim and Anand Ghanekar jointly directed this work.

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✉ Anand Ghanekar
Anand.Ghanekar@uhn.ca

Extended author information available on the last page of the article

Introduction

Kidney transplantation is the treatment of choice for end-stage renal disease, with clearly established quality of life and survival benefits [1]. Although much attention has been devoted to improving outcomes of kidney transplantation by optimizing immunological factors, medical management, surgical techniques, and organ preservation, there is increasing interest in how additional factors, such as kidney allograft size (i.e., mass or volume), may influence both graft performance and long-term graft survival [2].

It is hypothesized that transplantation of greater nephron mass will decrease glomerular hypertension and hyperfiltration and increase graft survival [3]. However, studies examining the effect of kidney allograft size on long-term graft function have revealed conflicting results [4–8]. Furthermore, these studies are limited by relatively small cohort

sizes and inconsistent methods of kidney volume or weight measurements. The interaction between donor weight, kidney graft weight or volume, recipient weight, and recipient outcomes is important to characterize, as these factors could potentially be incorporated into kidney allocation algorithms to optimize outcomes.

In contrast to deceased donor kidney transplantation, living donor kidney transplantation (LDKT) offers a unique opportunity to specifically study the effect of donor kidney volume on recipient outcomes. The relatively uniform acceptance criteria for living donors, elective nature of the procurement surgery, consistently short cold ischemia times, and very low rates of delayed graft function or primary non-function following LDKT contrasts with the wide variety of confounding donor and recipient variables that may influence short and long-term graft function in deceased donor kidney transplantation. Furthermore, the universal availability of high resolution cross-sectional imaging of the living donor as part of their preoperative evaluation allows for the accurate measurement of kidney volume [9]. With the increasing importance of kidney exchange programs to match otherwise incompatible living donor-recipient pairs, it is conceivable that kidney volume, based on preoperative imaging studies, could be incorporated into matching algorithms to further optimize outcomes.

In this study, we sought to characterize the relationship between preoperatively measured donor kidney volume and recipient estimated glomerular filtration rate (eGFR) in LDKT.

Methods

Study population

This study included all adult patients who underwent LDKT at the Toronto General Hospital between April 2007 and November 2016. Patients with a history of prior kidney or non-kidney transplant, primary graft non-function (defined as insufficient kidney function resulting in dialysis dependence for at least 3 months after transplantation), graft failure, loss to follow-up or death within 1-month post-transplant, delayed graft function (defined as the need for dialysis in the first 7 days after transplantation), acute rejection within the first month post-transplant, or unavailable donor kidney volume were excluded.

Data captured consisted of demographics for donor and recipient, including gender, age at donation/transplantation, body mass index (BMI) and race. Donor data included serum creatinine, eGFR, and kidney volume (described below). Recipient-specific data included cause of kidney failure, duration of dialysis prior to transplantation, previous transplantation, induction and maintenance immunosuppression therapy, and panel-reactive antibodies (PRA). Follow-up data included graft function, biopsy-proven acute rejection episodes, graft loss (i.e., return to dialysis or preemptive re-transplant) and death within the first 6-month post-transplantation.

Data were prospectively entered into the Comprehensive Renal Transplant Research Information System [10] and the Organ Transplant Tracking Record (Chronic Care Solutions; Omaha, NE) and analyzed, retrospectively. The study was approved by the University Health Network Research Ethics Board.

Kidney computed tomography volumetry

Kidney parenchymal volumes were measured from pre-operative computed tomography (CT) images using the Myrian® software package (intrasense; Paris) as previously described [9]. Briefly, enhancing kidney parenchyma was highlighted using built-in software tools based on CT attenuation values. Surrounding structures, such as blood vessels and collecting system, were excluded from the volume determination.

Surgical procedures and post-operative management

Donor and recipient clinical care was provided according to standard procedures. Briefly, kidneys were retrieved from living donors laparoscopically or via subcostal mini-incision open approach. Kidneys were perfused with cold organ preservation solution and maintained in static cold storage until implantation in the recipient. Kidney back-table preparation included removal of extraneous perinephric tissues, mobilization of the renal artery and vein, and preservation of the ureter. Donor kidney weight was recorded on a digital scale after back-table preparation was complete. Kidneys were transplanted heterotopically onto the iliac vessels in the recipient and end to side ureterocystostomy performed over a stent. Immunosuppression consisted of induction with thymoglobulin or basiliximab followed by maintenance with corticosteroids, mycophenolate, and a calcineurin inhibitor.

Laboratory evaluations consisted of bloodwork and urinalyses as per routine clinical management. Imaging and biopsies of kidney grafts were only performed for cause. Recipient (eGFR) was calculated at 1, 3, and 6 months post-transplant using the Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) formula [11].

Statistical analyses

Descriptive statistics for continuous variables are presented as mean ± standard deviation or median with 25th and 75th percentiles. For categorical variables, percentages of each category are presented. A multivariable linear regression

model was used to evaluate the association between donor kidney volume and recipient eGFR after controlling for potential confounders. Predictive models were built to predict recipient eGFR and fivefold cross-validation was used to validate the predictive models. In this validation method, the data were first split into five parts. The first part was used as test data with the other four parts being used as training data. A predictive model was built using the training data. The model was then used on the test data to predict the outcome, comparing the predicted values with the observed values, and calculating the mean squared error. This process was repeated by consecutively changing the test data to the second, third, fourth and fifth parts and using the remaining parts as training data. This allowed for the generation of five mean squared errors. Subsequently, the average of all five mean squared errors was obtained to generate the test mean squared error. The smaller the mean squared error, the higher the predictive accuracy of the model.

Statistical calculations were performed using Stata MP/4, version 12 (StataCorp, College Station, TX, www.stata.com). Two-tailed P values < 0.05 were considered statistically significant.

Results

Study population

A total of 743 patients were transplanted in the study period. As shown in Fig. 1, 305 patients were excluded, and 438 were included in the final analysis. Of the excluded patients, the majority (202) were omitted for not having measurable kidney volumes on CT. This group consisted of patients that were part of a paired exchange (CT done at an outside institution and not permanently stored on our institutional imaging server) and those CT scans that were of insufficient quality or inadequate sequence for 3D rendering. Donor, recipient and immunosuppression characteristics of these excluded patients are compared to the included patients in Supplementary Table 1. Recipient history of diabetes, time on dialysis and peak PRA were statistically different between patients with CT volumes included in the study and patients who were excluded for lack of CT volume, but not clinically significant. The numbers of delayed graft function, primary non-function and death were small ($n = 31$; Fig. 1) and no correlations to any study characteristics could be found when these cases were analyzed for cause (data not shown).

The baseline characteristics of included patients are shown in Table 1. Mean donor age was 45.7 (± 12.1), 41.9% were male, and 74.7% were white race. Mean donor eGFR at donation was 94.4 (± 14.6) mL/min/1.73 m^2 (CKD-EPI). Mean recipient age at transplant was 45.9 (± 13.7) years, 57.1% of recipients were male, and 75.4% were white race.

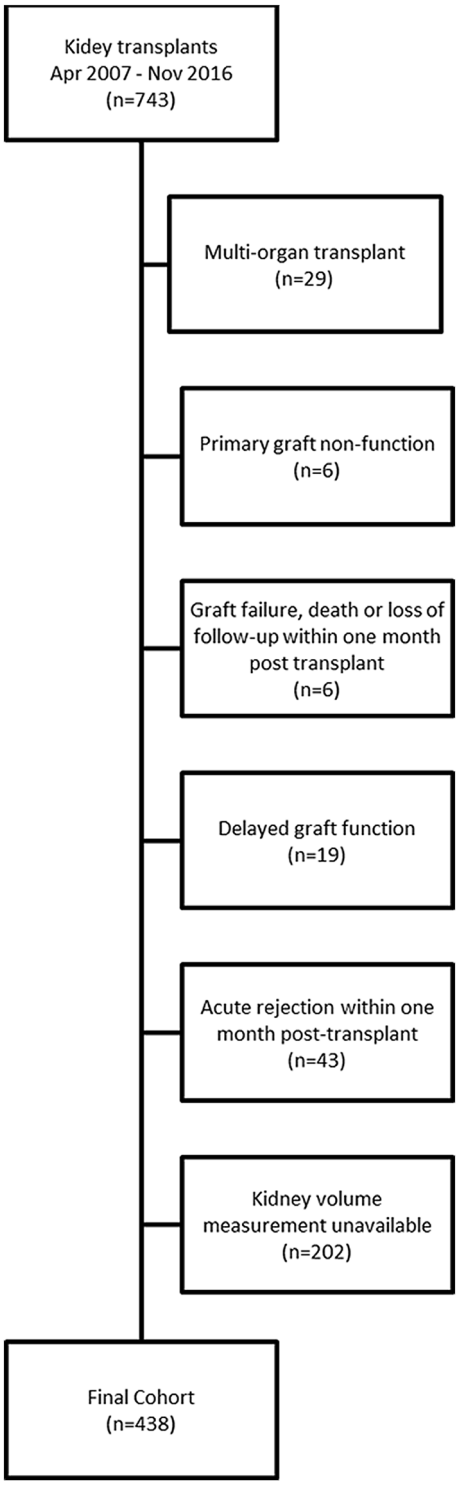

Fig. 1 Inclusion and exclusion flow chart. All living donor kidney transplants between April 2007 and November 2016 were included in the study. The number of patients excluded for each criteria is listed. Kidney volume measurements unavailable includes those patients with CT scans that could not be rendered into 3D volumes, CT scans done at outside institutions and paired exchanges

Table 1 Recipient, donor, and immunosuppression characteristics

	Number of patients ($n=438$)	Value
Donor		
Age (years)	438	45.7 ± 12.1
Sex (% Male)	437	41.9
eGFR at donation (CKD-EPI) (mL/min/1.73 m^2)	432	94.4 ± 14.6
Race (%)		
White	192	74.7
Black	13	5.1
Asian	44	17.1
Other	8	3.1
Recipient		
Age (years)	438	45.9 ± 13.7
Sex (% Male)	438	57.1
BMI (Kg/m^2)	423	26.5 ± 5.8
History of diabetes (%)	438	25.8
Time on dialysis (years)	438	1 (0.0, 2.3)
Peak PRA > 0 (%)	437	39.1
Race (%)		
White	285	75.4
Black	25	6.6
Asian	63	16.7
Other	5	1.3
Immunosuppression		
Type of Induction (%)		
Non-depleting	138	31.7
Depleting	298	68.4
CNI at 1 month (%)		
Tacrolimus	364	84.1
Cyclosporine	69	15.9

Data expressed as mean (± standard deviation) or median (25th percentile, 75th percentile)

Mean recipient BMI was 26.5 (± 5.8) and 25.8% had diabetes mellitus. Median time on dialysis prior to transplant was 1.0 (0.0, 2.3) years. 39.1% of recipients had peak PRA > 0%. No recipients had donor-specific antibodies at the time of transplantation. Induction therapy with a depleting agent was used in 68.4% of recipients, and 84.1% were maintained on tacrolimus at 1-month post-transplant.

Kidney volume versus weight

The average volume of the donated kidney, measured by CT volumetry, was 157.3 (± 32.3) cm^3. The mass of the donated kidney was measured in a subset of 106 patients, with a median weight of 186.7 (± 48.7) g. Figure 2 illustrates a modest, but significant correlation of donor kidney mass to donor kidney volume, with an $r=0.57$ and r^2 of 0.33 (both $P<0.001$).

Factors influencing recipient eGFR

On univariable analysis, kidney volume is significantly associated with recipient eGFR ($P<0.001$): for every 10 cc increase in kidney volume, the mean recipient eGFR at 1 month increases by 1.86 (1.27, 2.44) mL/min/1.73 m^2 (Table 2). Univariable analysis also revealed that recipient age, sex, race, BMI, and history of diabetes were significantly associated with recipient eGFR at 1 month. In addition, donor age, sex and eGFR were significantly associated with recipient eGFR at 1 month. On multivariable analysis, kidney volume remained significant: for every 10 cc increase in kidney volume, the mean recipient eGFR at 1 month increases by 1.68 (1.06, 2.30) mL/min/1.73 m^2 ($P<0.001$; Table 2). Multivariable analysis also showed that recipient age, race, BMI, time on dialysis and type of CNI remained significant risk factors for eGFR at 1 month, along with donor age, race and donor eGFR. All of the above mentioned risk factors were also significant at 3 months on both univariable and multivariable analysis (Table 3). In addition, donor sex and donor race were significant on univariate and multivariate analysis, respectively.

To determine the long-term effects of donor kidney volume, the analysis was extended to 6-month post-transplant. On univariable analysis, kidney volume was significantly associated with recipient eGFR ($P<0.001$): for every 10 cc increase in kidney volume, the mean recipient eGFR at 6 months increases by 1.28 (0.70, 1.78).

Univariable analysis also revealed that recipient age, sex, BMI, and history of diabetes were significantly associated with recipient eGFR at 6 months. In addition, donor age, sex and eGFR were significantly associated with recipient eGFR at 6 months. On multivariable analysis, kidney volume remained significant: for every 10 cc increase in kidney volume, the mean recipient eGFR at 6 months increases by 0.97 (0.34, 1.59) mL/min/1.73 m^2 ($P=0.002$; Table 4). Multivariable analysis also showed that recipient age, BMI, time on dialysis and donor age and eGFR remained significant risk factors for eGFR at 6 months.

Prediction model

Based on the significant risk factors in the multivariable analysis, and other a priori clinically relevant factors associated with eGFR, we created a model to predict recipient eGFR at 6-months. After considering different parameterizations of the linear regression model (e.g., polynomial linear regression and cubic regression splines), the conventional linear regression model was determined to be the predictive model with the smallest test mean squared error (MSE) of 311 (Table 5).

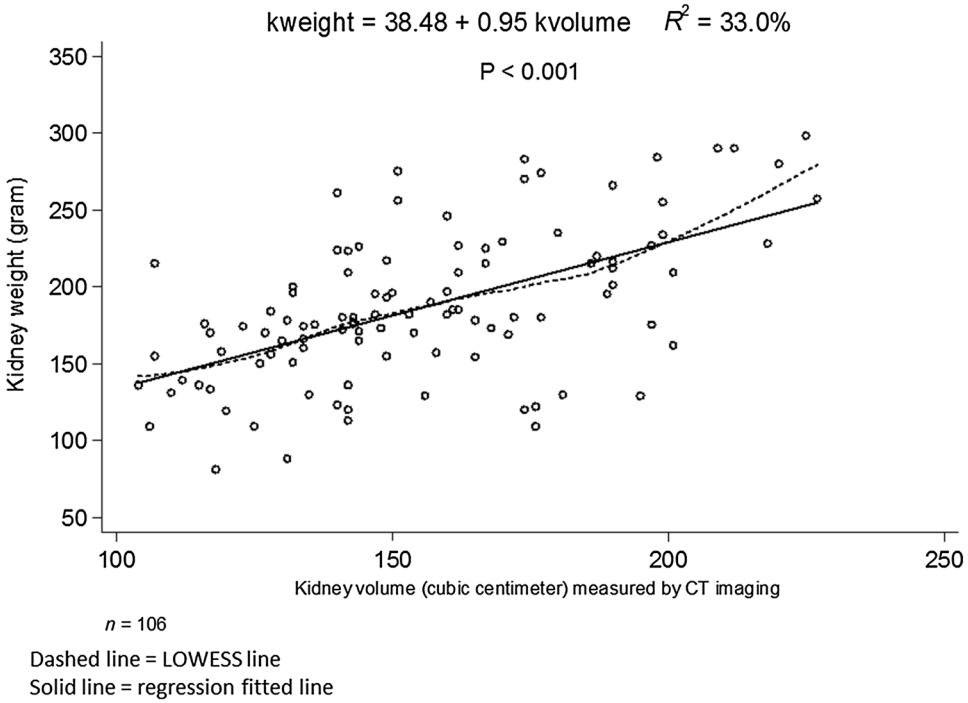

Fig. 2 Relation of kidney volume to kidney weight. Donor kidney volume was plotted against the actual kidney weight for a cohort that had weight recorded. The weight was taken after preparation of the graft for implantation (Dashed = LOWESS line, Solid = regression fitted line)

Table 2 Linear regression for effect of risk factors on recipient eGFR at 1 month (N = 438)

Risk factors	Univariable		Multivariable	
	Coefficient (95% CI)	*P* value	Coefficient (95% CI)	*P* value
Kidney volume (every 10 cubic centimeters increase)	1.86 (1.27, 2.44)	< 0.001	1.68 (1.06, 2.30)	< 0.001
Recipient age (every 1 year increase)	− 0.45 (− 0.59, − 0.31)	< 0.001	− 0.22 (− 0.35, − 0.09)	0.001
Recipient sex (female vs. male)	6.46 (2.50, 10.42)	0.001	2.20 (− 1.27, 5.67)	0.21
Recipient race (white vs. non-white)	− 6.58 (− 11.24, − 1.79)	0.01	− 11.73 (− 18.6, − 4.85)	0.001
Recipient BMI (every 1 kg/m^2 increase)	− 1.15 (− 1.48, − 0.88)	< 0.001	− 0.93 (− 1.24, − 0.63)	< 0.001
Recipient history of diabetes mellitus (Yes vs. No)	− 7.32 (− 11.97, − 2.84)	0.001	− 2.76 (− 6.73, 1.20)	0.17
Time on dialysis before transplant (every 1 year increase)	− 0.66 (− 1.60, 0.37)	0.16	− 1.02 (− 1.85, − 0.20)	0.02
Peak PRA (> 0% vs. = 0%)	− 0.94 (− 5.00, 3.12)	0.65	− 1.95 (− 5.46, 1.56)	0.28
Donor age (every 1 year increase)	− 0.59 (− 0.75, − 0.44)	< 0.001	− 0.30 (− 0.47, − 0.13)	0.001
Donor sex (female vs. male)	− 6.04 (− 10.02, − 2.06)	0.003	1.63 (− 2.24, 5.40)	0.41
Donor race (White vs. Non-white)	− 2.40 (− 8.01, 3.21)	0.40	8.43 (− 1.21, 15.65)	0.02
Donor eGFR at donation (every 1 mL/min/1.73 m^2 increase)	0.52 (0.40, 0.65)	< 0.001	0.22 (0.07, 0.36)	0.004
Type of induction (depleting agent vs. non-depleting agent)	2.74 (− 1.51, 6.99)	0.21	2.89 (− 0.70, 6.47)	0.11
Type of CNI (cyclosporine vs. tacrolimus)	− 3.26 (− 8.71, 2.18)	0.24	− 5.52 (− 10.2, − 0.84)	0.02

CI confidence interval

The risk factors in the models were kidney volume, recipient age, sex, race, BMI, history of diabetes mellitus, time on dialysis before transplant and peak PRA and donor age, sex, race, eGFR, induction type, and calcineurin inhibitor (CNI) use at 30-day post-transplant. The linear regression model is:

$$\text{Recipient eGFR} = 78.43628 + 0.11060 \times \text{kidney volume} - 0.24492 \times \text{recipient age} + 3.01350 \times \text{I (recipient sex = Female)} - 10.26592 \times \text{I (recipient race = White)} - 0.61945 \times \text{recipient BMI} - 0.15083 \times \text{I (recipient history of diabetes mellitus = Yes)} - 1.06387 \times \text{time on dialysis before transplant} + 1.34535 \times \text{I (peak PRA > 0\%)} - 0.41449 \times \text{donor age} + 2.06715 \times \text{I (donor sex = Female)} + 12.30735^{*}\text{I (donor race = White)} + 0.18918 \times \text{donor eGFR} - 2.11374 \times \text{I (Induction type = Depleting agent)} - 2.80137 \times \text{I (CNI at 30-day post-transplant = Cyclosporine)}$$

where I () is an indicator variable that equals 1 if the condition inside the parentheses is satisfied and equals 0 otherwise.

Table 3 Linear regression for effect of risk factors on recipient eGFR at 3 months ($N=438$)

Risk factors	Univariable		Multivariable	
	Coefficient (95% CI)	*P* value	Coefficient (95% CI)	*P* value
Kidney volume (every 10 cubic centimeters increase)	1.52 (0.95, 2.09)	< 0.001	1.25 (0.65, 1.85)	< 0.001
Recipient age (every 1 year increase)	− 0.43 (− 0.56, − 0.29)	< 0.001	− 0.22 (− 0.34, − 0.09)	0.001
Recipient sex (Female vs. Male)	5.07 (1.27, 8.87)	0.01	1.18 (− 2.21, 4.57)	0.49
Recipient race (White vs. Non-white)	− 5.45 (− 10.04, − 0.86)	0.02	− 8.59 (− 15.13, − 2.05)	0.01
Recipient BMI (every 1 kg/m^2 increase)	− 1.02 (− 1.34, − 0.70)	< 0.001	− 0.81 (− 1.10, − 0.52)	< 0.001
Recipient history of diabetes mellitus (Yes vs. No)	− 6.70 (− 10.99, − 2.41)	0.002	− 2.35 (− 6.24, 1.54)	0.24
Time on dialysis before transplant (every 1 year increase)	− 0.54 (− 1.44, 0.36)	0.24	− 0.89 (− 1.70, − 0.08)	0.03
Peak PRA (> 0% vs. = 0%)	0.07 (− 3.82, 3.96)	0.97	− 0.57 (− 4.02, 2.88)	0.75
Donor age (every 1 year increase)	− 0.59 (− 0.74, − 0.45)	< 0.001	− 0.30 (− 0.47, − 0.13)	< 0.001
Donor sex (Female vs. Male)	− 5.37 (− 9.19, − 1.56)	0.01	1.14 (− 2.64, 4.92)	0.55
Donor race (White vs. Non-white)	− 1.78 (− 6.88, 3.31)	0.49	6.50 (− 0.34, 13.33)	0.06
Donor eGFR at donation (every 1 mL/min/1.73 m^2 increase)	0.53 (0.41, 0.65)	< 0.001	0.25 (0.11, 0.39)	0.001
Type of induction (depleting agent vs. non-depleting agent)	1.47 (− 2.61, 5.55)	0.48	1.33 (− 2.21, 4.87)	0.46
Type of CNI (cyclosporine vs. tacrolimus)	− 3.26 (− 8.45, 1.93)	0.22	− 5.15 (− 9.73, − 0.56)	0.03

CI confidence interval

Table 4 Linear regression for effect of risk factors on recipient eGFR at 6 months ($N=438$)

Risk factors	Univariable		Multivariable	
	Coefficient (95% CI)	*P* value	Coefficient (95% CI)	*P* value
Kidney volume (every 10 cubic centimeters increase)	1.28 (0.70, 1.87)	< 0.001	0.97 (0.34, 1.59)	0.002
Recipient age (every 1 year increase)	− 0.41 (− 0.55, − 0.27)	< 0.001	− 0.20 (− 0.34, − 0.07)	0.003
Recipient sex (Female vs. Male)	6.20 (2.33, 10.07)	0.002	2.81 (− 0.77, 6.40)	0.12
Recipient race (White vs. Non-white)	− 3.51 (− 8.21, 1.19)	0.14	− 5.5 (− 12.5, 1.51)	0.12
Recipient BMI (every 1 kg/m^2 increase)	− 0.93 (− 1.26, − 0.61)	< 0.001	− 0.69 (− 1.00, − 0.38)	< 0.001
Recipient history of diabetes mellitus (Yes vs. No)	− 6.17 (− 10.55, − 1.80)	0.01	− 2.05 (− 6.13, 2.02)	0.32
Time on dialysis before transplant (every 1 year increase)	− 0.66 (− 1.59, 0.28)	0.17	− 1.16 (− 2.02, − 0.29)	0.01
Peak PRA (> 0% vs. = 0%)	1.00 (− 2.96, 4.96)	0.62	0.80 (− 2.80, 4.40)	0.66
Donor age (every 1 year increase)	− 0.60 (− 0.75, − 0.45)	< 0.001	− 0.36 (− 0.54, − 0.19)	< 0.001
Donor sex (female vs. male)	− 4.30 (− 8.20, − 0.40)	0.03	2.06 (− 1.90, 6.01)	0.31
Donor race (white vs. non-white)	− 0.77 (− 6.32, 4.78)	0.79	5.21 (− 2.12, 12.54)	0.16
Donor eGFR at donation (every 1 mL/min/1.73 m^2 increase)	0.51 (0.38, 0.63)	< 0.001	0.24 (0.09, 0.38)	0.002
Type of induction (depleting agent vs. non-depleting agent)	0.12 (− 4.04, 4.29)	0.95	− 0.40 (− 4.11, 3.30)	0.83
Type of CNI (cyclosporine vs. tacrolimus)	− 2.89 (− 8.19, 2.42)	0.29	− 4.29 (− 9.11, 0.53)	0.08

Discussion

In this study, we investigated the role of donor kidney volume, as measured by CT scan, on recipient eGFR in a large cohort of patients undergoing LDKT. We have shown that in addition to validated donor variables known to be significant in predicting recipient outcomes (age, BMI, and race) [2, 12], donor kidney volume is significantly associated with recipient eGFR at 1, 3, and 6 months in the statistical models ($P<0.001$). On multivariable analysis, for every 10 cc increase in kidney volume, eGFR increased by 1.68 mL/min, 1.25 mL/min and 0.97/min/1.73 m^2 at 1, 3, and 6 months, respectively. These findings suggest that transplantation of greater volume has the potential to improve recipient GFR.

We examined the correlation between actual measured kidney weight and kidney volume determined by CT volumetry in a subset of our patient cohort and found only a modest positive correlation ($r=0.57$). This correlation between volume and actual weight is similar to what was found in a previous study using the prolate ellipsoid method [6]. Kidney volume tended to underestimate kidney weight. This is likely related to the exclusion of non-parenchymal structures (vessels, perinephric fat, and collecting system) from CT volumetric calculations, but necessary inclusion of

Table 5 Predictive Linear regression for outcome of eGFR at 1 month

Flexibility	Predictive models		Notes	Test mean squared error
increase	Simple linear regression	Kidney volume only		453
		All risk factor except kidney volume		384
		All risk factors		369
	Polynomial linear regression	Kidney volume only		453
		All risk factor except kidney volume	Polynomial transform with degree 2 on donor eGFR	385
			Polynomial transform with degree 2 on all continuous risk factors	392
		All risk factors	Polynomial transform with degree 2 on donor eGFR	370
	Cubic linear regression	Kidney volume only		462
		All risk factor except kidney volume	Polynomial transform with degree 3 on donor eGFR	380
			Polynomial transform with degree 3 on all continuous risk factors	414
		All risk factors	Polynomial transform with degree 3 on donor eGFR	365
	Cubic regression splines	Kidney volume only		462
		All risk factors		375

these structures with the procured kidney graft that contributed to the measured weight. Since the weight of non-parenchymal structures can vary unpredictably and these tissues do not contribute to functional nephron mass, we feel that kidney parenchymal volume is a better variable to utilize as a predictor of graft outcome. Furthermore, kidney volume data can be obtained preoperatively in the setting of LDKT and can thus be incorporated into clinical decision making.

We then assessed the value of including donor kidney volume into a predictive model for LDKT. We found the addition of kidney volume to other risk factors for recipient graft function strengthened the predictive model using linear regression. Other predictive models, such as polynomial linear regression yielded MSE higher than that of a conventional linear regression model. This suggests that the relationship between risk factors and eGFR is quite linear, and a conventional linear regression can best predict the trend of the data.

Having observed that donor kidney allograft volume has a significant effect on recipient outcomes, we propose that the inclusion of donor kidney volume as a variable in matching algorithms for kidney paired donation be investigated as a way to further optimize outcomes in LDKT. Furthermore, our observations suggest that discrepancies between donor and recipient body mass that raise concerns about insufficient donor kidney volume in LDKT may, in some cases, provide a basis for the inclusion of immunologically compatible pairs to participate in kidney paired donation programs to improve recipient outcomes. Moreover, our observations provide a rationale for taking predicted kidney volume into account when selecting the most appropriate donor if multiple living donor candidates are available for a single recipient. Further validation studies will be needed to determine whether kidney volume should become part of other established risk indices for LDKT [2]. In addition, future prospective studies are required to assess how well this model can predict long-term eGFR post-transplant.

Our study has several limitations. First, it is a retrospective study at a single institution. However, since kidney volume was not considered for donor–recipient matching at our center, kidney volume is unlikely to be confounding by factor related to recipient outcomes. Second, although this is the largest cohort examining this issue to date, the relatively small sample size may reduce the precision of our estimates. A consequence of this is that there were significant differences in some recipient factors (history of diabetes, time on dialysis and peak PRA) between patients studied and those excluded from our analysis for having inadequate or unavailable CT volumetrics, though these factors are unlikely to have significantly influenced the short-term outcomes examined in this study. Third, we have created a model using fivefold cross-validation, however, the

true test of our model is to validate on an external dataset. Fourth, potential confounders are the quality and timing contrast administration in the CT scans used to generate volume calculations. Therefore, properly timed and high-quality CT scans are essential for accurate prediction of recipient eGRF after transplant. Despite these limitations, we feel we have provided a meaningful analysis to a question where randomized controlled trials are not possible.

Conclusion

Donor kidney volume is a risk factor for recipient eGFR and may be successfully incorporated into a predictive model of eGFR after transplant. Future studies should attempt to validate this predictive model and investigate the potential utility of incorporating kidney allograft volume into donor selection algorithms to optimize recipient outcomes.

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Authors' contributions Al-Adra: Project development, Data collection and Management, Data analysis, Manuscript writing and editing. Lambadaris: Project development, Data collection and Management, Data analysis, Manuscript writing and editing. Barbas: Data collection and Management. Li: Data analysis. Selzner: Manuscript writing and editing. Singh: Manuscript writing and editing. Famure: Project development, Data analysis. Kim: Project development, Data analysis, Manuscript writing and editing. Ghanekar: Project development, Data analysis, Manuscript writing and editing.

Compliance with ethical standards

Conflict of interest The authors of this manuscript have no conflicts of interest to disclose. Research was approved by University Health Network Institutional Review Board.

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Affiliations

David P. Al-Adra[1,2,3] · Maria Lambadaris[1] · Andrew Barbas[1,2,3] · Yanhong Li[1] · Markus Selzner[1,2,3] · Sunita K. Singh[1,4,5] · Olusegun Famure[1] · S. Joseph Kim[1,4,5] · Anand Ghanekar[1,2,3,6]

1 Kidney Transplant Program, Toronto General Hospital, University Health Network, Toronto, Canada

2 Division of General Surgery, University Health Network, Toronto, Canada

3 Department of Surgery, University of Toronto, Toronto, Canada

4 Division of Nephrology, University Health Network, Toronto, Canada

5 Department of Medicine, University of Toronto, Toronto, Canada

6 Toronto General Hospital, 11 PMB 171, 585 University Avenue, Toronto, ON M5G 2N2, Canada