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OPEN

Robotic-assisted Versus Open Technique for Living Donor Kidney Transplantation: A Comparison Using Propensity Score Matching for Intention to Treat

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Background. Living donor robotic-assisted kidney transplantation (RAKT) is an alternative to open kidney transplantation (OKT), but experience with this technique is limited in the United States. **Methods.** A retrospective review of living donor kidney transplants performed between 2016 and 2018 compared RAKT with OKT with regard to recipient, donor, and perioperative parameters. A 1:1 propensity score matching was performed on recipient/donor age, sex, body mass index, race, preoperative dialysis, and calculated panel reactive antibodies. **Results.** Outcomes of patient survival, graft survival, and postoperative complications were assessed for 139 transplants (47 RAKT and 92 OKT). Propensity score analysis (47:47) showed that RAKT recipients had longer warm ischemic times (49 versus 40 min; $P<0.001$) and less blood loss (100 versus 150 mL; $P=0.005$). Operative time and length of stay were similar between groups. Postoperative serum creatinine was similar during a 2-y follow-up. Post hoc analysis excluding 4 open conversions showed lower operative time with RAKT (297 versus 320 min; $P=0.04$) and lower 30-d (4.7% versus 23.4%; $P=0.02$) and 90-d (7% versus 27.7%; $P=0.01$) Clavien-Dindo grade ≥3 complications. **Conclusions.** Our findings suggest that RAKT is a safe alternative to OKT.

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INTRODUCTION

Although minimally invasive surgery has replaced much of our traditional open surgical procedures within most surgical specialties, such approaches in transplantation remain novel. Outside of laparoscopic donor nephrectomy[1] and donor hepatectomy,[2] few transplant procedures widely use minimally invasive procedures. With newer technology, there is opportunity to reimagine certain procedures. Robotic-assisted surgery provides advantages over standard laparoscopic surgery, such as high-definition 3D imaging, increased magnification and camera stability, and articulation of instruments aiding in suturing. As access to these devices is limited at many institutions, their use in transplantations was initiated with robotic-assisted donor nephrectomy. Enhanced ergonomics, improved outcomes, and shorter length of stay resulting from minimally invasive surgical approaches have been shown by several centers.[3-5]

Initial and follow-up reports by Oberholzer et al[6] have revealed that the advent of robotic-assisted kidney transplant (RAKT) has increased the accessibility of kidney transplantation for obese patients, although minimizing morbidity. The da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA) was first used as an adjunct to open kidney transplantation (OKT) by Hoznek et al[7] in 2001, where this group completed a hybrid procedure with an open incision and robotic-assisted dissection, isolation of vessels, and anastomosis, with an assistant providing retraction. This was followed up in 2009 when Giulianotti et al[8] described an RAKT performed on an obese man, where surgeons used a hand-assisted technique to manipulate the graft intracorporeally. In 2013, Menon et al[9,10] published research describing a nonhand-assisted technique

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for implantation for all patients, providing an alternative approach for robotic kidney transplants. Although several centers in Europe have used the nonhand-assisted approach,[11] there is a dearth of experience with this approach in the heterogeneous US population. Furthermore, there is a lack of data directly comparing perioperative and postoperative outcomes between RAKT and OKT.

Given increased interest in RAKT, we evaluated the short-term and long-term outcomes of patients undergoing living donor RAKT and OKT by performing a propensity score-matched analysis in an early series of RAKT. As with other minimally invasive procedures, we assessed the effect of RAKT on length of hospital stay and opioid use during the study time frame.

MATERIALS AND METHODS

Study Design and Patient Population

A retrospective record review analysis of all living donor kidney transplants performed at Henry Ford Hospital in Detroit, Michigan, between January 2016 and December 2018 was conducted after approval by the Henry Ford Hospital Institutional Review Board (12269). Robotic kidney transplants began in 2014, and 8 RAKTs were performed through the end of 2015. To minimize bias from initial cases, we selected a cohort from January 2016 to December 2018. The determination of which patients received RAKT was predominantly based on da Vinci robot availability and no other parameters. Living donor kidney transplants were grouped according to the initial surgical approach (OKT or RAKT). The inclusion criteria included the following: irreversible renal disease (symptomatic patients with glomerular filtration rate <20 mL/min or the need for dialysis), age ≥18 y old, absence of significant cardiovascular disease, and avoidance of complex vascular anatomy (>2 arteries or >2 veins). The exclusion criteria for a robotic kidney transplant were the following: previous transplant, complex abdominal surgeries, autosomal dominant polycystic kidney disease, or significant aortoiliac disease. A total of 128 (92.1%) patients completed a follow-up period of at least 2 y after transplant. The median follow-up time for the entire cohort was 37.3 mo (interquartile range [IQR] 29.3–46.7).

Surgical Procedure

All donor kidneys were procured from living donors via minimally invasive donor nephrectomy, which included pure laparoscopic, hand-assisted laparoscopic, and robotic-assisted laparoscopic donor nephrectomy. Recipient operations were generally staggered, with occasional procedures performed sequentially. All organs were flushed and stored in histidine-tryptophan-ketoglutarate solution before implantation.

Robotic operations were performed using the da Vinci Si, X, or Xi Surgical Systems (Intuitive Surgical). The cases were performed primarily by 2 senior surgeons, 1 who had extensive experience in robotic surgery and the second who was trained throughout the duration of the study period. The RAKT technique was previously described by Menon et al[10] in the IDEAL phase 2a study. Specific modifications of that procedure include the use of the curved robotic scissors to perform the arteriotomy with a cruciate incision and the use of 5-0 PDS (Ethicon, Somerville, NJ) sutures for ureteroneocystostomy (modified Lich-Gregoir technique). Periumbilical incisions were generally <6 cm and modified according to kidney size. All anastomoses were performed with 6-0 GORE-TEX (Gore Medical, Flagstaff, AZ) sutures. The back-table preparation was completed in standard fashion with care to ligate any possible source of bleeding. Kidneys were then wrapped in ice-gauze jackets with marking stitches to maintain orientation before implantation.

OKTs were performed following standard retroperitoneal technique via Gibson incision. Renal artery and renal vein anastomoses were performed with 6-0 PROLENE (Ethicon, Somerville, NJ) sutures using 2.5-magnification loupes. Ureteroneocystostomy was performed using the modified Lich-Gregoir technique with 5-0 PDS sutures.

Irrespective of operative technique, all patients received triple immunosuppression therapy. Induction was either basiliximab or antithymocyte globulin (Thymoglobulin), per Henry Ford Hospital Protocol.

Study Variables and Outcomes

Data for sociodemographic variables, surgical and functional outcomes, and early postoperative complications with a minimum follow-up of 90 d were retrospectively collected. Furthermore, we calculated a Charlson Comorbidity Index for each patient, an algorithm used to measure patients' comorbid disease status.[12] Perioperative variables included warm ischemia time (WIT), cold ischemia time, extraperitoneal versus intraperitoneal implantation, estimated blood loss, operative time, and induction and maintenance immunosuppression. Total operative time was calculated from case start (ie, incision time) until case end (ie, closure), as tracked by nursing staff in the electronic medical record. This included back-bench time and any additional time waiting for donor nephrectomy to be completed. Delayed graft function was defined as the need for dialysis within a week following transplantation. The functional parameter evaluated was serum creatinine (SCr) on postoperative days (POD) 7, 14, 180, 1 y, and 2 y. Patient and graft survival were assessed at 1 y, 2 y, and overall posttransplant. Additionally, analgesic requirements administered (morphine equivalents) and length of hospital stay were analyzed. Opioid utilization was calculated using a standard conversion chart to tabulate total oral morphine equivalents consumed. Postoperative complications were recorded 30 and 90 d after transplant and included ileus (defined as requiring placement of a nasogastric tube for gastric decompression), need for any blood product transfusion, and need for vascular and ureteral interventions. The latter included urinary leaks and ureteral obstruction. Postoperative complications occurring within 30 and 90 d of the transplant were graded using the Clavien-Dindo classification system.[13]

Propensity Score Matching

A propensity score was constructed using logistic regression and was based on the predicted probability of receiving an RAKT.[14] This analysis was performed to control for the effect of confounding variables and represents a method for addressing selection bias. Covariates selected were ones that may have influenced the decision for the type of procedure (OKT versus RAKT) and therein represent a source of potential selection bias. These included recipient age, sex, body mass index, race, preemptive dialysis, diabetes mellitus, calculated panel reactive antibodies, and donor age. Matching was then performed using these covariates in a 1:1 ratio between

RAKT and OKT using an optimal matching method. This matching method finds the matched samples with the smallest average absolute distance across the matched pairs. Matching quality and covariate balance were evaluated with standardized mean differences between the treated and control groups. A difference of <0.2 standardized mean difference between covariates was used as indicative of a negligible imbalance between groups.[14] Final groups comprised 47 patients each. A sensitivity analysis using an additional matched RAKT versus OKT cohort was performed, excluding RAKT cases requiring conversions. This was referred to as "per-protocol" analysis.

Statistical Analysis

Descriptive data for continuous variables were expressed as medians and IQR for nonnormally distributed variables and compared using the Mann-Whitney *U* test. Categorical variables were expressed as number and percentage and were compared using chi-square and Fisher exact tests. Overall survival was estimated using the Kaplan-Meier method, and groups were compared via log-rank tests. After matching, a univariable Cox proportional hazard model was used to evaluate the exposure hazard (surgical approach) on the outcome of death. For graft survival analysis, rather than the Kaplan-Meier method, which censors for the competing event of death, a cumulative incidence approach was used to account for the presence of a competing risk of death with graft failure.[15] The cumulative incidence was calculated using subdistribution estimates for each cause, and a Gray modified log-rank test was used to compare subdistribution estimates. To assess for the relative change in the hazard of graft failure, a Fine-Gray proportional subdistribution hazard model was used to account for death as a competing event.[16] A *P* value of <0.05 was considered statistically significant. Statistical analyses were performed using R (R version 4.0.2 [2020-06-22], R Foundation for Statistical Computing, Vienna, Austria). Matching was performed using the MatchIt and Optmatch packages.

RESULTS

Overall Cohort: Patient Characteristics

A total of 139 patients who received kidney transplantation (47 RAKT; 92 OKT) was identified in the study period. Although not significantly different, the OKT group comprised older recipients (median [IQR], 54 [43–63] versus 48 [36–60] y; $P = 0.07$). Of the 92 patients who received OKT, 71% were White, 19% were Black, and 11% had "other" listed in the medical record. Of the 47 patients who received RAKT, 47% were White, 36% were Black, and 17% had "other" listed in the medical record. Of the patients who required dialysis before the kidney transplant, the duration of dialysis was longer in the RAKT group (median [IQR], 14 [6–22] versus 24 [9–32] mo; $P = 0.04$) (Table 1).

Overall Cohort: Perioperative Factors

A higher proportion of ureteral stents were placed in the RAKT group (68.5 versus 95.7%; $P = 0.001$). Ureteral stents were placed in nearly all of the RAKT patients, as was standard of care during the study period. The decision to place ureteral stents in OKT patients was dependent upon individual surgeon preference. Left-sided donor nephrectomy was completed in all patients except for 1 patient in the OKT group. Implantation occurred on the right side in 100% (47/47) of patients in the RAKT group and 79% (73/92) of patients in the OKT group. The median operative time was similar between the groups (median [IQR], OKT 313 [273–349] versus RAKT 299 [261–325] min; $P = 0.10$). The RAKT group had longer median WIT in minutes (median [IQR], 40 [34–48] versus 49 [43–53] min; $P < 0.001$). The median estimated blood loss was lower in the RAKT group (median [IQR], 150 [100–200] versus 100 [50–150] mL; $P = 0.004$) (Table 2).

RAKT Requiring Conversion to OKT

Conversion to an open approach was required in 4 robotic procedures (9%). All 4 patients had good renal

TABLE 1.

Propensity score matching, patient characteristics

	Before matching				After matching			
Characteristic	OKT n = 92 (66.2%)	RAKT n = 47 (33.8%)	*P*	SMD	OKT n = 47 (50%)	RAKT n = 47 (50%)	*P*	SMD
Recipient age, median (IQR)	54 (43–63)	48 (36–60)	0.07	0.34	50 (40–60)	48 (36–60)	0.60	0.09
Recipient male sex, N (%)	62 (67.4)	31 (66.0)	1.00	0.03	31 (66.0)	31 (66.0)	1.00	<0.001
Recipient race, N (%)			0.02	0.50			0.77	0.15
White	65 (70.7)	22 (46.8)			23 (48.9)	22 (46.8)		
Black	17 (18.5)	17 (36.2)			14 (29.8)	17 (36.2)		
Other	10 (10.9)	8 (17.0)			10 (21.3)	8 (17.0)		
Recipient body mass index, kg/m^2, median (IQR)	28.1 (24.6–31.2)	29.6 (25.0–33.6)	0.40	0.12	28.4 (24.4–34.2)	29.6 (25.0–33.6)	0.96	0.02
Diabetes mellitus, N (%)	35 (38.0)	16 (34.0)	0.78	0.08	12 (25.5)	16 (34.0)	0.50	0.19
Recipient PRA			0.37	0.21			0.52	0.24
0–20 (not sensitized)	80 (87.0)	40 (85.1)			39 (83.0)	40 (85.1)		
(20–80) sensitized	12 (13.0)	6 (12.8)			8 (17.0)	6 (12.8)		
>80 (highly sensitized)	0 (0.0)	1 (2.1)			0 (0.0)	1 (2.1)		
Preemptive dialysis, N (%)			0.93	0.07			1.00	<0.001
Preemptive	29 (31.5)	14 (29.8)			14 (29.8)	14 (29.8)		
Hemodialysis	44 (47.8)	22 (46.8)			24 (51.1)	22 (46.8)		
Peritoneal dialysis	19 (20.7)	11 (23.4)			9 (19.1)	11 (23.4)		
Duration of dialysis, mo, median (IQR)	14 (6–22)	24 (9–32)	0.04	0.24	14 (7–25)	24 (9–32)	0.16	−0.09
Donor age, median (IQR)	43 (33–52)	40 (30–52)	0.41	0.15	43 (33–51)	40 (30–52)	0.39	0.15

IQR, interquartile range; OKT, open kidney transplantation; PRA, panel reactive antibodies; RAKT, robotic-assisted kidney transplantation; SMD, standard mean difference.

TABLE 2.

Propensity score matching, perioperative factors

Perioperative factors	Before matching OKT n = 92 (66.2%)	Before matching RAKT n = 47 (33.8%)	P	SMD	After matching OKT n = 47 (50%)	After matching RAKT n = 47 (50%)	P	SMD
Induction, N (%)			0.24	0.30			0.71	0.17
None	13 (14.1)	4 (8.5)			6 (12.8)	4 (8.5)		
Thymoglobulin	25 (27.2)	19 (40.4)			16 (34.0)	19 (40.4)		
Simulect	54 (58.7)	24 (51.1)			25 (53.2)	24 (51.1)		
Number of arteries, N (%)			0.67	0.18			0.51	0.24
1	72 (78.3)	39 (83.0)			36 (76.6)	39 (83.0)		
2	19 (20.7)	8 (17.0)			10 (21.3)	8 (17.0)		
3	1 (1.1)	0 (0.0)			1 (2.1)	0 (0.0)		
Operative time in min, median (IQR)	313 (273–349)	299 (261–325)	0.10	0.34	314 (275–354)	299 (261–325)	0.07	0.41
CIT in min, median (IQR)	76 (57–107)	77 (60–112)	0.99	0.17	76 (55–117)	77 (60–112)	0.88	0.24
WIT in min, median (IQR)	40 (34–48)	49 (43–53)	<0.001	0.82	40 (34–49)	49 (43–53)	<0.001	0.72
Estimated blood loss, mL, median (IQR)	150 (100–200)	100 (50–150)	0.004	0.33	150 (100–200)	100 (50–150)	0.03	0.22
Graft function, N (%)			0.23	0.23			0.71	0.15
Immediate	80 (87.0)	44 (93.6)			42 (89.4)	44 (93.6)		
Delayed	1 (1.1)	3 (6.4)			5 (10.6)	3 (6.4)		
POD 1 morphine equivalent, median (IQR)	33 (21–54)	38 (19–60)	0.53	0.16	39 (25–59)	38 (19–60)	0.54	0.09
POD 2 morphine equivalent, median (IQR)	20 (10–45)	23 (8–42)	0.76	0.04	32 (11–53)	23 (8–42)	0.31	0.07

CIT, cold ischemia time; IQR, interquartile range; OKT, open kidney transplantation; POD, postoperative day; RAKT, robotic-assisted kidney transplantation; SMD, standard mean difference; WIT, warm ischemia time.

TABLE 3.

RAKT cases requiring conversion to OKT

Case 1: In this case, shortly after normal reperfusion, the kidney became cyanotic; therefore, the decision was made to convert to an open approach, made through a midline incision. The kidney was twisted, which raised a concern of arterial intimal injury and possible thrombus; thus, the arterial anastomosis was revised.

Case 2: In this case, conversion to an open approach occurred because of early high bloody drain output following closure, although the patient was still in the operating room; negative exploratory laparotomy was performed; subsequent irrigation of Foley catheter found multiple clots with clot retention, with urine output improved.

Case 3: In this case, conversion to open approach occurred at the beginning of the operation because of significant adhesions from a previous exploratory laparotomy for a gunshot wound, preventing insufflation.

Case 4: In this case, conversion to an open approach occurred because of a twist of the renal vein, which required removal of the kidney, repeat cold-perfusion, and repeat anastomoses.

OKT, open kidney transplantation; RAKT, robotic-assisted kidney transplantation.

TABLE 4.

Propensity score matching, patient outcomes

Patient outcomes	Before OKT n = 92 (66.2%)	Before RAKT n = 47 (33.8%)	P	SMD	After OKT n = 47 (50%)	After RAKT n = 47 (50%)	P	SMD
LOS in days, median (IQR)	4 (3–6)	3 (3–5)	0.08	0.36	4 (3–6)	3 (3–5)	0.11	0.40
Preoperative SCr, median (IQR)	6.0 (4.2–8.7)	6.0 (4.7–9.2)	0.94	0.01	7.4 (5.6–9.0)	6.0 (4.7–9.2)	0.21	0.20
SCr (1 wk)	1.5 (1.1–2.2)	1.6 (1.3–2.1)	0.20	0.16	1.5 (1.1–2.4)	1.6 (1.3–2.1)	0.62	0.09
SCr (2 wk)	1.4 (1.1–1.9)	1.5 (1.2–2.0)	0.22	0.17	1.3 (1.1–2.0)	1.5 (1.2–2.0)	0.40	0.18
SCr (6 mo)	1.3 (1.1–1.7)	1.4 (1.2–1.7)	0.27	0.24	1.3 (1.1–1.7)	1.4 (1.2–1.7)	0.27	0.25
SCr (1 y)	1.3 (1.1–1.6)	1.3 (1.1–1.7)	0.62	0.07	1.3 (1.1–1.6)	1.3 (1.1–1.6)	0.77	0.07
SCr (2 y)	1.2 (1.1–1.7)	1.5 (1.2–1.7)	0.13	0.19	1.2 (1.1–1.7)	1.5 (1.2–1.7)	0.18	0.34
Follow-up, mo (IQR)	38.0 (29.3–47.2)	36.6 (29.4–45.2)	0.55	0.15	40.2 (31.4–46.3)	36.6 (29.4–45.2)	0.23	0.29
30-d readmission, N (%)	24 (26.1)	11 (23.4)	0.89	0.06	12 (25.5)	11 (23.4)	1.00	0.05
90-d readmission, N (%)	25 (27.2)	14 (29.8)	0.90	0.06	11 (23.4)	14 (29.8)	0.64	0.15
Conversion to open, N (%)	–	4 (8.5)	–	–	–	4 (8.5)	–	–
Ileus, N (%)	4 (4.3)	3 (6.4)	0.91	0.09	3 (6.4)	3 (6.4)	1.00	<0.001
Ureteral complications, N (%)	5 (5.4)	3 (6.4)	1.00	0.04	3 (6.4)	3 (6.4)	1.00	<0.001
Reoperation, N (%)	6 (6.5)	1 (2.1)	0.48	0.22	4 (8.5)	1 (2.1)	0.36	0.29
Transfusion, N (%)	3 (3.3)	0 (0.0)	0.53	0.26	2 (4.3)	0 (0.0)	0.48	0.30
Lymphocele drain placement, N (%)	6 (6.5)	0 (0.0)	0.18	0.37	5 (10.6)	0 (0.0)	0.07	0.49
Hernia, N (%)	1 (1.1)	1 (2.1)	1.00	0.08	1 (2.1)	1 (2.1)	1.00	<0.001
Clavien ≥3 (30 d), N (%)	18 (19.6)	5 (10.6)	0.27	0.25	11 (23.4)	5 (10.6)	0.17	0.35
Clavien ≥3 (90 d), N (%)	21 (22.8)	6 (12.8)	0.23	0.27	13 (27.7)	6 (12.8)	0.12	0.38

IQR, interquartile range; LOS, length of stay; OKT, open kidney transplant; RAKT, robotic kidney transplant; SCr, serum creatinine; SMD, standard mean difference.

function at 1 y, with SCr levels of 0.9 mg/dL, 1.4 mg/dL, 1.1 mg/dL, and 1.7 mg/dL. Please refer to Table 3 for a description of cases.

Overall Cohort: Posttransplant Outcomes

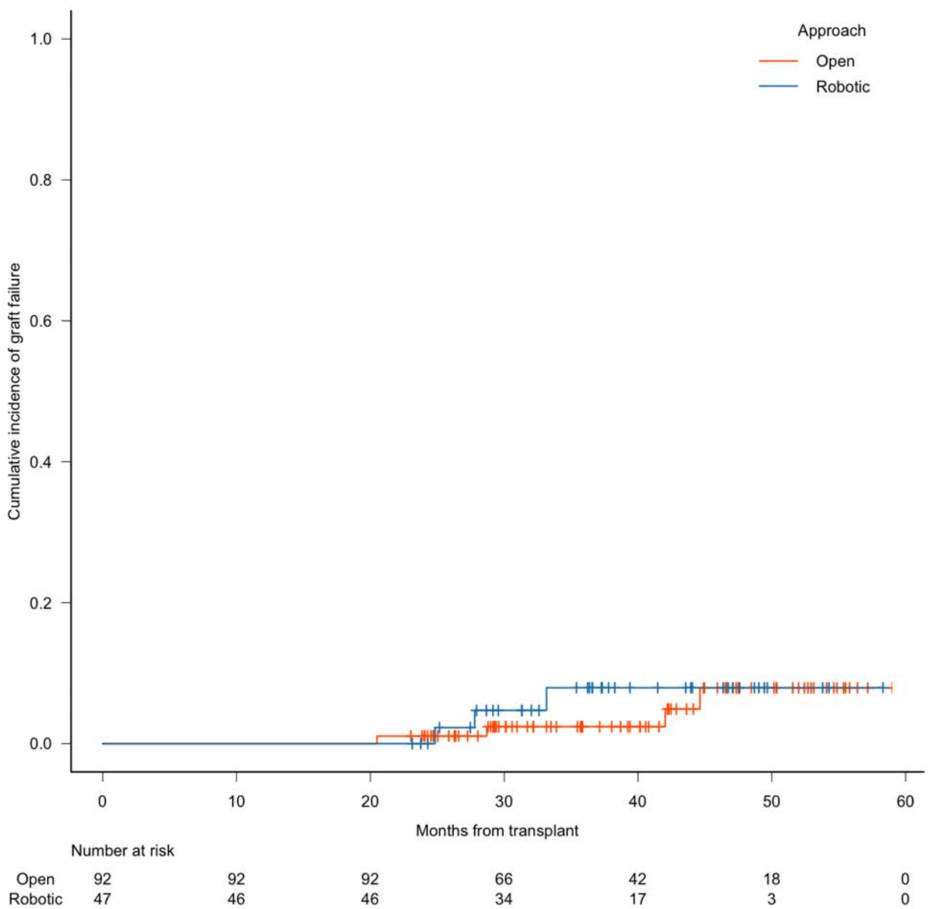
Length of stay was similar between groups (median [IQR], 4 [3–6] versus 3 [3–5] d; $P = 0.08$), as were SCr levels at up to 2 y posttransplantation. In addition, there were similar rates of readmission, reinterventions, and postoperative complications (Table 4). The cumulative incidence of graft failure was similar (at 1 y [95% CI], OKT 0% [0-0] versus RAKT 0% [0-0], $P = 0.17$; at 2 y, OKT 1.1% [0.1-5.3] versus RAKT 0% [0-0], $P = 0.22$; at 3 y, OKT 2.4% [0.5-7.7] versus RAKT 7.9% [1.9-19.6], $P = 0.22$; and at 4 y, OKT 7.9% [2.2-18.5] versus RAKT 7.9% [1.9-19.6], $P = 0.57$; overall Gray's modified log-rank test $P = 0.56$) (Figure 1). Similarly, patient survival was equivalent between the groups >4 y (at 1 y [95% CI], OKT 100% [100-100] versus RAKT 97.9% [93.8-100], $P = 0.16$; at 2 y, OKT 98.9% [96.8-100] versus RAKT 97.9% [93.8-100], $P = 0.63$; at 3 y, OKT 94.9% [89.4-100] versus RAKT 95.6% [89.8-100], $P = 0.79$; and at 4 y, OKT 94.9% [89.4-100] versus RAKT 80.0% [61.2-100], $P = 0.17$; overall log-rank $P = 0.17$) (Figure 2).

Matched Cohort: Patient Characteristics

After 1:1 propensity score matching, 47 patients were included in each group. After matching, the 2 groups were similar in recipient age, sex, ethnicity, body mass index, comorbidities, preoperative renal replacement therapy, calculated panel reactive antibodies, donor age, and cold ischemia time (Table 1). Additional variables have been listed in Table S1 (SDC, http://links.lww.com/TXD/A418).

Matched Cohort: Perioperative Factors

The matched RAKT group had lower estimated blood loss (median [IQR], 150 [100–200] versus 100 [50–150] mL; $P = 0.03$). The matched OKT group had shorter WIT than the



Gray's modified log-rank test p=0.56

	1-year (95% CI)	2-year (95% CI)	3-year (95% CI)	4-year (95% CI)
Open	0 (0-0)	1.1 (0.1-5.3)	2.4 (0.5-7.7)	7.9 (2.2-18.5)
Robotic	0 (0-0)	0 (0-0)	7.9 (1.9-19.6)	7.9 (1.9-19.6)

FIGURE 1. Four-year cumulative incidence of graft failure (before matching).

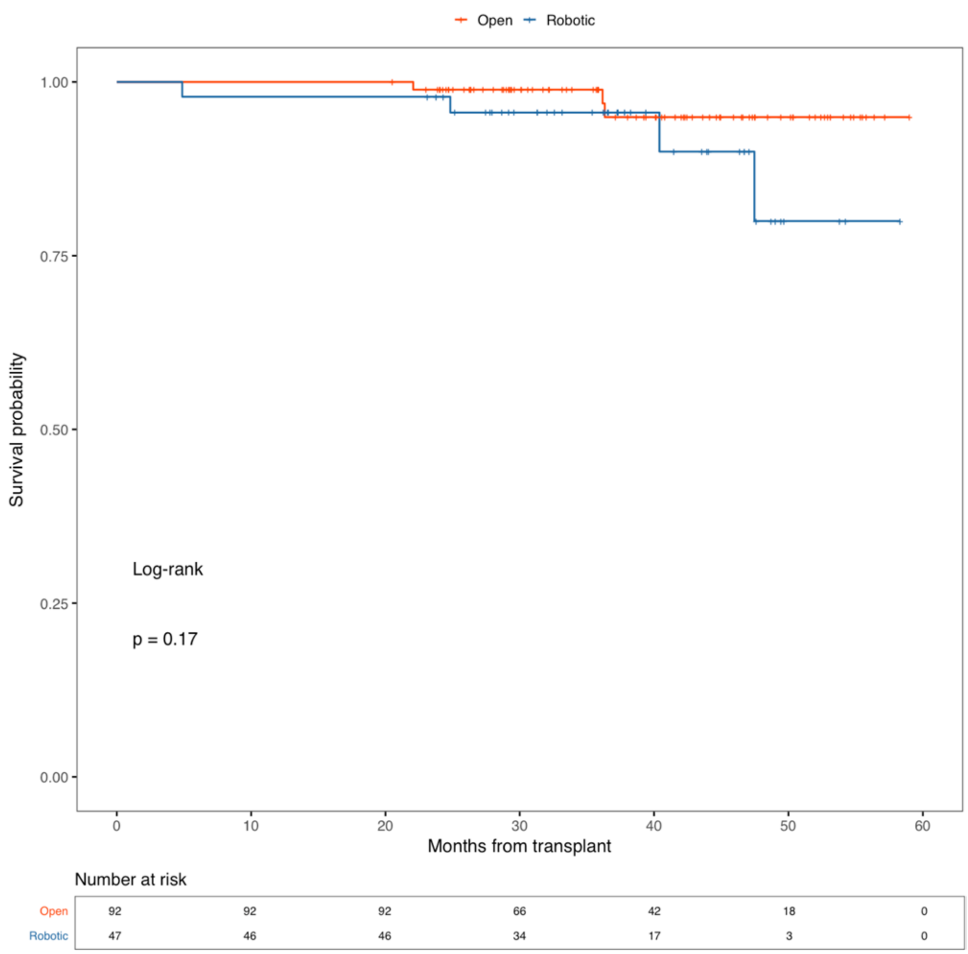
RAKT group (median [IQR], 40 [34–49] versus 49 [43–53] min; *P* < 0.001) (Figure 3). There were also significantly fewer ureteral stents placed in the OKT group (29 [61.7%] versus 45 [95.7%]; *P* < 0.001) (Table 2). There was no significant difference between the groups regarding overall operative time or morphine equivalents prescribed on POD 1 or POD 2 (Table 2).

Matched Cohort: Posttransplant Outcomes

There was no significant difference between the matched groups in length of stay, 30-d readmissions, or 90-d readmissions. Postoperative SCr was equivalent at 1 wk, 2 wks, 6 mo, 1 y, and 2 y. There were no significant differences between the matched groups in complications, including ileus, ureteral complications, transfusions, image-guided drain placement, hernia, reintervention/reoperation at 30 or 90 d, and Clavien-Dindo grade ≥3 complications at 30 and 90 d (Table 4; see Table S5, SDC, http://links.lww.com/TXD/A418). The cumulative incidence of graft failure was equivalent between the groups (at 1 y, OKT 0% versus RAKT 0%, *P* = 0.32; at 2 y, OKT 0% versus RAKT 0%, *P* = 0.08; at 3 y, OKT 0% versus RAKT 7.9%, *P* = 0.08; and at 4 y, OKT 5.0% versus RAKT 7.9%, *P* = 0.27; overall Gray's modified log-rank test *P* = 0.28). The robotic approach resulted in a similar subdistribution hazard of graft failure (Fine-Gray subdistribution hazard ratio for graft failure reference: open, 3.1, 95% CI, 0.33-28.74; *P* = 0.32) (Figure 4). Patient survival was equivalent between the groups up to 3 y (at 1 y, OKT 100% versus RAKT 97.9%, *P* = 0.32; at 2 y, OKT 100% versus RAKT 97.9%, *P* = 0.32; and at 3 y, OKT 100% versus RAKT 95.6%, *P* = 0.32). The matched RAKT group had a significantly lower survival at 4 y posttransplant (at 4 y, OKT 100% versus RAKT 80.0%; overall log-rank *P* = 0.04) (Figure 5).

Matched Cohort: Posttransplant Outcomes (Excluding Converted Cases)

After excluding RAKT cases that had converted to an open approach, RAKT demonstrated a significant advantage over OKT for reintervention/reoperation at 30 d (23.3% versus 4.7%; *P* = 0.03), reintervention/reoperation at 90 d



	1-year (95% CI)	2-year (95% CI)	3-year (95% CI)	4-year (95% CI)
Open	100% (100-100)	98.9% (96.8-100)	94.9% (89.4-100)	94.9% (89.4-100)
Robotic	97.9% (93.8-100)	97.9% (93.8-100)	95.6% (89.8-100)	80.0% (61.2-100)

FIGURE 2. Four-year patient survival (before matching).

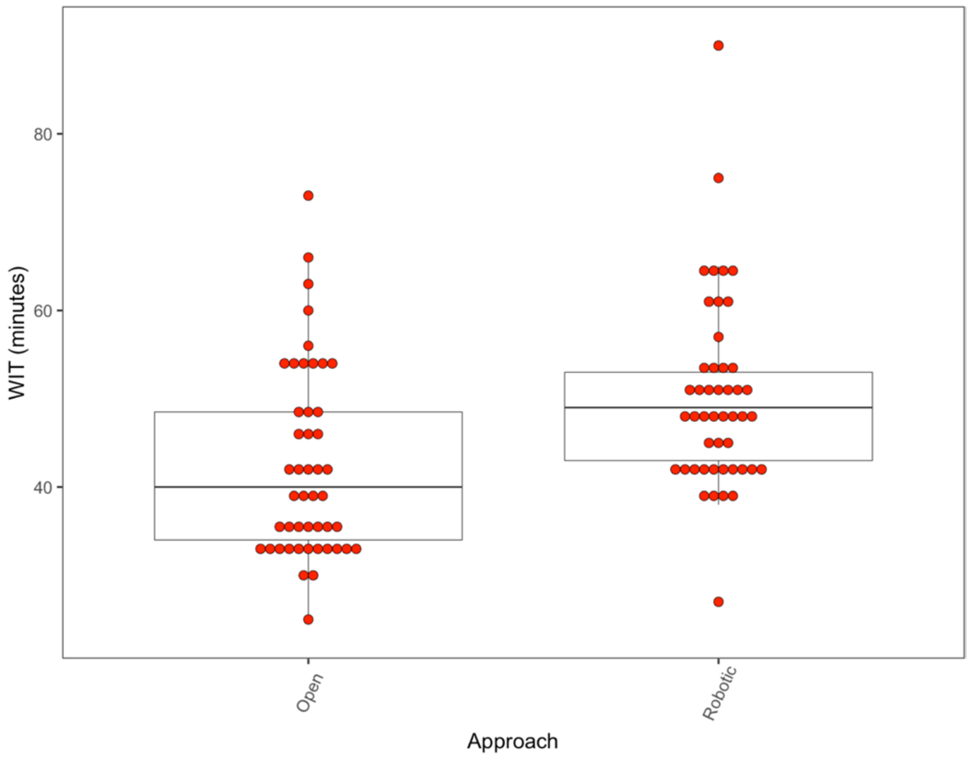


FIGURE 3. Distribution of warm ischemia time by approach. WIT, warm ischemia time.

(30.2% versus 7.0%%; $P = 0.01$), Clavien-Dindo grade ≥3 complications at 30 d (23.3% versus 4.7%; $P = 0.03$), and Clavien-Dindo grade ≥3 complications at 90 d (30.2% versus 7.0%; $P = 0.01$) (Table S4, SDC, http://links.lww.com/TXD/A418). The cumulative incidence of graft failure was equivalent between the groups (at 1 y, OKT 0% versus RAKT 0%, $P = 0.32$; at 2 y, OKT 0% versus RAKT 0%, $P = 0.32$; at 3 y, OKT 2.6% versus RAKT 8.7%, $P = 0.32$; and at 4 y, OKT 8.0% versus RAKT 8.7%, $P = 0.61$; overall Gray's modified log-rank test $P = 0.57$). The robotic approach had a similar subdistribution hazard of graft failure (Fine-Gray subdistribution hazard ratio for graft failure reference: open approach subdistribution hazard ratio 1.5, 95% CI, 0.26-9.00; $P = 0.63$) (Figure S1, SDC, http://links.lww.com/TXD/A418). Similarly, 1-, 2-, and 3-y patient survival was equivalent between the groups (at 1 y, OKT 100% versus RAKT 97.7%, $P = 0.32$; at 2 y, OKT 100% versus RAKT 97.7%, $P = 0.63$; and at 3 y, OKT 100% versus RAKT 95.2%, $P = 0.17$). The RAKT group had a significantly lower survival at 4 y posttransplant (at 4 y, OKT 100% versus RAKT 77.7%; overall log-rank $P = 0.03$) (Figure S2, SDC, http://links.lww.com/TXD/A418). Additional information regarding patient characteristics and perioperative factors for matched cohort (excluding converted cases) can be found in Tables S2 and S3 (SDC, http://links.lww.com/TXD/A418).

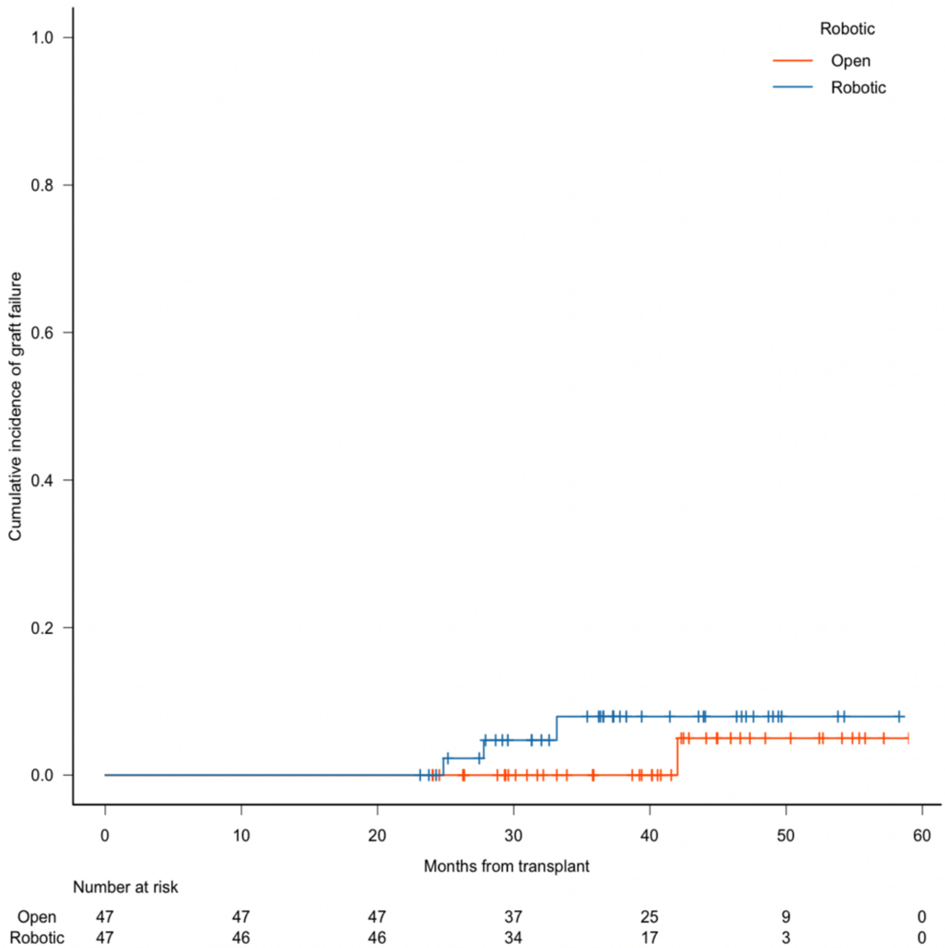
DISCUSSION

We have described outcomes in a propensity-matched cohort of kidney transplant patients who were followed for at least 2 y after having had transplant surgery with either RAKT or OKT. We observed equivalence between the groups in postoperative SCr, length of stay, and 30-d and 90-d readmissions. After rematching and excluding RAKT cases requiring open conversion (per-protocol patients), the RAKT group had lower rates of Clavien-Dindo grade ≥3 complications at both 30 and 90 d after transplantation. Additionally, the RAKT group had lower rates of reoperation and reintervention at both 30 and 90 d, as well as lower estimated blood loss. The OKT group had shorter WIT than the RAKT group but equivalent operative time and postoperative pain control (ie, morphine equivalents administered).

A higher proportion of ureteral stents was placed in the RAKT group. The decision to place a stent is based on surgeon preference. In our current practice, stents are intermittently placed in RAKT. The difference in WIT was principally because of placement and alignment of the kidney before anastomosis, which takes approximately 10 min. The equivalent intention-to-treat and improved per-protocol outcomes with RAKT demonstrate its potential as an alternative to OKT.

A discussion of the 4 early cases where RAKT required conversion to a traditional open approach is critical. The post hoc analysis included matching on RAKT patients who did not require conversion to open procedure. In this, the RAKT group demonstrated clear advantages in perioperative complications (eg, Clavien-Dindo grade ≥3 complications at both 30 and 90 d, reoperation/reintervention at both 30 and 90 d). The intention-to-treat analysis represents a real-life scenario, as conversions are occasionally unavoidable. They also reflect a learning curve. The per-protocol thus represents the best-case scenario if patients receive their intended therapy. It is conceivable that, with an increase in procedural experience, the rate of conversions will decrease and afford patients the benefits of the robotic approach.

This investigation is unique in the heterogeneous population sample, unlike other international references and the published US experience focusing on an obese population



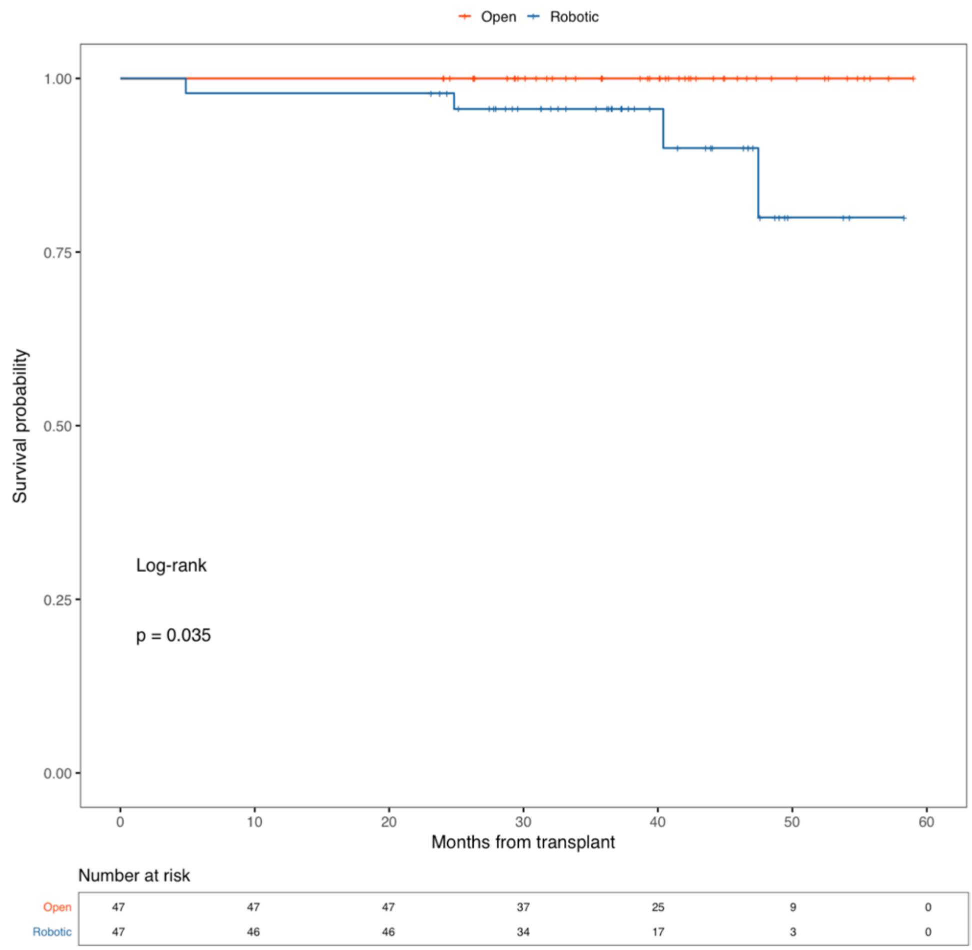
Fine-gray subdistribution hazard ratio for graft failure
Robotic (ref: Open, sHR 3.1 [95% CI 0.33-28.74]; p=0.32)
Gray's modified log-rank test p=0.28

	1-year (95% CI)	2-year (95% CI)	3-year (95% CI)	4-year (95% CI)
Open	0 (0-0)	0 (0-0)	0 (0-0)	5.0 (0.3-21.1)
Robotic	0 (0-0)	0 (0-0)	7.9 (1.9-19.6)	7.9 (1.9-19.6)

FIGURE 4. Four-year cumulative incidence of graft failure (after matching).

group.[17] Our study used propensity score matching to compare open versus robotic kidney transplantation, including analysis from an intention-to-treat standpoint. Using propensity score matching developed variable-matched comparison groups to adjust for potential confounders that are likely to affect outcomes and procedure choice. Consequently, this adjustment can decrease the impact of such confounding variables by homogenizing the cohort to improve the evaluation of the surgical approach's impact on short- and long-term postoperative outcomes. Our findings align with previous literature, demonstrating early advantages of a robotic approach. To date, multiple investigations have demonstrated comparable outcomes for death-censored graft survival and patient survival when comparing conventional OKT to minimally invasive kidney transplant,[18] as well as open (Gibson incision) with RAKT[6]; however, reports assessing minimally invasive techniques have suggested lower surgical site infection[6] and reduced incisional hernia rates[18] with improved cosmetic results[19] and postoperative pain.[20,21] Disadvantages included prolonged WIT[20] and total operation time.[18-20] We found lower rates of Clavien-Dindo grade ≥3 complications at both 30- and 90-d postsurgery in the RAKT group after propensity score matching. This finding is consistent with previous reports in kidney transplants and also in line with other comparisons of minimally invasive techniques with open equivalents in other surgical procedures.[22,23]

Of note, we observed significantly lower 4-y patient survival in the RAKT group after propensity score matching. The reason for the long-term difference in survival between the groups is not clear, but it is unlikely to be related to the surgical procedure itself, given that the patient survival at 1 y and at 2 y was equivalent and the overall incidence of graft failure was the same as well. It is possible that there may be differences between the groups in terms of confounding factors that



	1-year (95% CI)	2-year (95% CI)	3-year (95% CI)	4-year (95% CI)
Open	100% (100-100)	100% (100-100)	100% (100-100)	100% (100-100)
Robotic	97.9% (93.8-100)	97.9% (93.8-100)	95.6% (89.8-100)	80.0% (61.2-100)

FIGURE 5. Four-year patient survival (after matching).

were not included in the match that may explain the discrepancy in long-term survival. These could include differences in the distribution of both type and severity of comorbidities, such as cardiorespiratory diseases. Consequently, these variables may represent sources of unmeasured confounding.

Improved perioperative pain control is often described as an advantage of minimally invasive techniques, including RAKT.[20,21] Our analysis did not reveal a statistically significant difference in morphine equivalents administered postoperatively; however, we did see a nonsignificant trend toward reduced morphine equivalents administered on the second POD in the RAKT group. Notably, morphine equivalents consumed may not accurately reflect a patient's level of pain, as multiple factors may influence administration of narcotics in the postoperative period, including but not limited to patients' preoperative opioid use, patients' pain threshold, and nursing opioid administration practices. Additionally, as kidney transplant patients are typically discharged home on the third or fourth POD at our institution, an analysis of long-term benefits in pain control remains challenging to assess. We did find a nonsignificant trend toward a reduced length of stay in the RAKT group, which may indicate improved perioperative pain control. Future investigations may benefit from analysis of narcotics consumed after discharge date. Additionally, preoperative education regarding the advantages of a minimally invasive approach and the expected narcotic requirements in the perioperative period may further reduce narcotic requirements following transplant.

However, limitations preventing the widespread clinical application of RAKT as an alternative to OKT exist. Ganpule et al[24] suggested that the cost and logistical complexity of robotic surgery might stymie implementation within existing transplant programs and expansion into the deceased donor population. Although the feasibility of RAKT in deceased donors has been demonstrated at other institutions,[6-8,11,25] we chose to limit our experience to living donors because of the ease of logistical complexity of establishing operative block time with trained personnel. RAKT was first adopted at our institution in 2014, and the number of cases has increased over time, from 5 in 2014 to 27 in 2019. Currently, the robotic-assisted approach represents approximately 40% of our living donor kidney transplants. In 2016, we established a robotic block time in the operating room schedule, allowing involvement of fellows and other staff surgeons. Additionally, patient selection is based on robot availability, allowing for a heterogeneous population and reduced selection bias. As value-based health care is pushed to the forefront, a cost-analysis of RAKT in the living donor population must be explored. Furthermore, with the expanded use of robotic-assisted techniques in general surgery, an analysis of the learning curve required to master complex procedures like renal implantation is warranted. With expanded knowledge of cost-efficacy and technical mastery, the use of RAKT in the deceased donor population may offer a future avenue of development.

This study adds to a body of evidence supporting use of minimally invasive kidney transplantation techniques as equivalent to traditional open approaches regarding graft survival and patient survival and as potentially superior in terms of perioperative morbidity. It lays the groundwork for future exploration into the benefits of robotic-assisted techniques in solid-organ transplantation. In the future, a nationalized database of robotic-assisted cases would aid future comparisons of minimally invasive approaches to traditional open cases. A randomized controlled trial assessing the differences between open and minimally invasive approaches would provide a more definitive comparative evaluation of the impact on short- and long-term outcomes of each approach. Additionally, as more programs integrate RAKT, analysis of the learning curve necessary to gain proficiency with the technique will aid understanding of successful implementation.[25]

This study is limited by its retrospective and nonrandomized study design, with the potential for selection bias. Resulting from the single-institutional nature of the study, results may not be directly generalizable to other centers. Although the study sample represents the largest North American single-institution comparison of RAKT and OKT in nonobese recipients, the study sample is relatively small, limiting the study's statistical power to detect differences between examined groups. Despite covariate adjustment using propensity score matching, the potential for residual confounding and type 1 error remains. This is an early experience, and the small sample size limits the ability to detect individual differences in graft survival and patient outcomes. Overall, the similarities are notable, as the experience with RAKT is limited compared with OKT.

In conclusion, this study compared RAKT to OKT within a heterogeneous study population using propensity scoring, the first of its kind in the United States. Despite the significantly longer WIT with RAKT, we found that SCr in the early and intermediate RAKT postoperative period was equivalent to that for OKT. Moreover, length of stay, graft survival, and patient survival were equivalent between the groups. Reoperation or reintervention and Clavien-Dindo grade ≥3 perioperative complication rates were lower in the RAKT group. As a novel technique with an associated learning curve, RAKT represents a feasible and safe technique for living donor kidney transplantation. The combination of reduced short-term complication rates and equivalent long-term outcomes favors the robotic approach when feasible.

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