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IMPACT OF INTRAOPERATIVE ASSESSMENT OF RENAL ALLOGRAFT ARTERIAL BLOOD FLOW ON VASCULAR COMPLICATIONS AND THEIR PREVENTION STRATEGIES

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Objective: to use intraoperative fluorometry to assess the impact of renal allograft arterial blood flow on vascular complications. **Materials and methods.** The study included 285 patients who underwent kidney transplantation (KT) at Shumakov National Medical Research Center of Transplantology and Artificial Organs (from May 2022 to July 2023). Patients were distributed into 2 comparison groups. Group 1 (49 patients, 17.2%) underwent intraoperative flowmetry, while group 2 (236 patients, 82.8%) did not. Following graft reperfusion, renal transplant arterial blood flow was measured in real time. Next, ureteroneocystostomy was performed, and then the graft was placed in the iliac fossa in its optimal position and the measurement was repeated. **Results.** Intraoperative vascular complications occurred in 6 patients (12.2%) in the intraoperative flowmetry group. Those with vascular complications exhibited statistically significantly lower renal arterial volumetric blood flow (VBF) rate immediately after reperfusion (94 ± 93 *vs.* 291 ± 147; p = 0.002) and after reassessment at the end of ureteroneocystostomy (160 ± 88 *vs.* 349 ± 157; p = 0.006). A VBF of less than 120 mL/min contributed to the intraoperative decision to immediately revise the anastomosis. Following revision and reanastomosis of the arterial channel, there was no significant difference in VBF rate and PI values between recipients with the complications and the group without. **Conclusion.** Prophylactic application of intraoperative fluorometry in KT allows to obtain objective data about the quality of vascular anastomosis and timely prevent irreversible vascular complications, thus preserving the renal graft in the postoperative period.

Keywords: kidney transplantation, vascular complications in renal transplantation, intraoperative fluorometry, prevention of vascular complications.

INTRODUCTION

Vascular complications remain the leading cause of early kidney graft loss following transplantation. These complications may arise from various factors, including technical errors during vascular anastomosis formation, complex arterial reconstruction in cases involving multiple renal arteries, vascular intimal injury, compartment syndrome, diminished arterial inflow due to iliac artery spasm, vascular kinking or torsion, suboptimal graft positioning within the retroperitoneal space, and underlying coagulopathies [1–4].

In clinical practice, the assessment of graft reperfusion injury is frequently based on the surgeon's subjective judgment, supplemented by limited objective indicators such as immediate urine output, and the color and turgor of the graft. Therefore, the availability of reliable intraoperative tools for evaluating graft perfusion is critical. Such tools should be safe, easy to use, and capable of delivering rapid and reproducible results. Most importantly, they must provide a quantitative assessment of arterial blood flow and tissue perfusion. A robust intraoperative evaluation of renal graft hemodynamics is essential for early detection of vascular complications, prediction of graft function, and prevention of graft loss [5].

Intraoperative transit time flowmetry (TTFM) is a non-invasive technique that measures the "transit time" of ultrasound signals transmitted between two transducers across a blood-filled vessel. This method provides objective and real-time information regarding the quality of arterial anastomoses, particularly following arterial reconstructions, and helps identify potential technical errors [6]. The use of intraoperative TTFM to assess the quality of anastomoses of arteriovenous fistulas, aortocoronary shunts, as well as in the performance of native renal artery reconstructions has ben shown to reduce the rate of intraoperative anastomotic revisions from 8% to 3% [6].

This study aimed to evaluate the impact of arterial blood flow quality in renal allograft vessels, as measured

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by intraoperative TTFM, on the incidence of vascular complications and the effectiveness of subsequent intraoperative interventions.

MATERIALS AND METHODS

Between May 2022 and July 2023, a total of 298 kidney transplants were performed at Shumakov National Medical Research Center of Transplantology and Artificial Organs. The study included 285 patients with end-stage chronic kidney disease who were candidates for kidney transplantation (KT), aged from 1 to 70 years (mean age: 38.1 ± 17.8 years). These included 160 men (56.1%) and 125 women (43.9%). Thirteen patients were excluded from the study due to receiving kidneys from a donation after cardiac death, as such grafts are more frequently associated with delayed graft function.

The patients were divided into two groups for comparison: Group 1 (49 patients, 17.2%) underwent intraoperative TTFM, while Group 2 (236 patients, 82.8%) did not. KT was performed using a standard technique, regardless of donor type. In 90% of cases, vascular anastomoses were created end-to-side with the external iliac vessels. Arterial blood flow in the graft was measured in real time using the Veri-Q system (Medistim ASA, Oslo, Norway) immediately following graft reperfusion (Fig. 1).

Following next was ureteroneocystostomy, where the kidney graft was positioned optimally in the iliac fossa, and a second arterial blood flow measurement was performed. The space between the flow probe and the arterial vessel was filled with sterile saline.

Ultrasound transit-time flowmetry uses a specialized probe sized according to the diameter of the target vessel. The probe emits ultrasound signals in the direction of blood flow, and measures the "transit time" of the signal between transmitting and receiving transducers via a reflector within the bloodstream. During measurement, parameters such as mean volumetric blood flow rate, pulsatility index (PI) and percentage of diastolic volume filling are determined [7–9].

Among these, PI is a key indicator of anastomotic quality and graft perfusion. It is calculated as the difference between maximum and minimum flow velocities divided by the mean flow velocity, and is expressed as an absolute value. A PI in the range of 1–2 is generally considered acceptable, while higher values suggest increased flow resistance – commonly due to vascular stenosis [7, 9].

Mean volumetric blood flow (VBF) is not always a reliable standalone marker of anastomotic integrity, as it is influenced by several variables, including blood viscosity, graft resistance, the caliber of the recipient artery, and the anatomical and functional characteristics of the graft. The percentage of diastolic volume filling reflects the proportion of diastolic-phase blood flow returning through the anastomosis during the cardiac cycle [7, 9].

Immunosuppressive therapy consisted of calcineurin inhibitors, with dose adjustments based on therapeutic drug monitoring, in combination with mycophenolate

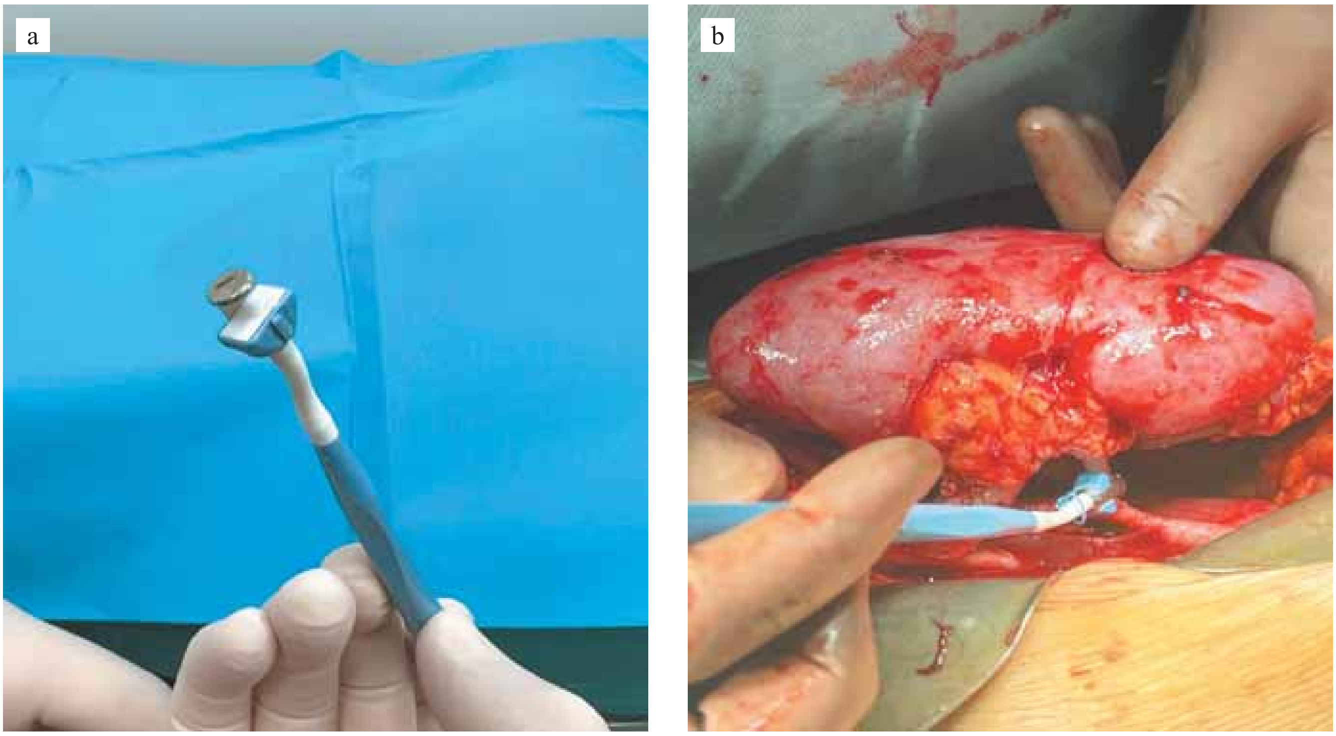

Fig. 1. Intraoperative flowmetry: a, probe; b, intraoperative renal artery flowmetry performed after graft reperfusion

mofetil and/or mycophenolic acid, and methylprednisolone administered in standard dosages.

Following data collection, all patient information was compiled into a unified spreadsheet for analysis. Statistical processing was carried out using SPSS version 26 (IBM SPSS Inc., USA). Parametric variables were expressed as mean ± standard deviation (M ± SD), while nonparametric data were presented as median (Me) and interquartile range (IQR = Q3–Q1).

For dependent sample comparisons, the paired Wilcoxon signed-rank test was employed, while independent groups were compared using the Mann–Whitney U test. Receiver operating characteristic (ROC) curve analysis was used to calculate the area under the curve (AUC), and to determine the sensitivity, specificity, and threshold values for each parameter.

To evaluate the prognostic significance of renal arterial VBF rate and PI in predicting vascular complications, univariate logistic regression analysis was performed. Model calibration was assessed using the Hosmer–Lemeshow test, and predictive power was expressed via the Nagelkerke coefficient of determination. The overall significance of the model was evaluated using the Wald chi-square test. A p-value of <0.05 was considered statistically significant for all tests.

STUDY RESULTS

A comparative analysis of the clinical characteristics of kidney transplant recipients included in the study was conducted (Table 1).

Patients in group 1 were statistically significantly older than those in group 2 (p = 0.007). Gender distribution between the groups was comparable (p = 0.633). Body mass index (BMI) was also significantly higher in group 1 compared to group 2 (p = 0.043). A comparative analysis of underlying diagnoses, types and durations of renal replacement therapy (RRT), and types of transplantation revealed no statistically significant differences between the groups (p > 0.05 for all variables). However, there was a trend toward more frequent use of flowmetry in patients undergoing peritoneal dialysis (14% in group 1 *vs.* 6% in group 2; p = 0.058).

A comparative analysis of donor characteristics showed that donors in group 1 (where flowmetry was performed) were significantly older than those in group 2 (median age 54 [IQR 44–62] *vs.* 48 [IQR 38–57]; p = 0.011). Other donor characteristics, including BMI, gender, and laboratory results, were comparable between groups (p > 0.05 for all).

A comparative analysis of surgical characteristics based on the use of intraoperative TTFM was conducted. Parameters such as surgery duration, intraoperative blood loss, ischemic time, graft type, and frequency of vascular reconstructions were evaluated. No statistically

Table 1

Comparison of clinical characteristics of recipient groups

Indicator	Flowmetry, n = 49	Non-flowmetry, n = 236	P-value
Age, years, Me (IQR)	46.4 (32.4–59)	37.9 (23.1–51.5)	**0.007**
Sex, n (%)			
Men	26 (53%)	134 (57%)	0.633
Women	23 (47%)	102 (43%)	
BMI, kg/m^2, Me (IQR)	25.8 (20.1–27.9)	22.4 (19.5–26)	**0.043**
Diagnosis, n, %			
Chronic glomerulonephritis	9 (18%)	59 (25%)	0.322
Diabetic nephropathy	10 (20%)	29 (12%)	0.132
CAKUT	8 (16%)	54 (23%)	0.312
Nephropathy of unknown etiology	5 (10%)	37 (16%)	0.325
Polycystic disease	7 (14%)	19 (8%)	0.168
Other	10 (20%)	38 (16%)	0.464
RRT (HD), n, %	34 (69%)	171 (72%)	0.663
RRT (PD), n, %	7 (14%)	15 (6%)	0.058
RRT time to KT, months, Me (IQR)	18 (9–55)	27 (12–58)	0.469
RRT (HD) time to KT, months, Me (IQR)	20.1 (8.7–55.4)	29.3 (12.8–58.5)	0.437
RRT (PD) time to KT, months, Me (IQR)	16.8 (8.9–84.2)	14.5 (9.2–29.1)	0.671
Type of transplantation, n, %			
Living donor	17 (35%)	85 (37%)	0.792
Deceased donor	31 (65%)	142 (63%)	

Note: BMI, body mass index; CAKUT, congenital anomalies of the kidney and urinary tract; RRT, renal replacement therapy; HD, hemodialysis; PD, peritoneal dialysis; KT, kidney transplantation.

significant differences were observed between the groups for any of these characteristics ($p > 0.05$ for all).

Additionally, a subgroup analysis was performed on 49 patients who underwent intraoperative TTFM, comparing renal arterial VBF rate (Q) and PI at two time points: after graft reperfusion and after completion of ureteroneocystostomy. Patients were categorized based on the presence or absence of intra- or postoperative vascular complications. Among these, 6 patients (12.2%) developed vascular complications, while 43 patients (87.8%) did not.

In patients with vascular complications, the VBF rate was significantly lower both after graft reperfusion ($p = 0.002$) and after ureteroneocystostomy ($p = 0.006$) compared to patients without complications. Conversely, PI values measured after graft reperfusion were significantly higher in the complication group ($p = 0.037$). However, PI values following ureteroneocystostomy did not differ significantly between the groups ($p = 0.079$).

ROC analysis was performed to assess the prognostic significance of renal arterial VBF rate and PI in relation to the development of vascular complications (Fig. 2).

Renal arterial VBF rates measured both after graft reperfusion and following ureteroneocystostomy were found to be statistically significant predictors of vascular complications ($p < 0.001$). These parameters demonstrated high predictive accuracy, with VBF rates providing 87.2% and 85.7% accuracy at the respective time points.

Table 2

Results of comparative analysis of flowmetric indicators

Indicator	Vascular complications, n = 6	No vascular complications, n = 43	P-value
Volumetric blood flow rate through the renal artery after graft reperfusion (ml/min), Mean ± SD	94 ± 93	291 ± 147	**0.002**
PI after graft reperfusion, Me (IQR)	2 (1.7–2.1)	1.3 (0.8–2)	**0.037**
Renal arterial VBF after ureteroneocystostomy (mL/min), Mean ± SD	160 ± 88	349 ± 157	**0.006**
PI after ureteroneocystostomy, Me (IQR)	1.7 (1.5–2)	1.2 (0.7–1.6)	0.079

Note: VBF, volumetric blood flow; PI, pulsatility index; SD, standard deviation; Me, mean; IQR, interquartile range.

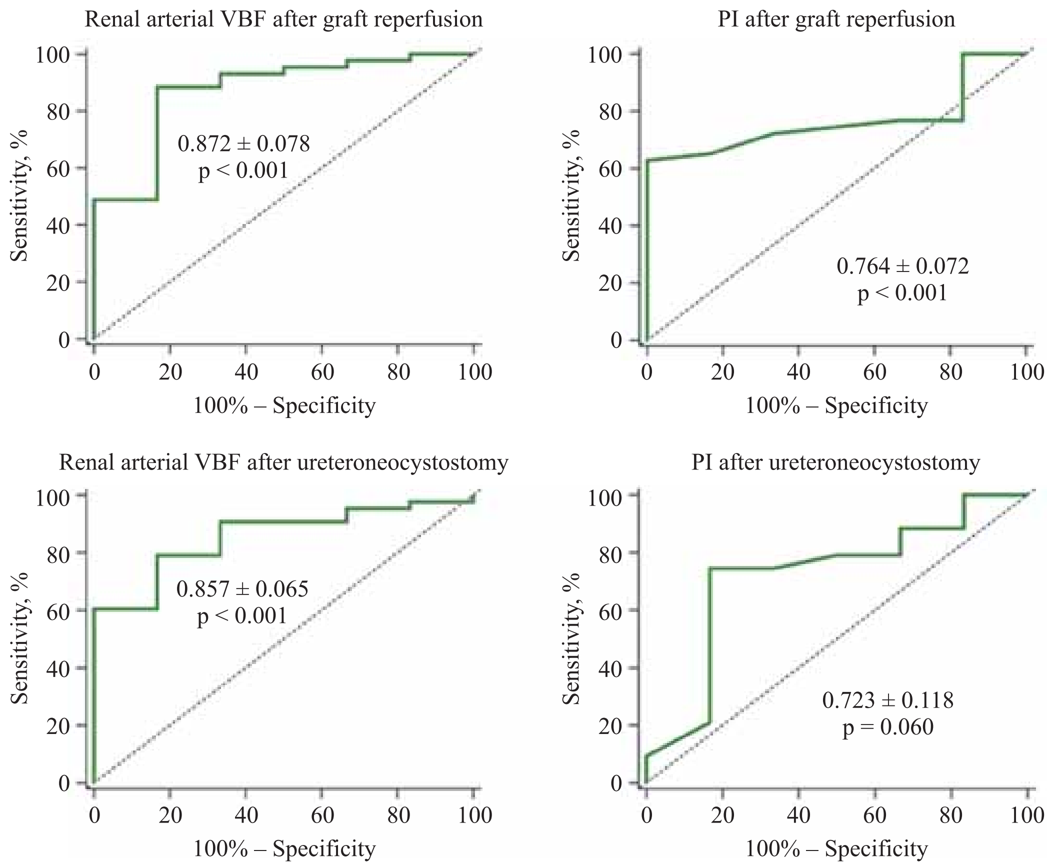

Fig. 2. Assessment of the prognostic significance of indicators of vascular complications (ROC analysis results)

A post-reperfusion VBF rate ≤120 mL/min was associated with an increased risk of vascular complications, demonstrating a sensitivity of 83.3% and a specificity of 88.4%. Similarly, a post-ureteroneocystostomy VBF rate ≤230 mL/min predicted complications with 83.3% sensitivity and 79.1% specificity.

Similarly, a post-reperfusion PI was also significantly associated with vascular complications ($p < 0.001$), with a predictive accuracy of 76.4%. A post-reperfusion PI ≥1.65 yielded a sensitivity of 83.3% and specificity of 65.1% for predicting complications. However, the PI value obtained after ureteroneocystostomy did not demonstrate statistically significant predictive value ($p = 0.060$).

Results of comparative analysis of flowmetric indicators by donor type and vascular reconstruction

Among the 49 kidney transplant recipients who underwent intraoperative TTFM, 18 patients (36.7%) received grafts from living related donors, while 31 patients (63.3%) received grafts from deceased donors. A comparative analysis was performed to evaluate renal arterial VBF rate and PI both after graft reperfusion and following ureteroneocystostomy, stratified by donor type (Table 3).

The post-ureteroneocystostomy PI was significantly lower in patients who received a renal graft from a living related donor compared to those who received a graft from a deceased donor ($p = 0.011$). However, other parameters – renal arterial VBF rate after reperfusion and after ureteroneocystostomy, as well as post-reperfusion PI – did not show statistically significant differences between the two donor groups ($p > 0.05$ for all indicators).

A comparative analysis of renal arterial VBF rate and PI was performed based on whether vascular reconstruction was required (Table 4). Among the 49 patients, vascular reconstruction was performed in 16 cases (32.7%), while 33 patients (67.3%) did not undergo any vascular reconstruction.

Our comparative analysis revealed that following vascular reconstruction, there was a statistically significant decrease in renal arterial VBF rate ($p = 0.007$) and PI ($p = 0.022$) after graft reperfusion. In contrast, VBF rate and PI measured after ureteroneocystostomy did not differ significantly between the groups. However, the VBF rate after ureteroneocystostomy in patients who underwent vascular reconstruction was slightly lower than in those without reconstruction, with a difference approaching statistical significance ($p = 0.058$).

Regression analysis confirmed that vascular complications were significantly associated with renal arterial VBF rate both after graft reperfusion ($p = 0.011$) and following ureteroneocystostomy ($p = 0.018$) (Table 5). In contrast, PI did not demonstrate a statistically significant predictive value for vascular complications.

The regression coefficients for renal arterial VBF rate were negative, indicating that higher flow rates are associated with a lower risk of vascular complications. Specifically, the likelihood of complications decreases by approximately 1% for each unit increase in VBF rate. The probability of complications was explained by 40.8% of the variance in VBF rate after graft reperfusion and by 32.6% of the variance in VBF rate after ureteroneocystostomy, suggesting that post-reperfusion

Table 3

Comparative analysis of flowmetric indicators depending on donor type

Indicator	Living related donor, n = 18	Deceased donor, n = 31	P-value
Renal arterial VBF after graft reperfusion (mL/min), Mean ± SD	298 ± 170	249 ± 146	0.288
PI after graft reperfusion, Me (IQR)	1.15 (0.8–1.9)	1.6 (1–2.3)	0.209
Renal arterial VBF after ureteroneocystostomy (mL/min), Mean ± SD	351 ± 168	312 ± 159	0.422
PI after ureteroneocystostomy, Me (IQR)	0.85 (0.6–1.2)	1.4 (0.8–1.8)	**0.011**

Note: VBF, volumetric blood flow; PI, pulsatility index; SD, standard deviation; Me, mean; IQR, interquartile range.

Table 4

Comparative analysis of flowmetric indicators by donor type

Indicator	Vascular reconstruction, n = 16	No vascular reconstruction, n = 33	P-value
Renal arterial VBF after graft reperfusion (mL/min), Mean ± SD	184 ± 135	308 ± 149	**0.007**
PI after graft reperfusion, Me (IQR)	1.8 (1.5–2.05)	1.2 (0.7–1.7)	**0.022**
Renal arterial VBF after ureteroneocystostomy (mL/min), Mean ± SD	264 ± 153	357 ± 160	**0.058**
PI after ureteroneocystostomy, Me (IQR)	1.4 (0.9–1.7)	1 (0.6–1.6)	0.152

Note: VBF, volumetric blood flow; PI, pulsatility index; SD, standard deviation; Me, mean; IQR, interquartile range.

Table 5

Regression analysis results

Factor	Regressor, B ± SE	Constant, B ± SE	HL test	R^2	P-value
Renal arterial VBF after graft reperfusion (mL/min)	–0.015 ± 0.006	0.627 ± 0.864	0.553	0.408	**0.011**
PI after graft reperfusion	0.242 ± 0.148	–2.583 ± 0.596	0.164	0.142	0.101
Renal arterial VBF after ureteroneocystostomy (mL/min)	–0.011 ± 0.005	0.758 ± 1.002	0.868	0.326	**0.018**
PI after ureteroneocystostomy	0.274 ± 0.17	–2.5 ± 0.587	0.214	0.091	0.108

Note: VBF, volumetric blood flow; B, regression coefficient; SE, standard error; HL test, Hosmer–Lemeshow test; R^2, Nagelkerke's coefficient of determination.

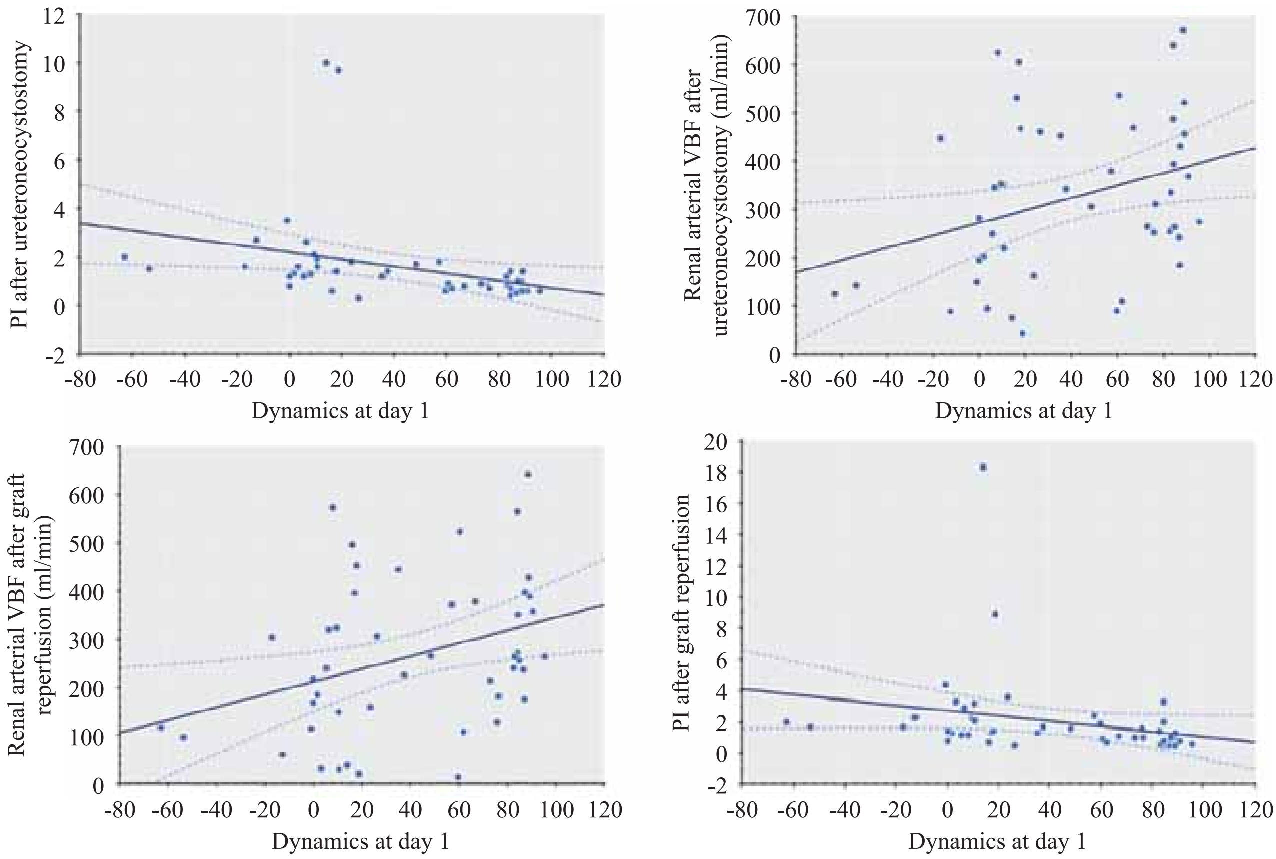

Fig. 3. Calculation of complication probabilities. PI, pulsatility index

measurements are a more robust predictor than pos-ureteroneocystostomy values.

Based on these findings, we calculated the estimated probabilities of vascular complications using the VBF rates obtained after graft reperfusion and after ureteroneocystostomy (Fig. 3).

The assessment of the predictive significance of these indicators revealed that they do not play a statistically significant role in predicting vascular complications.

DISCUSSION

Despite being widely practiced and successfully performed by many surgeons globally, KT poses challenges in predicting vascular complications and graft dysfunction, even with extensive experience. Transplant surgeons often rely on careful intraoperative visual and ultrasound evaluation, yet these measures do not always predict the development of complications [10–11].

The occurrence of vascular complications in the perioperative period significantly impacts graft function and survival, underscoring the importance of preventing such complications. Analysis of the causes of these complications reveals three key areas that require special attention: donor organ characteristics (such as angioarchitecture and potential vascular damage during procurement), recipient risk factors (including vascular abnormalities, blood coagulation disorders, and atherosclerotic lesions of major arteries), and the technical aspects of the surgical procedure [12–14]. However, there is currently no unified approach for the intraoperative prevention of vascular complications. The use of flowmetric parameters in solid organ transplantation remains a novel and insufficiently explored method of prophylaxis, offering both research and practical significance.

Bhatt et al. were among the first to apply this technique in KT. The authors assessed blood flow through the renal artery of the graft, which was found to be 114–120 mL/min. They also temporarily occluded the external iliac artery distal to the renal graft arterial anastomosis, resulting in a near doubling of blood flow to 205 mL/min. Following this, the renal artery anastomoses were revised twice, after which blood flow rates returned to normal. In one case, a high PI (>5) indicated a technical imperfection in the anastomosis. In another case, an accidental entrapment of the graft in the suture of the opposite side of the arterial anastomosis was observed [6].

In our study, 6 patients (12.2%) in the group where intraoperative TTFM was used experienced intraoperative vascular complications, while the remaining 43 patients (87.8%) did not. In the group with vascular complications, intraoperative TTFM revealed statistically significantly lower renal arterial VBF rates immediately after reperfusion (94 ± 93 *vs.* 291 ± 147; p = 0.002) and after re-evaluation at the end of ureteroneocystostomy (160 ± 88 *vs.* 349 ± 157; p = 0.006). A VBF rate of less than 120 mL/min contributed to the intraoperative decision to immediately revise the anastomosis. After revision and repeated anastomosis of the arterial bed, VBF rates and PI values did not differ significantly between recipients with and without complications. In the postoperative period, no further vascular complications were observed in patients after correction of the arterial anastomosis.

In addition to the efficacy of intraoperative blood flow measurement using flowmetry for monitoring the patency of vascular anastomoses and assessing the technical challenges of renal arterial reconstruction, intraoperative flowmetry data have also been shown to correlate with graft function [15–16].

Król et al. conducted intraoperative TTFM in 72 kidney transplant patients with a single renal artery. They excluded cases of acute rejection, early graft loss, and primary non-function from their analysis, then categorized the remaining patients into groups with primary and delayed graft function. A high perioperative resistive index (RI) was identified as a predictor of delayed graft function (52.6% *vs.* 15% for patients with an RI >0.70) and poorer long-term kidney graft function, extending up to 2 years post-transplant [17].

Hoff et al. demonstrated the successful use of intraoperative Doppler ultrasound in surgical decision-making for KT involving two graft veins. The Doppler ultrasound revealed the presence of retrograde diastolic flow, enabling the surgeons to perform an anastomosis of the inferior polar renal vein with the external iliac vein without compromising renal perfusion [18].

CONCLUSION

The prophylactic use of intraoperative flowmetry during KT provides objective data on the quality of vascular anastomoses, allowing for timely intervention to prevent irreversible vascular complications and thereby preserving kidney graft function post-transplant.

The authors declare no conflict of interest.

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