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ORIGINAL PAPER

Noninvasive assessment of chronic rejection in kidney transplant recipients with linear probe shear wave elastography

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Abstract

Purpose To compare linear and convex probe shear wave elastography (SWE) for the diagnosis of chronic rejection in renal transplant recipients.

Methods In this prospective study, 84 patients (42 with stable and 42 with unstable graft function) underwent SWE examinations using linear and convex probes. Elasticity values, resistive index (RI), and laboratory parameters (creatinine, eGFR, and proteinuria) were analyzed. Chronic rejection was confirmed by biopsy in patients with unstable graft function.

Results Linear probe SWE values were significantly higher in patients with rejection than in those without rejection (15.91 vs. 12.3 kPa, $p < 0.05$). A cutoff value of 15.45 kPa predicted rejection with 66.7% sensitivity and 80% specificity (AUC: 0.76). Convex probe SWE showed no diagnostic utility. Linear SWE values correlated with elevated creatinine levels ($p < 0.05$), increased proteinuria ($p < 0.05$), and reduced eGFR ($r = -0.436$). RI values were not predictive.

Conclusion Linear probe SWE provides superior performance compared with convex probe SWE in detecting chronic rejection, representing a potential noninvasive tool to support biopsy decisions and monitor fibrosis.

Keywords Renal transplantation · Sonoelastography · Shear Wave Elastography (SWE) · Chronic allograft dysfunction · Chronic allograft rejection

Introduction

With the global increase in kidney transplantations, more than 3,000 transplants are performed annually in Turkey [1]. The reduction in acute graft rejection rates resulting from advances in immunosuppressive therapies has prolonged the survival of transplanted kidneys. However, long-term renal graft survival has not improved to the same extent. Consequently, chronic rejection, a progressive and insidious condition characterized by interstitial fibrosis (IF) and tubular atrophy (TA), remains a major cause of renal allograft loss [2].

Elevated serum creatinine levels, decreased glomerular filtration rates (GFRs), and proteinuria may indicate graft injury. However, a significant increase in serum creatinine levels is typically detected only after more than 60% of renal

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function has been lost [3]. In other words, deterioration in renal function parameters represents a late manifestation of graft dysfunction associated with advanced fibrosis, at which stage the damage may already be irreversible.

The gold standard method for assessing chronic rejection is renal biopsy. However, performing biopsies to evaluate graft function whenever clinical fluctuations occur is not feasible in renal transplant recipients. Furthermore, even when indicated, biopsy is an invasive procedure associated with potential complications, including bleeding, arteriovenous fistula formation, infection, and pseudoaneurysm [4]. Therefore, noninvasive imaging approaches have gained increasing importance in the evaluation of graft dysfunction, including renal allograft assessment.

Among these approaches, conventional ultrasonography (US) and Doppler ultrasonography, which are widely available, cost-effective, rapid, and non-nephrotoxic, play an important role in the evaluation of renal allografts. Although the resistive index (RI) is frequently used to predict allograft rejection during routine Doppler examinations, its prognostic value remains controversial [5].

Sonoelastography (SE), one of the newer ultrasonographic modalities, is becoming increasingly widespread. SE provides a quantitative assessment of tissue stiffness, reflecting the qualitative information obtained through palpation during clinical examination.

Shear wave elastography (SWE), a dynamic SE technique, enables more accurate assessment of tissue stiffness and provides quantitative information regarding fibrosis by measuring the propagation of shear waves at multiple points within the image under grey-scale B-mode US guidance. SWE is widely used for the evaluation of liver fibrosis due to its high sensitivity and is also employed in the diagnosis of breast and thyroid malignancies.

Based on this background, the present study was designed to evaluate the diagnostic performance of linear probe SWE compared with convex probe SWE for the noninvasive assessment of chronic allograft rejection characterized by IF and TA in renal transplant recipients.

Materials and methods

Study design and setting

This single-center prospective study was conducted in the Organ Transplant Clinic and Department of Radiology of Akdeniz University Faculty of Medicine Hospital, a tertiary university hospital in Turkey, between December 2022 and June 2023. The study protocol was approved by the institutional ethics committee (approval no. 7.12.2022/704). The study was conducted in accordance with the ethical principles of the revised Declaration of Helsinki (2000) promulgated by the World Medical Association. Written informed consent was obtained from all participants. The study was financially supported by the Akdeniz University Scientific Research Project Fund (Project No. 6284).

Population and sample

The study population consisted of 94 patients who had undergone renal transplantation at least 1 year previously, were followed at the Organ Transplant Clinic, and were subsequently referred to the Department of Radiology at Akdeniz University Faculty of Medicine Hospital between December 2022 and June 2023.

Patients with conditions affecting renal function, including advanced hydronephrosis (grade III–IV) ($n=6$) and renal artery stenosis ($n=4$), were excluded. The remaining 84 patients were included in the study and divided into two groups: 42 patients with stable renal function and 42 patients with unstable renal function.

Renal function stability was determined based on renal function parameters, including serum creatinine levels, estimated glomerular filtration rate (eGFR), and the presence of proteinuria. A serum creatinine cutoff value of 1.4 mg/dL was adopted, corresponding to the threshold routinely used in clinical practice at our hospital's Organ Transplant Clinic.

Patients were classified according to whether an increase in serum creatinine levels had occurred during the last three follow-up visits. Proteinuria was defined as a protein level of 1 g/dL or higher in spot urine samples.

Renal biopsy was performed in patients with clinically unstable graft function. Patients diagnosed with chronic active antibody-mediated rejection and/or T-cell-mediated rejection based on histopathological findings, and who subsequently received appropriate treatment, were classified as the chronic rejection group.

Patients with stable clinical and laboratory findings, for whom renal biopsy was not considered appropriate due to the associated risks, constituted the control group (Fig. 1).

Imaging protocol

Ultrasound (US) examinations were performed by two experienced radiologists using grey-scale B-mode ultrasonography, renal duplex ultrasonography (RDUS), and SWE modalities with a Toshiba Aplio 500 US system equipped with 6C1 curvilinear and 14L5 linear transducers. Examinations were performed in a semi-darkened room with patients in the supine position. All images were stored on the ultrasound system's hard drive and transferred to the Sectra picture archiving and communication system (PACS).

Using conventional US, the following parameters were evaluated: transplanted kidney dimensions, parenchymal thickness, presence of stones within the renal collecting

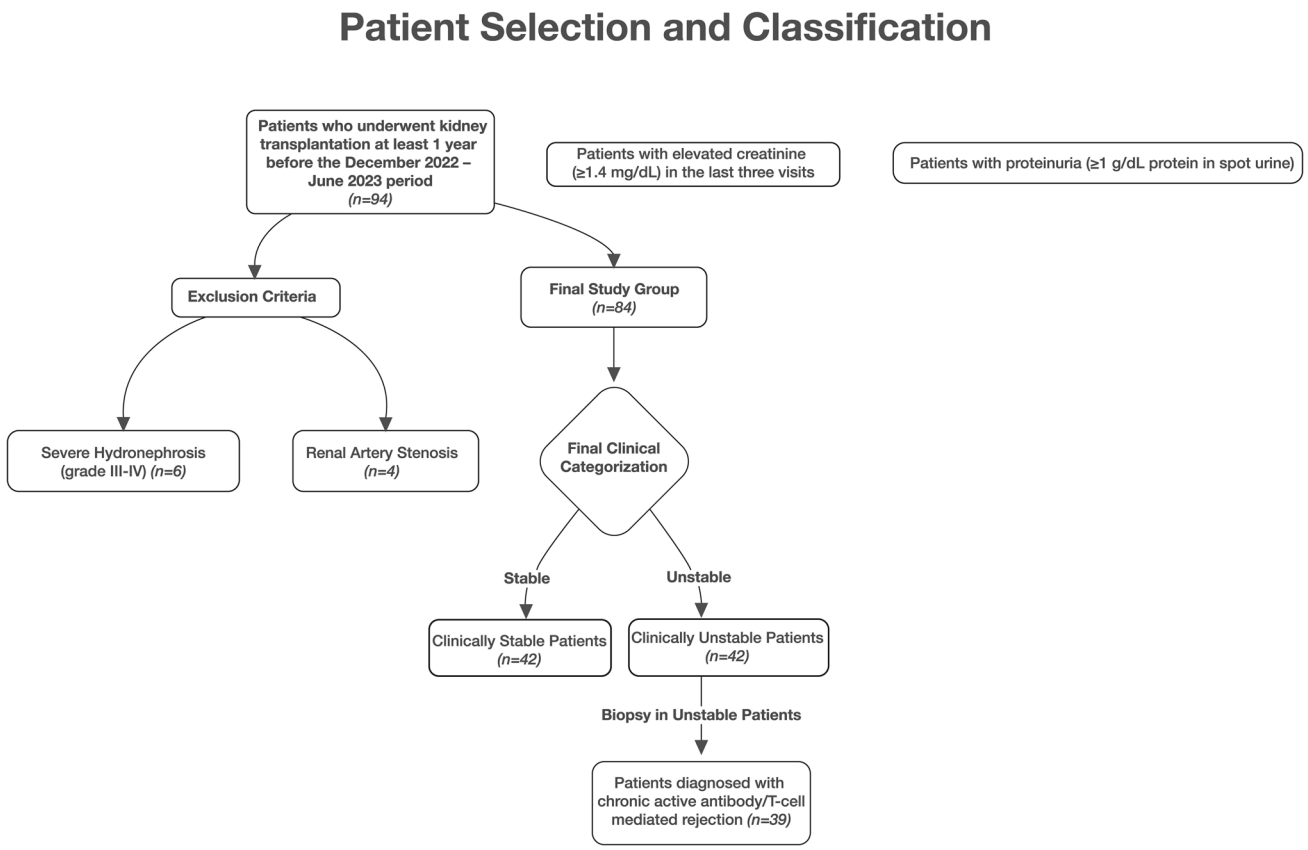


Fig. 1. Flow diagram illustrating patient selection and grouping in the study

system, pelvicalyceal structures, perirenal region, and renal vascularity. The resistive index (RI) was also measured. SWE measurements were performed immediately after completion of grey-scale B-mode US and RDUS examinations.

Analysis of imaging findings

Parenchymal echogenicity was graded on a 4-point scale (Grades 0–3) by comparing the echogenicity of the transplanted kidney cortex with that of the adjacent liver or splenic parenchyma. Grade 0 was defined as normal echogenicity (cortex hypoechoic to the liver), whereas Grade 3 represented severe hyperechogenicity with loss of corticomedullary differentiation, as previously described in the literature [6].

SWE examinations were performed with patients at rest, and excessive transducer pressure was avoided. For SWE examinations performed with both convex and linear probes, regions of interest (ROIs) were placed within the renal cortical parenchyma at a depth of no more than 1 cm from the capsule. Elasticity values were calculated in kilopascals (kPa).

Care was taken to ensure that ROIs remained entirely within the renal parenchyma and avoided major vascular structures and adjacent soft tissues. Transplanted kidneys were initially evaluated using the convex probe. A total of 12 measurements were obtained, with four measurements performed in each of the upper, middle, and lower thirds of the renal cortex. For each cortical region, the mean elasticity value was calculated separately.

Subsequently, transplanted kidneys were evaluated using the linear probe. Seventy-three patients with a subcutaneous tissue thickness of ≤4 cm at the anterior abdominal wall were examined using the linear probe. The elasticity value was calculated as the mean of four measurements obtained from ROIs placed in the portion of the transplanted kidney cortex closest to the anterior abdominal wall (Fig. 2).

Statistical analysis

Statistical analyses were performed using SPSS software, version 23.0 (Statistical Package for the Social Sciences for Windows, Version 23.0; IBM Corp., Armonk, NY, USA, 2015). Continuous variables with a normal distribution were expressed as mean ± standard deviation, whereas non-normally distributed continuous variables were presented as median values with minimum and maximum ranges.

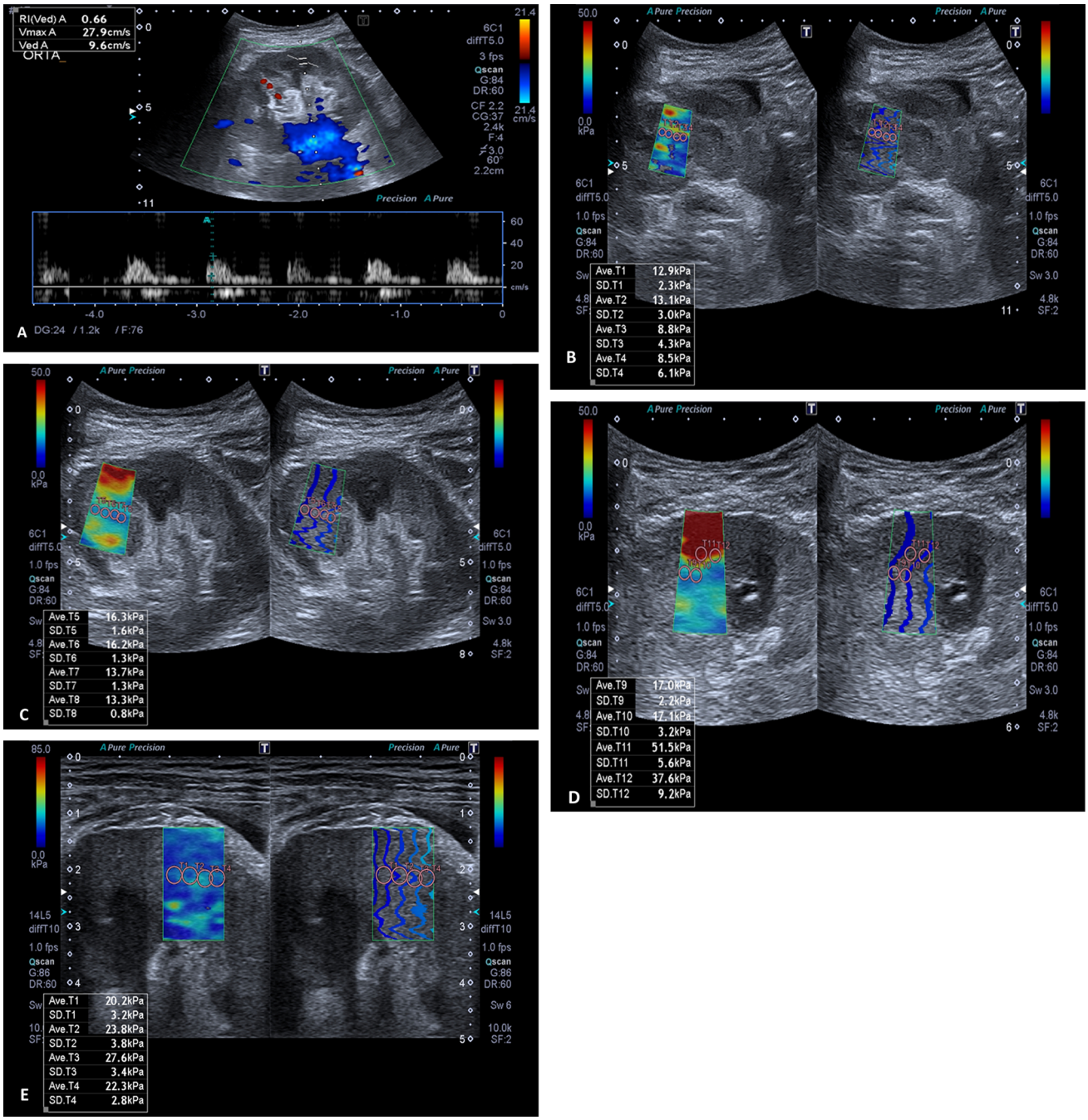


Fig. 2. A 49-year-old male patient with a 9-year history of renal transplantation from a living donor. The patient had unstable graft function, elevated serum creatinine levels, and significant proteinuria. His serum creatinine level was 4.51 mg/dL. The transplanted kidney was normal in size, and parenchymal echogenicity was Grade II. **a** Mean RI value measured in the upper section of the transplanted kidney cortex: 0.66. **b–d** Mean elasticity values measured using convex probe SWE in the upper, middle, and lower sections of the transplanted kidney cortex: 10.8 kPa, 14.9 kPa, and 30.8 kPa, respectively. **e** Mean elasticity value measured using linear probe SWE: 23.5 kPa, exceeding the cutoff value of 15.45 kPa established for predicting chronic allograft rejection. Due to unstable clinical findings, renal biopsy was performed. Histopathological examination revealed chronic active antibody-mediated rejection

Categorical variables were expressed as frequencies (*n*) and percentages (%).

The normality of continuous variables was assessed using the Shapiro–Wilk and Kolmogorov–Smirnov tests. The independent-samples t-test and Mann–Whitney U test were used to compare normally and non-normally distributed continuous variables between two independent groups, respectively. One-way analysis of variance (ANOVA) and

the Kruskal–Wallis test were used to compare normally and non-normally distributed continuous variables among more than two independent groups, respectively. Differences in categorical variables between groups were assessed using the chi-square test.

Receiver operating characteristic (ROC) curve analysis was performed to evaluate the diagnostic performance of radiological parameters in predicting chronic rejection. A p-value ≤ 0.05 was considered statistically significant.

Results

Patient characteristics

The median age of the study population was 40.5 years (range: 3.0–69.0 years), and 54.8% of patients were female. The mean age was 39.6 ± 13.0 years. The mean duration since transplantation was 7.9 years. The mean serum creatinine level was 1.8 mg/dL, the mean estimated glomerular filtration rate (eGFR) was 58.0 mL/min/1.73 m², the mean proteinuria level was 0.93 g/dL, the mean transplanted kidney length was 113.8 mm, and the mean parenchymal thickness was 15.2 mm.

Renal transplantation was performed from a living donor in 83.3% of patients and from a deceased donor in 16.7% of patients. The predominance of living-donor transplantation reflects the distribution of donor sources in the national transplant registry of Turkey, where living donation represents the main source of renal grafts.

Among patients with elevated serum creatinine levels, 51.2% were classified as clinically unstable and 50.0% as clinically stable. This discrepancy was due to one patient who presented with elevated creatinine levels at the time of evaluation and was initially classified as clinically unstable because of a diagnosis of acute gastroenteritis. During subsequent follow-up, creatinine levels decreased, the patient was reclassified as clinically stable, and renal biopsy was not performed.

The transplanted kidney was located in the right lower quadrant in 96.4% of patients. Parenchymal echogenicity was classified as Grade 1 in 25.0% of patients and Grade 2 in 5.5%. Grade 1 polycystic kidney disease (PKD) was present in 1.2% of patients, and Grade 2 PKD was present in 3.6%.

Imaging findings

The mean RI values, one of the evaluated radiological parameters, were 0.6529, 0.6577, and 0.6538 for the upper, middle, and lower sections of the transplanted kidney cortex, respectively. The mean value of these three measurements was 0.6548.

The mean convex probe SWE elasticity values were 24.35 kPa, 31.15 kPa, and 31.86 kPa for the upper, middle, and lower sections of the transplanted kidney cortex, respectively. The overall mean convex probe SWE elasticity value was 29.12 kPa. The mean linear probe SWE elasticity value in the study population was 15.91 kPa (Table 1).

Mean serum creatinine levels, proteinuria values, and linear probe SWE elasticity values were significantly higher, whereas eGFR values were significantly lower, in renal transplant recipients with biopsy-confirmed chronic rejection compared with those without chronic rejection ($p < 0.05$) (Table 2).

The mean RI value of the lower section of the transplanted kidney cortex, the mean convex probe SWE elasticity values of the upper and middle sections, and the overall mean convex probe SWE elasticity value were significantly higher in patients who received kidneys from deceased donors than in those who received kidneys from living donors ($p < 0.05$).

The mean linear probe SWE elasticity value was significantly lower in the clinically stable group than in the clinically unstable group ($p < 0.05$) (Table 3). Similarly, patients with serum creatinine levels $\geq$1.4 mg/dL had significantly higher mean linear probe SWE elasticity values than those with serum creatinine levels <1.4 mg/dL ($p < 0.05$) (Table 4).

The mean linear probe SWE elasticity value was significantly higher in renal transplant recipients with proteinuria (protein level $\geq$1 g/dL) than in those without proteinuria (protein level <1 g/dL) ($p < 0.05$).

No significant correlations were observed between RI values and SWE elasticity values or between time since transplantation and radiological parameters ($p > 0.05$). Conversely, a moderate negative correlation was observed between eGFR and linear probe SWE elasticity values ($r = -0.436$, $p < 0.001$).

ROC curve analysis

ROC curve analysis demonstrated that the mean elasticity value obtained with the linear probe SWE significantly predicted chronic rejection ($p < 0.05$). In contrast, the mean convex probe SWE elasticity values measured in the upper, middle, and lower sections of the transplanted kidney cortex, as well as their average value, did not show significant predictive ability for chronic rejection ($p > 0.05$) (Fig. 3). A cutoff value of 15.45 kPa for linear probe SWE elasticity predicted chronic allograft rejection with 66.7% sensitivity and 80.0% specificity (Fig. 4).

Table 1 Patients' clinical, laboratory and elastography characteristics

Characteristics (unit)	*n*	Mean ± SD	Median [Min. – Max.]
Demographic and clinical characteristics			
Age (years)	84	39.6 ± 13.0	40.5 [3.0–69.0]
Transplantation duration (years)	84	7.9 ± 5.6	6.0 [1.0–25.0]
Laboratory characteristics			
Creatinine level (0.7–1.4 mg/dL)	84	1.79 ± 1.13	1.47 [0.61–6.20]
e-GFR value(mL/min/1.73m^2)	84	58.0 ± 27.8	54.9 [8.1–114.8]
Protein level (g/dL)	84	0.93 ± 1.66	0.20 [0.04–8.43]
Morphometric characteristics			
Size of transplanted kidney (mm)	84	113.8 ± 12.3	115.0 [74.0–145.0]
Parenchymal thickness (mm)	84	15.2 ± 3.0	15.0 [7.0–24.0]
Doppler USG and SWE characteristics			
RI values			
Upper section	84	0.65 ± 0.06	0.65 [0.52–1.00]
Middle section	84	0.66 ± 0.06	0.65 [0.54–1.00]
Lower section	84	0.65 ± 0.06	0.64 [0.55–1.00]
Average of the mean RI values	84	0.65 ± 0.06	0.65 [0.56–1.00]
SWE values (Convex probe)			
Upper section (kPa)	84	24.35 ± 15.03	21.00 [3.80–71.70]
Middle section (kPa)	84	31.15 ± 18.95	27.35 [6.80–97.80]
Lower section (kPa)	84	31.86 ± 20.67	26.45 [6.10–128.30]
Average of the mean SWE values (kPa)	84	29.12 ± 14.45	25.38 [5.57–82.87]
SWE value (Linear probe) (kPa)	73	15.91 ± 7.26	14.10 [5.50–38.60]

e-GFR Estimated glomerular filtration rate, *RI* Resistive index, *SWE* Shear wave elastography, *kPa* Kilopascal, *SD* Standard deviation, *Min* Minimum, *Max* Maximum

Discussion

In this study, we comparatively evaluated the diagnostic performance of convex and linear probe SWE for the non-invasive assessment of chronic renal allograft rejection. SWE is an advanced ultrasonographic technique that enables quantitative evaluation of tissue stiffness. Our findings demonstrated that linear probe SWE elasticity values significantly predicted chronic allograft rejection characterized by interstitial fibrosis (IF) and tubular atrophy (TA) in renal transplant recipients.

We also identified significant associations between linear probe SWE parameters and laboratory markers routinely used in clinical follow-up, including serum creatinine, proteinuria, and eGFR. During the past decade, extensive research on liver elastography has led to the widespread adoption of elastography for the assessment of liver fibrosis. During this period, technical standards regarding elastography acquisition, patient preparation, and positioning have been established, and consensus has been reached regarding the interpretation of liver stiffness measurements based on the interquartile range-to-median ratio (IQR/M) [7].

Similarly, the use of elastography for evaluating chronic kidney disease and renal tissue stiffness has attracted increasing attention, and studies involving native kidneys are being performed to establish standardized methods. In one such study, the median Young's modulus (elastic modulus, E) of 25 patients with chronic kidney disease was significantly higher than that of 20 healthy controls (9.40 kPa, IQR = 5.55–22.35 kPa vs. 4.40 kPa, IQR = 3.68–5.70 kPa; $p = 0.002$) [8].

The mean and maximum durations after transplantation in our study population were 7.9 and 25 years, respectively. No significant association was observed between longer transplantation duration and chronic rejection, possibly because the progression of chronic allograft injury varies according to individual clinical characteristics. The higher kPa values observed in the unstable group may therefore reflect underlying histopathological changes associated with chronic rejection rather than transplantation duration alone.

However, some studies have reported associations between transplantation duration and pathological findings of chronic allograft injury. In a study involving 104 renal transplant recipients, Yoo et al. demonstrated significant associations between six Banff renal allograft pathology scores (t, cg, ct, ci, mm, and ah) and the time elapsed from transplantation to renal biopsy, although no significant association was found between these scores and acoustic radiation force impulse (ARFI) imaging or supersonic shear imaging (SSI) parameters [9]. Another study including 36

Table 2 Distribution of patients' clinical, laboratory and elastography characteristics by chronic allograft rejection status

Characteristics	Patients with no chronic rejection ($n=45$)	Patients with chronic rejection ($n=39$)	p value
Demographic and clinical characteristics			
Age (years)	40.24 ± 14.58	38.95 ± 11.16	0.653
Transplantation duration (years)	7.98 ± 5.82	7.77 ± 5.47	0.867
Laboratory Characteristics			
Creatinine level (0.7–1.4 mg/dL)	1.14 ± 0.35	2.55 ± 1.25	**< 0.001**
e-GFR value(mL/min/1.73m^2)	75.57 ± 22.76	37.75 ± 17.55	**< 0.001**
Protein level (g/dL)	0.19 ± 0.18	1.77 ± 2.15	**< 0.001**
Morphometric characteristics			
Size of transplanted kidney (mm)	112.80 ± 11.42	114.90 ± 13.24	0.438
Parenchymal thickness (mm)	15.00 ± 2.43	15.45 ± 3.53	0.494
Doppler USG and SWE Characteristics			
RI values			
Upper section	0.64 ± 0.05	0.66 ± 0.07	0.134
Middle section	0.65 ± 0.06	0.66 ± 0.07	0.543
Lower section	0.65 ± 0.05	0.66 ± 0.07	0.631
Average of the mean RI values	0.65 ± 0.05	0.66 ± 0.07	0.352
SWE values (Convex probe)			
Upper section (kPa)	21.87 ± 11.83	27.20 ± 17.77	0.116
Middle section (kPa)	30.24 ± 20.56	32.21 ± 17.11	0.637
Lower section (kPa)	29.57 ± 15.43	34.51 ± 25.38	0.277
Average of the mean SWE values (kPa)	27.22 ± 12.91	31.31 ± 15.94	0.199
SWE value (Linear probe) (kPa)	13.03 ± 5.04	19.40 ± 8.05	**< 0.001**

p values given in bold numbers indicate statistical significance ($p \leq 0.05$)

e-GFR Estimated glomerular filtration rate, *RI* Resistive index, *SWE* Shear wave elastography, *kPa* Kilopascal

Table 3 Distribution of patients' radiological characteristics by clinical stability

Characteristics	Clinical stability group	n	Mean ± SD	p value
Mean RI (upper section)	Clinically stable	42	0.64 ± 0.05	0.197
	Clinically unstable	42	0.66 ± 0.07	
Mean RI (middle section)	Clinically stable	42	0.65 ± 0.05	0.529
	Clinically unstable	42	0.66 ± 0.07	
Mean RI (lower section)	Clinically stable	42	0.65 ± 0.05	0.465
	Clinically unstable	42	0.66 ± 0.07	
Average of the mean RI values	Clinically stable	42	0.65 ± 0.05	0.342
	Clinically unstable	42	0.66 ± 0.07	
Mean convex probe SWE (upper section) (kPa)	Clinically stable	42	22.00 ± 12.03	0.155
	Clinically unstable	42	26.69 ± 17.37	
Mean convex probe SWE (middle section) (kPa)	Clinically stable	42	30.61 ± 20.78	0.793
	Clinically unstable	42	31.70 ± 17.16	
Mean convex probe SWE (lower section) (kPa)	Clinically stable	42	29.96 ± 15.86	0.401
	Clinically unstable	42	33.77 ± 24.61	
Average of the mean convex probe SWE values (kPa)	Clinically stable	42	27.52 ± 13.07	0.314
	Clinically unstable	42	30.72 ± 15.70	
Mean linear probe SWE (kPa)	Clinically stable	37	13.12 ± 5.19	**0.001**
	Clinically unstable	36	18.76 ± 8.02	

RI Resistive index, *SWE* Shear wave elastography, *kPa* Kilopascal, *SD* Standard deviation

p values given in bold numbers indicate statistical significance ($p \leq 0.05$)

Table 4 Distribution of patients' radiological characteristics by creatinine levels

Characteristics	Creatinine level	*n*	Mean ± SD	*p* value
Mean RI (upper section)	< 1.4	40	0.64 ± 0.04	0.138
	≥ 1.4	44	0.66 ± 0.08	
Mean RI (middle section)	< 1.4	40	0.65 ± 0.05	0.358
	≥ 1.4	44	0.66 ± 0.07	
Mean RI (lower section)	< 1.4	40	0.65 ± 0.05	0.223
	≥ 1.4	44	0.66 ± 0.07	
Average of the mean RI values	< 1.4	40	0.65 ± 0.04	0.195
	≥ 1.4	44	0.66 ± 0.07	
Mean convex probe SWE (upper section) (kPa)	< 1.4	40	23.57 ± 13.36	0.655
	≥ 1.4	44	25.05 ± 16.53	
Mean convex probe SWE (middle section) (kPa)	< 1.4	40	31.37 ± 21.43	0.919
	≥ 1.4	44	30.95 ± 16.62	
Mean convex probe SWE (lower section) (kPa)	< 1.4	40	28.69 ± 15.13	0.181
	≥ 1.4	44	34.75 ± 24.48	
Average of the mean convex probe SWE values (kPa)	< 1.4	40	27.88 ± 13.27	0.456
	≥ 1.4	44	30.25 ± 15.51	
Mean linear probe SWE (kPa)	< 1.4	36	13.67 ± 5.83	**0.009**
	≥ 1.4	37	18.08 ± 7.91	

Creatinine levels are given in mg/dL. *p* values given in bold numbers indicate statistical significance ($p \leq 0.05$)

RI Resistive index, *SWE* Shear wave elastography, *kPa* Kilopascal, *SD* Standard deviation

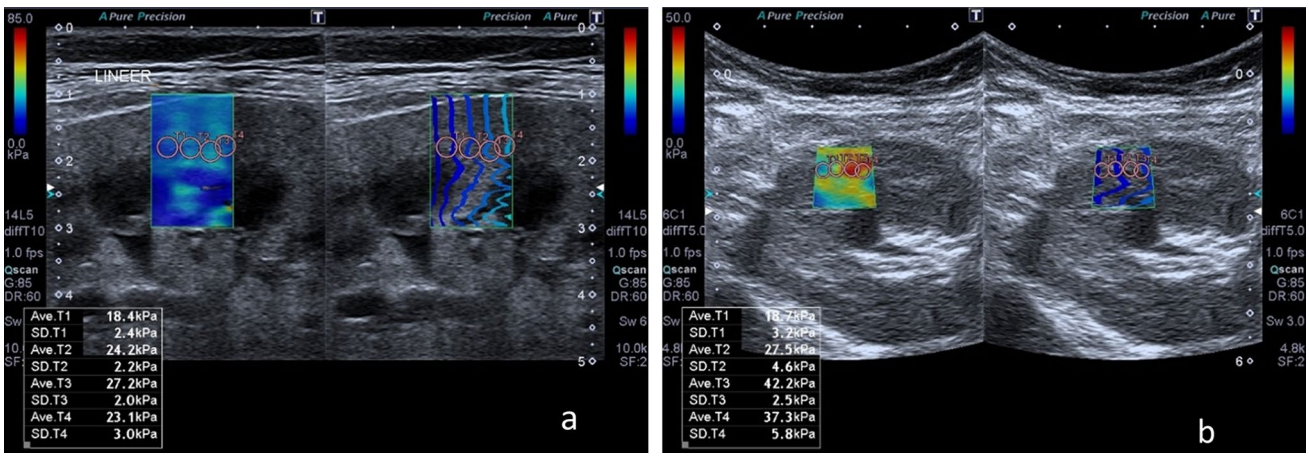


Fig. 3. Comparison of linear and convex probe shear wave elastography (SWE) in a renal transplant recipient. **a** SWE image obtained using a high-frequency linear probe. The renal cortex shows higher spatial resolution, with a stable and homogeneous color map within the region of interest (ROI), resulting in a mean elasticity value of 15.8 kPa in this patient with biopsy-confirmed chronic rejection. **b** SWE image of the same patient obtained using a convex (curvilinear) probe. Although deeper structures are visualized, cortical detail and elastographic image uniformity are reduced compared with the linear probe acquisition

renal transplant recipients with biopsy-proven chronic allograft nephropathy reported a significant association between longer transplantation duration, increased mean tissue stiffness, and the percentage of cortex affected by IF/TA assessed by SWE [10].

Allograft parenchymal status influences allograft functional parameters. In our study, a significant association was observed between persistent elevation of serum creatinine levels (≥1.4 mg/dL), which may indicate renal allograft dysfunction, and linear probe SWE elasticity values ($p < 0.05$). In addition, both the convex probe SWE elasticity value of the lower section of the transplanted renal cortex and the linear probe SWE elasticity value were significantly higher in patients with spot urine protein levels ≥1 g/dL, classified

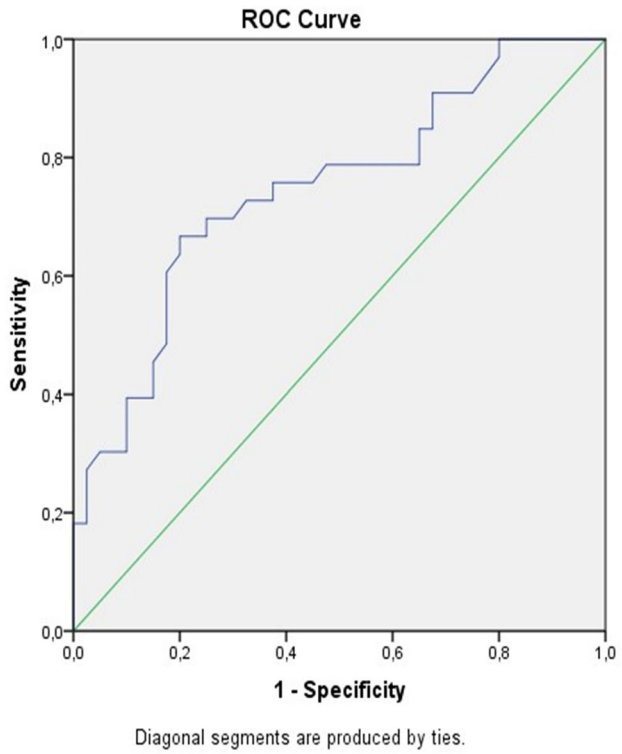


Fig. 4. ROC curve analysis of linear probe SWE elasticity for predicting chronic allograft rejection. The optimal cutoff value was 15.45 kPa (AUC: 0.747; $p = 0.000$)

as having proteinuria, than in those with spot urine protein levels <1 g/dL ($p < 0.05$). A moderate negative correlation was also observed between eGFR and linear probe SWE elasticity values ($r = -0.436$, $p < 0.001$).

Similarly, in a prospective study evaluating 40 renal transplant recipients using SWE, Sonal et al. reported that parenchymal stiffness was positively correlated with serum creatinine levels and negatively correlated with eGFR [2]. In another study involving 43 transplant recipients assessed with point SWE (pSWE), Qin et al. found significant differences in eGFR values between patients with grade 0–1 (none-to-mild) and grade 2–3 (moderate-to-severe) IF/TA ($p < 0.001$). They also demonstrated that renal cortical stiffness was significantly higher in patients with grade 2–3 IF/TA and that pSWE showed better performance than eGFR in assessing IF and TA in patients with moderate-to-severe IF/TA [11]. Furthermore, similar to our findings, cortical stiffness was positively correlated with proteinuria ($r = 0.526$, $p < 0.001$), weakly positively correlated with serum creatinine levels ($r = 0.372$, $p = 0.014$), and negatively correlated with eGFR ($r = -0.375$, $p = 0.013$).

No significant association was found between RI values, which reflect renal vascular resistance, and parenchymal stiffness. In contrast, in a study including 55 renal transplant recipients, Gonçalves et al. reported a significant association between RI values and parenchymal stiffness assessed using linear probe SWE [12]. They found that mean shear wave velocity, a marker of parenchymal stiffness, was significantly higher in patients with elevated RI values than in those with normal RI values (2.6 ± 0.4 m/s vs. 2.2 ± 0.4 m/s; $p = 0.013$). In a prospective study of 50 renal transplant recipients, Orlacchio et al. found that RI values were significantly lower in patients with mild-to-moderate fibrosis than in those with severe fibrosis [13]. Naesens et al. [14] and Viazzi et al. [15] reported that factors such as age, blood pressure, heart rate, and cardiac rhythm may influence RI values. Therefore, the clinical significance of elevated RI values in predicting allograft dysfunction remains uncertain. Several studies have suggested that sonoelastography may detect allograft injury earlier than RDUS [16].

In our study, the mean linear probe SWE elasticity value was significantly lower in the clinically stable group than in the clinically unstable group ($p < 0.05$). Similarly, in a prospective study using linear probe SWE, Bolboacă et al. reported significantly higher median elasticity values in patients with allograft dysfunction than in clinically stable patients (28.70 kPa, IQR = 25.68–31.98 kPa vs. 20.99 kPa, IQR = 16.08–27.68 kPa) [16]. Likewise, in a study including 40 renal transplant recipients (27 with graft dysfunction and 13 with stable graft function), Sonal et al. found that mean SWE elasticity values were significantly higher in patients with unstable graft function than in those with stable graft function (11.7 kPa, range 5–19 kPa vs. 6.15 kPa, range 5–8 kPa). They also reported that a SWE cutoff value of 8.23 kPa predicted graft dysfunction with 70% sensitivity and 100% specificity [2].

Although we found a significant association between chronic rejection and elasticity values measured by high-frequency linear probe SWE, which allows assessment at depths of up to 4 cm, no significant association was observed between chronic rejection and elasticity values obtained with convex probe SWE, which allows assessment at depths of up to 8 cm.

The superior performance of linear probe SWE in our study may be related to the superficial location of transplanted kidneys within the pelvic cavity compared with native kidneys, which are generally located deeper. In addition, the higher spatial resolution of linear probes may facilitate visualization of cortical structures, corticomedullary differentiation, and vascular anatomy. The variability observed in convex probe measurements, particularly the wide range of kPa values between different cortical regions, may reflect limitations related to curvilinear transducer geometry and focal depth optimization in superficial organs. These findings suggest that linear probe SWE may be a useful approach for more consistent assessment of renal allografts.

However, few studies have evaluated linear probe SWE in renal transplantation. In one such study, including 69

patients with stable allografts and 14 patients with unstable allografts, the median cortical stiffness values were significantly higher in unstable allografts than in stable allografts, consistent with our findings (28.70 kPa, IQR = 25.68–31.98 kPa vs. 20.99 kPa, IQR = 16.08–27.68 kPa; $p = 0.0142$) [16].

While some studies have demonstrated significant associations between convex probe SWE elasticity values and fibrosis in renal allografts [17–19], other studies have not demonstrated such associations, consistent with our findings [20, 21].

ROC analysis demonstrated that linear probe SWE elasticity values significantly predicted chronic rejection ($p < 0.05$). A cutoff value of 15.45 kPa predicted chronic allograft rejection with 66.7% sensitivity and 80.0% specificity. Similarly, in a study evaluating renal allograft parenchymal stiffness using a high-frequency linear probe, Yang et al. reported a significant association between parenchymal stiffness and chronic changes [22]. They found that SWE cutoff values of 18.9 kPa, 22.5 kPa, and 27.6 kPa predicted mild, moderate, and severe chronic changes, respectively. Additionally, a SWE cutoff value of 21.0 kPa differentiated mild chronic changes from moderate-to-severe chronic changes with 77.6% sensitivity and 77.6% specificity (AUC: 0.817; 95% CI: 0.756–0.878).

Limitations of the study

The primary limitation of our study was the relatively small sample size. Second, biopsy results were not available for patients with stable renal function, who were considered the control group, and therefore these patients were evaluated based solely on clinical and laboratory findings. Third, the diagnostic performance of SWE elastography may be affected in patients with markedly elevated body mass index (BMI), those unable to perform adequate breath-holding, and those unable to maintain the required examination position.

Fourth, although SWE elastography is generally less affected by transducer pressure than other elastography techniques, the amount of pressure applied may still influence measurements, particularly when using a linear probe. Finally, the single-center design may limit the generalizability of our findings.

Conclusion

The findings of our study, which is one of the few studies evaluating renal allograft with linear probe SWE, indicate that linear probe SWE may contribute to the early diagnosis and treatment of chronic allograft rejection. SWE may reduce unnecessary and repeat biopsies by providing guidance in selecting renal transplant patients to be biopsied and determining the biopsy area. In conclusion, adding SWE examination to the routine check-ups of renal transplant patients may help follow up their renal functions and reduce the need for renal biopsy, which carries the risk of serious complications.

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Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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