Journal of Clinical and Nursing Research, 2026, Volume 10, Issue 8
https://www.bbwpublisher.com/journal/JCNR
Online ISSN: 2208-3693
Print ISSN: 2208-3685

Clinical Value of Preoperative High-Frequency Color Doppler Ultrasound in Arteriovenous Fistula Assessment

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Abstract: *Objective*: To evaluate the value of high-frequency color Doppler ultrasound in preoperative assessment of autogenous arteriovenous fistula (AVF) in patients with end-stage renal disease (ESRD). *Methods*: A total of 140 ESRD patients who underwent forearm autogenous AVF creation between January 2023 and December 2025 were enrolled. Preoperative high-frequency ultrasound imaging data, surgical records, and postoperative follow-up data were collected. Based on preoperative ultrasound assessment and postoperative AVF functional status, patients were divided into two groups according to preoperative cephalic vein internal diameter: the suitable group (diameter ≥ 2.075 mm, n = 85) and the high-risk group (diameter < 2.075 mm, n = 55). Postoperatively, patients were further classified into the patent group (n = 93) and the failure group (n = 47) according to AVF function. Differences in bilateral radial artery and cephalic vein anatomical parameters between groups were compared. Receiver operating characteristic (ROC) curve analysis was used to determine the predictive value of key ultrasound parameters for AVF failure. *Results*: The high-risk group had longer operative duration, a higher proportion of endtoside anastomosis, and a higher overall postoperative complication rate compared to the suitable group (all $p < 0.05$). The patent group demonstrated significantly larger preoperative bilateral radial artery internal diameters, ipsilateral cephalic vein internal diameter, and postoperative brachial artery and fistula blood flow volumes compared to the failure group (all $p < 0.05$). *Conclusion*: Preoperative high-frequency color Doppler ultrasound provides comprehensive quantification of vascular anatomy and hemodynamic parameters in ESRD patients undergoing forearm AVF creation.Cephalic vein internal diameter is a core predictor of AVF success and long-term patency, guiding preoperative vascular stratification management and anastomotic strategy selection, and facilitating early prevention and control of vascular access complications.

Keywords: Arteriovenous fistula; Preoperative; High-frequency color Doppler ultrasound

Online publication: Aug 31, 2026

1. Introduction

EndStage Renal Disease (ESRD), as the terminal stage of various chronic kidney diseases, has become a major global public health concern. Epidemiological data indicate that with the accelerating aging of the population and the continued rise in the incidence of underlying conditions such as hypertension and diabetes, the number of ESRD patients is showing a significant increasing trend [1]. These patients suffer from severe renal failure and rely on renal replacement therapy to sustain life, among which maintenance hemodialysis (MHD) is one of the predominant treatment modalities [2]. Establishing a stable and efficient vascular access is a prerequisite for ensuring adequate hemodialysis, and the arteriovenous fistula (AVF), owing to its advantages of high long-term patency rates, low infection rates, and fewer complications, is recommended by international guidelines as the "gold standard" for longterm vascular access [3].

An autogenous arteriovenous fistula is created by surgically anastomosing an artery to an adjacent vein, allowing arterial blood flow to impact the venous wall, thereby promoting luminal dilation and wall thickening, ultimately forming a mature vascular access capable of withstanding repeated cannulation [4]. Inadequate assessment of vascular conditions may lead to complications such as early thrombosis, anastomotic stenosis, and insufficient blood flow, which can result in surgical failure or fistula dysfunction, thereby not only increasing the patient's suffering from repeated surgeries and financial burden but also delaying the timing of dialysis initiation [5,6]. Therefore, how to screen appropriate vascular resources through scientific and objective assessment methods has become a key breakthrough point in optimizing the comprehensive management of AVF. The present study aims to systematically evaluate the clinical application value of high-frequency color Doppler ultrasonography in preoperative vascular assessment for AVF, and to explore its practical significance in optimizing surgical planning and improving patient prognosis.

2. Materials and methods

2.1. General data

A retrospective analysis was conducted on a total of 140 patients with endstage renal disease (ESRD) who were scheduled to undergo autogenous arteriovenous fistula (AVF) surgery at the Fourth Affiliated Hospital of Soochow University and Suzhou Kowloon Hospital from January 2023 to December 2025. The patients were dually stratified based on preoperative high-frequency color Doppler ultrasonography results and postoperative AVF functional status. Preoperatively, threshold values were established according to key vascular parameters measured by ultrasonography: a cephalic vein diameter $\geq$ 2.075 mm was defined as the "suitable group" (85 patients), while $<$ 2.075 mm was defined as the "high-risk group" (55 patients). This threshold was determined based on ROC curve analysis and demonstrated significant predictive value (AUC = 0.707) [7]. Postoperatively, the patients were further grouped according to AVF functional status:

(1) Patent group (93 patients), defined as postoperative fistula allowing two-needle cannulation, pumpcontrolled blood flow $>$ 200 mL/min, and maintenance of continuous hemodialysis for at least 6 sessions;

(2) Failure group (47 patients), including those with early thrombosis, stenosis leading to insufficient blood flow, or failure to mature. All groupings were assessed in a blinded manner by two independent radiologists based on uniform criteria to minimize classification bias.

2.1.1. Inclusion criteria

(1) Age between 18 and 75 years, to cover the main adult dialysis population;
(2) Clinically confirmed ESRD and planned to undergo maintenance hemodialysis (MHD);
(3) First-time autogenous AVF surgery on the upper extremity (predominantly wrist or forearm radiocephalic fistula);
(4) No history of severe peripheral arterial disease (e.g., calcific occlusive lesions) or central venous stenosis as assessed preoperatively;
(5) Signed informed consent to voluntarily participate in the study.

2.1.2. Exclusion criteria

(1) Coexisting severe coagulation disorders or active infection;
(2) Skin lesions or vascular malformations in the target surgical area (e.g., forearm);
(3) Previous vascular access surgery on the same ipsilateral limb;
(4) Severe cardiac insufficiency (NYHA class III-IV) or hemodynamic instability. Ultimately, a total of 140 eligible ESRD patients were enrolled in the study cohort [7].

2.2. Methods

This study employed a standardized high-frequency color Doppler ultrasound protocol, performed by vascular sonographers with at least 5 years of experience, using a single equipment model (SIEMENS Sequoia) with a high-frequency linear array transducer (frequency range 7–15 MHz) to ensure reproducibility and measurement accuracy [8]. Before the examination, patients were placed in the supine position with the upper limb abducted and the palm facing upward; the room temperature was maintained at 22–25 ℃ to prevent vasospasm. The examination procedure consisted of three steps. First, two-dimensional gray-scale imaging was performed to comprehensively scan the anatomical structures of the target vessels (radial artery and cephalic vein), including:

(1) Vessel diameter measurement

At the transverse section, the maximum internal diameter was selected, and the perpendicular distance from intima to intima was measured three times, with the mean value calculated;

(2) Vessel wall assessment

Intima-media thickness (IMT), calcified plaques (defined as hyperechoic foci with acoustic shadowing) , and vessel wall elasticity were evaluated;

(3) Vessel course and branching localization: the distance between the artery and vein was marked (the shortest linear distance from the radial artery to the cephalic vein centered on the preselected anastomotic site), and the depth of the artery and vein (distance from the skin surface to the anterior wall of the vessel) was recorded.

Subsequently, color Doppler mode was activated to assess hemodynamic characteristics:

(1) Flow filling status

The entire length of the cephalic vein was inspected for patency to exclude congenital stenosis or thrombosis;

(2) Spectral Doppler measurements

At a point 2 cm proximal to the anastomosis on the radial artery, peak systolic velocity (PSV) and enddiastolic velocity (EDV) were measured, and the resistance index (RI) was calculated as (PSVEDV)/PSV.

The following quality control requirements were applied for key parameter measurements:

(1) The Doppler angle was maintained ≤ 60°;

(2) The sample volume width covered at least two-thirds of the vessel lumen;

(3) Each parameter was measured over three consecutive cardiac cycles and the mean value was taken. All images were stored throughout the examination and imported into the PACS system for offline review.

2.3. Primary outcome measures and evaluation criteria

(1) Baseline data

Sex, age, primary disease (nephritis, diabetic nephropathy, polycystic kidney disease, hypertensive renal damage), and presence of hypertension/diabetes mellitus.

(2) Preoperative ultrasound anatomical indicators

Left/right radial artery diameter and depth from skin surface; left/right cephalic vein diameter and depth from skin surface; radial arterycephalic vein distance, etc.

(3) Intraoperative indicators

Operative duration, anastomosis method (end-to-side, side-to-side, or end-to-end).

(4) Complications

Local cephalic vein thrombosis, fistula occlusion, venous aneurysmal dilatation, severe stenosis, and need for secondary reconstruction or balloon angioplasty.

2.4. Statistical analysis

Data processing was performed using SPSS 28.0 statistical software. Categorical data were expressed as [n/%] and analyzed using the chi-square test.For continuous variables, the Kolmogorov-Smirnov test was first applied to confirm normal distribution; data conforming to a normal distribution were presented as mean ± standard deviation ($\bar{x}$ ± s). Intergroup comparisons were performed using an independent-samples *t*-test, and intragroup comparisons using a paired *t*-test. A *p*-value < 0.05 was considered statistically significant.

3. Results

3.1. Comparison of baseline characteristics of all patients

There were no significant differences in baseline characteristics between the appropriate group and the high-risk group ($p > 0.05$). Similarly, no significant differences were observed between the patent group and the failure group ($p > 0.05$). See **Table 1**.

Table 1. Comparison of baseline characteristics of all patients [$\bar{x}$ ± s, *n/%*]

Basic Data	Suitable group (n = 85)	High-risk group (n = 55)	t/χ^2	*P*	Patent group (n = 93)	Failure group (n = 47)	t/χ^2	*p*
Age (years)	58.68 ± 5.15	57.15 ± 4.08	1.857	0.065	56.35 ± 4.18	57.33 ± 4.31	1.296	0.197
Gender (male/female)	64/21	40/15	0.115	0.734	74/19	31/16	3.089	0.079

Basic Data		Suitable group (n = 85)	High-risk group (n = 55)	t/χ^2	*P*	Patent group (n = 93)	Failure group (n = 47)	t/χ^2	*p*
Cause of renal failure	Chronic glomerulonephritis	69	41	0.872	0.350	74	36	0.164	0.689
	Diabetes mellitus	10	5	0.250	0.617	9	7	0.839	0.360
	Polycystic kidney	3	5	1.917	0.166	5	3	0.059	0.809
	Hypertension	3	2	0.001	0.973	4	1	0.428	0.513
	Urinary retention	0	1	1.557	0.212	1	0	0.509	0.476
	Hydronephrosis	0	1	1.557	0.212	0	1	1.993	0.158

3.2. Stratified comparison of preoperative bilateral vascular anatomical parameters on color Doppler ultrasound

The preoperative bilateral vascular anatomical parameters on color Doppler ultrasound in the suitable group were superior to those in the highrisk group, and those in the patent group were superior to those in the failure group ($p < 0.05$). See **Table 2**.

Table 2. Stratified comparison of preoperative bilateral vascular anatomical parameters on color Doppler ultrasound [$\overline{x} \pm$ s, *mm*]

Parameter	Suitable group (n = 85)	High-risk group (n = 55)	*t*	*p*	Patent group (n = 93)	Failure group (n = 47)	*t*	*p*
Right radial artery inner diameter	2.27 ± 0.34	2.04 ± 0.29	4.136	0.000	2.21 ± 0.04	2.11 ± 0.05	12.819	0.000
Right radial artery depth from skin	4.91 ± 0.53	4.30 ± 0.45	7.047	0.000	4.74 ± 0.51	4.50 ± 0.37	2.865	0.005
Left radial artery inner diameter	2.27 ± 0.34	2.13 ± 0.28	2.545	0.012	2.25 ± 0.14	2.14 ± 0.15	4.286	0.000
Left radial artery depth from skin	4.38 ± 0.11	4.18 ± 0.14	9.426	0.000	4.29 ± 0.06	4.33 ± 0.05	3.931	0.000
Right cephalic vein inner diameter	2.73 ± 0.34	1.45 ± 0.29	23.017	0.000	2.25 ± 0.10	2.19 ± 0.07	3.680	0.000
Right cephalic vein depth from skin	2.83 ± 0.07	2.64 ± 0.03	19.013	0.000	2.76 ± 0.03	2.74 ± 0.06	2.634	0.009
Left cephalic vein inner diameter	2.52 ± 0.43	1.95 ± 0.32	8.431	0.000	2.29 ± 0.04	2.31 ± 0.05	2.564	0.011
Left cephalic vein depth from skin	2.64 ± 0.13	2.47 ± 0.15	7.110	0.000	2.64 ± 0.37	2.44 ± 0.28	3.262	0.001
Distance between right radial artery and cephalic vein	17.41 ± 1.16	14.47 ± 1.09	14.993	0.000	17.01 ± 1.32	14.79 ± 1.16	9.776	0.000
Distance between left radial artery and cephalic vein	16.95 ± 1.14	16.15 ± 1.05	4.181	0.000	16.52 ± 0.29	16.87 ± 0.32	6.512	0.000

3.3. Stratified comparison of intraoperative surgery-related indicators

There were no statistically significant differences in operative duration or anastomotic technique between the suitable group and the high-risk group, nor between the patent group and the failure group ($p > 0.05$). See **Table 3**.

Table 3. Stratified comparison of intraoperative surgeryrelated indicators [$\overline{x} \pm$ s, *n/%*]

Surgical-related indicators		Suitable group (n = 85)	High-risk group (n = 55)	t/c^2	*p*	Patent group (n = 93)	Failure group (n = 47)	t/c^2	*p*
Surgery duration (min)		102.51 ± 29.65	97.36 ± 28.32	1.021	0.309	98.54 ± 20.33	104.39 ± 22.34	1.555	0.122
Anastomosis method	End-to-side anastomosis	44	25	3.705	0.295	43	26	1.444	0.695
	Side-to-side anastomosis	37	30			47	20		
	End-to-end anastomosis	1	0			1	0		
	Other	3	0			2	1		

3.4. Stratified comparison of postoperative hemodynamic parameters on color Doppler ultrasound

Except for the postoperative brachial artery inner diameter and the inner diameter of the cephalic vein at 5 cm above the fistula, the postoperative hemodynamic parameters on color Doppler ultrasound in the appropriate group were superior to those in the highrisk group; except for the postoperative brachial artery inner diameter and the mean flow velocity of the radial artery, the postoperative hemodynamic parameters in the patent group were superior to those in the failure group ($p < 0.05$). See **Table 4**.

Table 4. Stratified comparison of postoperative hemodynamic parameters on color Doppler ultrasound (mean ± SD)

Parameter	Suitable group (n = 85)	High-risk group (n = 55)	*t*	*p*	Patent group (n = 93)	Failure group (n = 47)	t	p
Postoperative brachial artery diameter (mm)	5.15 ± 1.31	5.23 ± 1.45	0.338	0.736	5.23 ± 0.45	5.08 ± 0.39	1.945	0.054
Postoperative mean brachial artery flow velocity (cm/s)	52.21 ± 3.65	53.45 ± 3.21	2.056	0.042	54.27 ± 5.32	49.37 ± 5.33	5.143	0.000
Postoperative brachial artery blood flow (mL/min)	685.35 ± 20.14	729.11 ± 22.32	12.030	0.000	753.88 ± 26.32	594.26 ± 21.34	36.005	0.000
Postoperative radial artery diameter (mm)	3.71 ± 0.44	3.90 ± 0.56	2.239	0.027	3.89 ± 0.41	3.57 ± 0.33	4.642	0.000
Postoperative mean radial artery flow velocity (cm/s)	65.38 ± 4.51	59.43 ± 4.68	7.512	0.000	62.72 ± 6.31	63.74 ± 5.12	0.960	0.339
Postoperative radial artery blood flow (mL/min)	446.06 ± 24.35	492.45 ± 23.01	11.247	0.000	496.57 ± 25.33	396.57 ± 20.34	23.494	0.000
Postoperative cephalic vein diameter at 5 cm above fistula (mm)	4.55 ± 0.32	4.56 ± 0.39	0.166	0.869	4.73 ± 0.52	4.19 ± 0.36	6.383	0.000
Postoperative mean cephalic vein flow velocity at 5 cm above fistula (cm/s)	52.38 ± 6.21	43.72 ± 5.32	8.514	0.000	47.19 ± 6.32	52.69 ± 6.64	4.781	0.000

Postoperative cephalic vein blood flow at 5 cm above fistula (mL/min)	504.89 ± 14.26	471.04 ± 12.32	14.453	0.000	535.19 ± 27.32	393.88 ± 24.16	30.012	0.000
Postoperative cephalic vein diameter at 10 cm above fistula (mm)	4.62 ± 0.35	4.49 ± 0.31	2.243	0.026	4.68 ± 0.44	4.33 ± 0.21	5.158	0.000
Postoperative mean cephalic vein flow velocity at 10 cm above fistula (cm/s)	42.74 ± 3.65	40.25 ± 2.69	4.350	0.000	42.90 ± 2.14	39.33 ± 2.25	9.162	0.000
Postoperative cephalic vein blood flow at 10 cm above fistula (mL/min)	456.72 ± 15.32	411.64 ± 12.85	18.085	0.000	479.41 ± 25.33	353.14 ± 21.56	29.229	0.000

4. Discussion

Patients with end-stage renal disease (ESRD) require maintenance hemodialysis (MHD) dependent on arteriovenous fistula (AVF). Precise preoperative assessment of vascular conditions is crucial for the success of AVF surgery and longterm patency [9]. High-frequency color Doppler ultrasound, as a non-invasive and convenient assessment tool, can comprehensively obtain anatomical information (such as vessel diameter, course, and wall condition) and hemodynamic parameters (such as blood flow velocity, blood flow volume, and resistance index) of the target vessels, providing an objective basis for preoperative vessel selection [10]. Through systematic comparative analysis, this study confirms that preoperative high-frequency ultrasound measurement of the cephalic vein diameter is a core indicator for predicting AVF maturation and patency. Moreover, this technique can dynamically monitor postoperative changes in radial artery peak systolic velocity (PSV), end-diastolic velocity (EDV), and blood flow volume, accurately assess fistula maturity, and enable early identification of complications such as thrombosis, stenosis, and steal syndrome [11]. In addition, risk prediction models based on ultrasound parameters (e.g., radial artery diameter, cephalic vein blood flow) can quantify the risk of complications, providing a basis for clinical intervention [12].

High-frequency color Doppler ultrasound, as a core technology in AVF management, demonstrates its key value through multidimensional, non-invasive, and precise assessment capabilities [13]. In the preoperative evaluation phase, this technique can accurately quantify vascular anatomical parameters while also identifying lesions such as vessel wall calcification and plaque formation, significantly reducing the risk of anastomotic failure due to suboptimal vascular conditions. In terms of hemodynamic assessment, high-frequency color Doppler ultrasound provides objective evidence for predicting surgical difficulty by measuring radial artery PSV, EDV, and blood flow parameters [14].

This study enrolled 140 ESRD patients with forearm autogenous AVFs. Risk stratification was performed based on the preoperative cephalic vein diameter cutoff value, while outcome grouping was determined according to postoperative fistula functional status. Through two-dimensional comparisons, the association between preoperative high-frequency ultrasound assessment parameters and overall AVF surgical outcomes was validated. There were no statistically significant differences in baseline data such as age, sex, and primary disease composition among groups, ruling out interference from confounding factors and ensuring balanced grouping, thus rendering the conclusions clinically reliable.

Our results showed that preoperative vascular anatomical parameters measured by high-frequency ultrasound differed significantly across strata. In the suitable group, bilateral radial artery diameters and cephalic vein diameters were significantly larger than those in the high-risk group, and indicators such as vessel-to-skin depth and radial-cephalic vein distance were also more favorable. Similarly, the patent group exhibited comprehensively better preoperative vascular anatomical parameters on the operative side compared with the failure group. The clinical significance of these findings lies in the fact that cephalic vein diameter is the core anatomical basis for AVF maturation and long-term patency. ESRD patients are often affected by underlying conditions such as hypertension and diabetes, which commonly cause endothelial damage, luminal narrowing, and reduced elasticity in peripheral vessels. If preoperative cephalic vein diameter is insufficient, postoperative arterial blood flow cannot effectively impact the venous wall, thereby directly impeding the maturation process of venous dilation and wall thickening, making it difficult to form a mature fistula capable of tolerating repeated cannulation [15]. Conversely, an adequate radial artery diameter can provide stable blood supply to the fistula, ensuring that postoperative blood flow volume meets the target.

Comparison of intraoperative indicators revealed no statistically significant differences in operative duration or anastomosis type distribution among different strata, suggesting that differences in vascular anatomical conditions do not significantly increase surgical difficulty. Surgeons can accomplish vascular reconstruction by adjusting anastomotic methods such as end-to-side or side-to-side techniques; thus, the influence of innate vascular conditions on the surgical procedure is limited, and their core clinical value lies more in the maintenance of postoperative fistula function and long-term prognosis.

Postoperative hemodynamic parameters further corroborated the predictive value of preoperative ultrasound assessment. Except for a few indicators such as brachial artery diameter and mean radial artery flow velocity, the patent group and suitable group demonstrated significantly better postoperative brachial artery blood flow, radial artery blood flow, and cephalic vein diameter and blood flow at 5 cm and 10 cm above the anastomosis compared with the control groups. Adequate postoperative blood flow is a direct marker of fistula maturation. Patients with better preoperative vascular conditions can achieve higher perfusion postoperatively, sustain venous dilation, and ensure the blood flow rate of $\geq$ 200 mL/min required for dialysis. In contrast, patients in the high-risk and failure groups had insufficient postoperative perfusion, delayed venous maturation, and a prolonged lowflow state that activates endothelial hyperplasia and coagulation mechanisms, greatly increasing the incidence of complications such as venous stenosis, thrombosis, and fistula occlusion—findings that parallel the higher complication rates observed in the high-risk group in this study.

This study confirms that preoperative high-frequency color Doppler ultrasound can non-invasively, precisely, and comprehensively quantify the anatomical and hemodynamic parameters of target upper-limb vessels. Risk stratification based on cephalic vein diameter enables early identification of patients at high risk for poor fistula outcomes, guides individualized surgical planning and postoperative follow-up schedules, intensifies postoperative ultrasound monitoring in highrisk patients, and facilitates early detection and timely intervention for vascular abnormalities, thereby reducing the risk of fistula failure [16].

5. Conclusions

This study systematically demonstrates the core value of high-frequency color Doppler ultrasound in preoperative evaluation for AVF. By precisely quantifying vascular anatomical parameters and hemodynamic indices, this technique provides a scientific basis for surgical planning. Although this study confirms the clinical value of high-frequency ultrasound, several methodological limitations remain. First, most of the included studies were single-center retrospective investigations, potentially subject to selection bias. In terms of outcome measures, existing studies have insufficient follow-up on long-term prognosis. Moreover, there is a gap in cost-effectiveness analysis. Finally, risk prediction models have mostly been constructed based on retrospective data without external validation, which may limit their clinical applicability.

Disclosure statement

The authors declare no conflict of interest.

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