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*Article*

# Application of Freehand 3D Ultrasound Guidance in Percutaneous Transluminal Angioplasty for Autogenous Arteriovenous Fistula Stenosis

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## Abstract

**Objective**: Using freehand three dimensional (3D) ultrasound imaging to evaluate arteriovenous fistula stenosis. Comparing the value of freehand 3D ultrasound and Doppler ultrasound in the application of percutaneous transluminal angioplasty (PTA) treatment for stenosis of an arteriovenous fistula. **Methods**: A retrospective analysis was conducted on 34 patients with arteriovenous fistula (AVF) stenosis who were treated at the 903RD Hospital of PLA and the Kidney Center of Zhejiang Provincial People's Hospital from August 2021 to August 2022. Based on the different types of surgical assistance, the patients were divided into two groups: the Doppler ultrasound group (Group A, n = 17) and the freehand 3D ultrasound imaging group (Group B, n = 17). Freehand 3D ultrasound and Doppler ultrasound were used to assess the narrowing of arteriovenous fistulas, and images and relevant data were collected before and after the PTA procedure. The differences in the time of puncture and sheath placement, guidewire insertion time, the duration of the procedure, complications, and methods to measure stenosis were compared between the two groups of patients, as well as the technical success rate, the initial patency rate, and the primary patency rates at 1, 3, 6 and 9 months post-surgery. This study discusses the clinical efficacy of using these two types of ultrasound to assist in the PTA treatment of arteriovenous fistula stenosis. **Results**: The differences in baseline demographics between the conventional ultrasound group (Group A) and the 3D ultrasound group (Group B) were not statistically significant ($p > 0.05$). The intraoperative guidewire insertion time (4.647 $\pm$ 1.347 min *vs*. 2.824 $\pm$ 0.326 min) and the operating times (75.941 $\pm$ 7.557 min *vs*. 59.824 $\pm$ 8.175 min) between the two groups were statistically significant (t = 2.788, 3.069, $p < 0.01$). The technical success rates for the two groups were 94.1% *vs*. 100%, not statistically significant (t = 1.03, $p = 0.31$). The first-time patency rates were 88.2% *vs*. 94.1%, with no statistically significant difference (t = 0.366, $p = 0.545$). No complications occurred in Group A, while one case of hematoma occurred postoperatively in Group B, with an incidence of 5.9% (1/17), which was not statistically significant (t = 1.03, $p > 0.05$). Comparing the primary patency rates at 1, 3, 6 and 9 months post-surgery between Groups A and B, there were no statistically significant differences ($p > 0.05$). However, the patency rates at different time points for Group B were consistently higher than Group A (94.1%, 82.4%, 82.4%, 82.4% *vs*. 88.2%, 82.4%, 76.5%, 76.5%). **Conclusion**: Freehand 3D ultrasound imaging can provide more intuitive, high-resolution, and high-definition three-dimensional images, clearly defining the lesion site and vascular structures. Its accuracy in assessing complications of arteriovenous fistulas is similar to that with conventional ultrasound. When used as an adjunct to PTA treatment, its efficacy is equivalent. It can significantly reduce guidewire insertion time and operation time, decrease postoperative recovery time, and alleviate the patients' concerns regarding surgical risks. It can be considered a new method for diagnosing, treating, and patients with AVF stenosis.

## Keywords

freehand 3D ultrasound imaging; Doppler ultrasound; autogenous arteriovenous fistula; percutaneous transluminal angioplasty; hemodialysis; stenosis; patency rate

## Introduction

Functional vascular fistulas are essential for effective hemodialysis. Autogenous arteriovenous fistulas (AVF) account for over 80% of dialysis access [1]. However, only 60% of patients maintain an open vascular access one year after an AVF procedure [2]. In addition, about 20%–25% of long-term dialysis patients experience AVF stenosis [3–5]. This is mainly due to changes in hemodynamics, repetitive vascular puncturing during dialysis, infection, genetic predispositions, and uremia, which leads to neointimal hy-

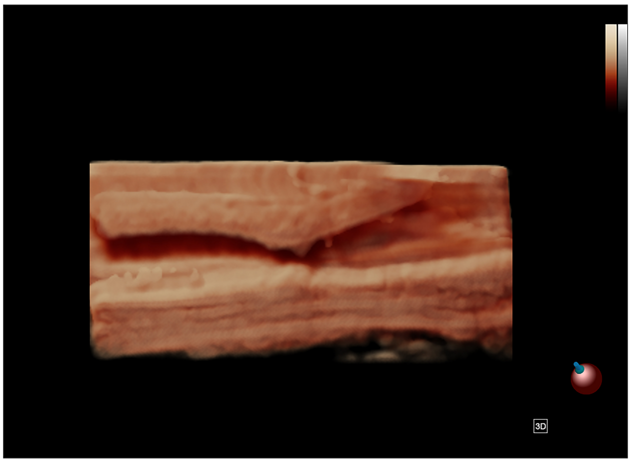

**Fig. 1. To show the narrowing of the arteriovenous fistulas (AVF) by freehand 3D ultrasound imaging.** 3D, three dimensional.

perplasia [6,7]. The Kidney Disease Outcomes Quality Initiative (KDOQI), and the guidelines of the European Society for Vascular Surgery (ESVS) unanimously recommend percutaneous transluminal angioplasty (PTA) as the primary treatment for AVF stenosis [1,8]. PTA is generally performed under the guidance of ultrasound or during digital subtraction angiography (DSA). Different imaging techniques have their respective limitations and advantages. With advances in equipment technology, information collection, image processing, and computational algorithms, three-dimensional ultrasound imaging technology has made significant progress. Among these techniques, freehand three-dimensional ultrasound imaging is a novel, portable, and user-friendly imaging technology [9], capable of providing a three-dimensional structural view of blood vessels and replicating the actual pathological conditions. This technology allows for rotation, translation, and scaling of reconstructed images, offering various perspectives for observing lesions (Fig. 1). To date, no reports have used three-dimensional ultrasound to assist in the PTA treatment of AVF stenosis.

This study aims to explore the clinical application and value of three-dimensional ultrasound imaging technology in the treatment of AVF stenosis, with the intention of enhancing the accuracy of diagnosing AVF stenosis and providing a reference for the monitoring and selection of surgical strategies for peripheral vascular access in clinical practice.

## Methods

### *Case Information*

This study collected 34 cases of patients with arteriovenous fistula (AVF) stenosis who met the inclusion and exclusion criteria from August 2021 to August 2022. The primary clinical presentation was AVF stenosis caused by various mechanisms leading to insufficient flow to support normal dialysis, and treated with percutaneous transluminal angioplasty (PTA) to relieve the stenosis.

### *Inclusion Criteria*

(1) Patients over 18 years old with a definitive diagnosis of end-stage renal disease (ESRD), who will receive or have received kidney replacement therapy. (2) The diameter of the stenosis site in the arteriovenous fistula is less than 50% of the surrounding normal blood vessels, accompanied by the following conditions [1]: fistula flow volume $<$500 mL/min; blood flow volume insufficient for dialysis needs (200 mL/min); increased dialysis venous pressure; difficulty in puncturing; decreased adequacy of dialysis; abnormal physical signs of AVF (including palpable pulsation, difficulty in compressing vessels; enhanced palpable thrill at stenosis, with the thrill becoming intermittent or disappearing in severe cases; high-pitched murmur audible on auscultation, especially during systole). (3) The ratio of peak systolic velocity (PSV) at the stenosis site to that in the normal venous segment 2 cm above the stenosis site (peak systolic velocity ratio, PSVR) $\geq$2.5 [10].

### *Exclusion Criteria*

(1) Patients with an infected fistula; (2) Patients with arterial stenosis or central venous stenosis; (3) Patients with severe calcification or continuous calcification of the fistula; (4) Patients known to be allergic to heparin and/or lidocaine; (5) Patients with a life expectancy of less than one year.

### *Classification of AVF Stenosis*

Type I: Stenosis within 5 cm of the anastomosis and outflow tract (vein) of the fistula;

Type II: Stenosis near the dialysis puncture site or between two puncture sites;

Type III: Stenosis at the juncture of the outflow tract and deep vessels (e.g., convergence of the cephalic vein, axillary vein);

Type IV: Stenosis of the artery supplying the fistula.

### *Study Methods*

#### Study Groups

This study consisted of 34 patients with AVF stenosis who met the inclusion and exclusion criteria from August 2021 to August 2022. The study subjects were divided into group A (conventional ultrasound) and group B (freehand three dimensional (3D) ultrasound imaging), with 17 cases in each group. Patients and their relatives were fully informed before surgery and signed informed consent forms.

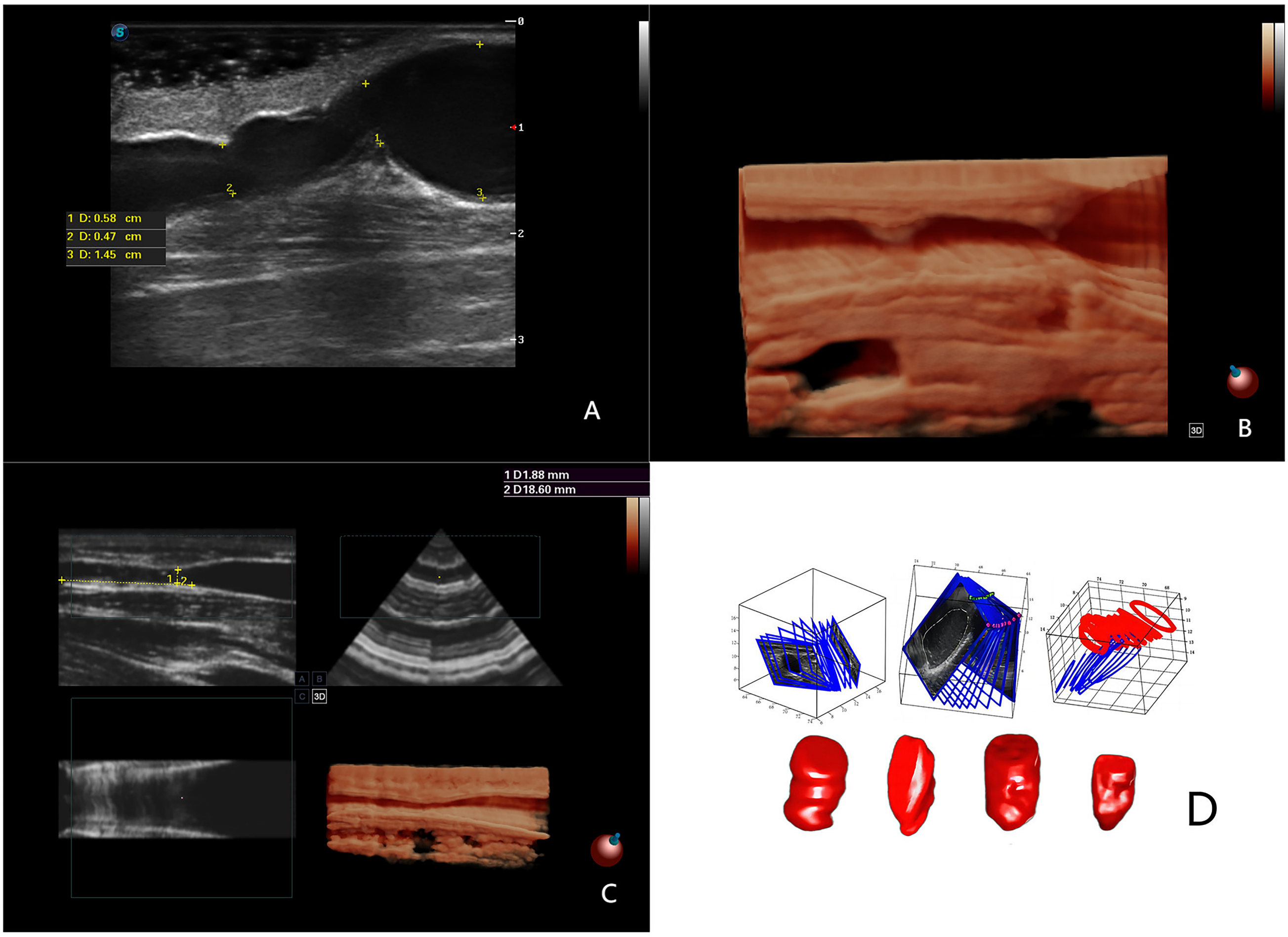


**Fig. 2. Principles of freehand 3D ultrasound imaging.** (A) The stenosis of the fistula is displayed by conventional ultrasound. (B) To return the stenosis lesions through freehand 3D ultrasound reconstruction. (C) Freehand 3D imaging Reconstruction Based on 2D Images. (D) Principles of freehand 3D ultrasound imaging. 2D, 2-dimensional.

## Operator Training and Experience

Ultrasonography is an inexpensive and safe technique to measure hemodynamics when calculating the severity of the internal fistula stenosis. However, ultrasonography relies heavily on the proficiency of the ultrasound operator. 2-dimensional (2D) and 3D ultrasound image acquisition and PTA treatment were performed by one of two specially trained and experienced nephrologists. All have obtained ultrasound qualification certification and advanced qualification of blood purification vascular access interventional technology.

## Principle of Freehand 3D Ultrasound Imaging

The operator holds a high-frequency probe and scans the target at any angle on the surface of the patient's body, without pre-setting the route, and moves as the probe moves to get a continuous two-dimensional image. Two-dimensional ultrasound images are acquired and processed by ultrasound machines into real-time 3D images. The add-on software generates the reconstructed AVF stereo images in seconds. A high-frequency linear array probe emits high-frequency sound waves into the body through a coupling agent. The waves are reflected by different structures within the tissues, and the reflected waves are received by the ultrasound receiver in the probe and converted into electrical signals transmitted to the signal processor. The three-dimensional coordinates of each point are calculated based on the probe position and the time delay and intensity of the reflected waves. These coordinates are integrated into a three-dimensional image using a three-dimensional interpolation algorithm. The signal processor can also perform filtering, gain adjustment, and rotation, to improve the clarity and contrast of the image and allow observation and measurement from different directions (Fig. 2) [9].

## Surgical Method

Preoperative. Patients are in the sitting or supine position with arm abduction. Images were obtained in the vascular cross-section using ultrasound B mode, containing separate images of the inflow, outflow vessels, anastomotic port, stenosis, and the brachial artery. The diameter of stenosis,

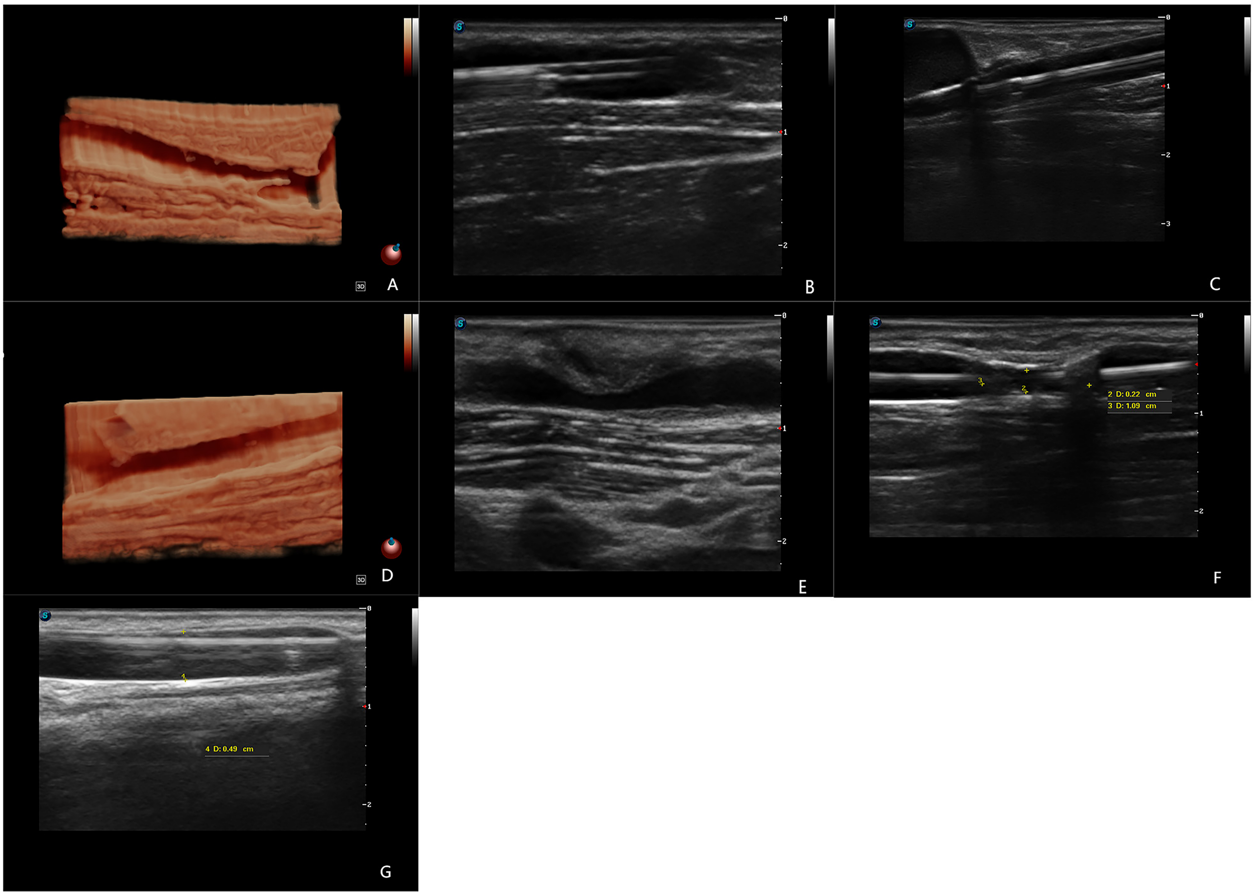


**Fig. 3. The whole process of PTA in relieving AVF stenosis was illustrated by 2D and 3D ultrasound images.** (A) Define the stenosis of the fistula through freehand 3D ultrasound imaging before surgery. (B) Guided by ultrasound, perform puncture and sheath placement for arteriovenous fistula. (C) Dilation of the balloon to relieve stenosis of AVF. (D) Observation of the effect using freehand 3D reconstruction technology after surgery. (E) Endovascular hyperplasia resulting in stenosis of the AVF tract. (F) Shows significant restriction during balloon dilation, which is called waist sign. (G) As the balloon pressure gradually increases, the waist sign is relieved.

vessel diameter of the normal segment, stenosis rate, PSVR, and brachial artery flow were measured and calculated. At least one three-dimensional ultrasound scan at the stenosis of the arteriovenous fistula was recorded for each patient. Repeat scans could be performed, if required.

Intraoperative. The patient was placed in the decubitus position, the internal fistula side arm was extended, the conventional operation area was disinfected with 0.5% povidone iodine solution (H33020943; Zhejiang Puluokangyu Pharmaceutical Co., Ltd., Dongyang, China), the ultrasound probe was covered with the coupling agent, and a sterile film sleeve was placed. The puncture site was treated with local infiltration of 1% lidocaine (H20057816, Hunan Kelun Pharmaceutical Co., Ltd.,Yueyang, China); the fistula was guided by retrograde puncture using the seldinger technique. Blood is drawn back to remove the needle core quickly, insert the guidewire, remove the puncture needle, introduce the puncture sheath along the guidewire, remove the guidewire and sheath needle, inject 2000 IU of ordinary heparin through the sheath, and add 3 mL of saline to fully heparinize the vascular sheath. A hydrophilic controllable guidewire (Boston Scientific Way, Marlborough, MA 01752, USA), 0.035 in, is inserted under ultrasound guidance through the vascular sheath. Under continuous ultrasound guidance, the posterior section of the wire was twisted to make the wire pass through the stenosis and the anastomosis of the arteriovenous fistula, and the wire head was left in the radial artery. The puncture time and guide wire passage time were recorded. A high pressure balloon catheter was introduced along the guide wire. After the balloon catheter was placed at the stenosis site, the vascular diameter was measured by conventional ultrasound, the blood flow was observed by Doppler ultrasound, and the stenosis was again confirmed from multiple angles. A saline filling pressure pump device was connected to the balloon dilatation catheter. The following maneuvers were then performed: hold the trigger, release the piston, rotate the piston handle clockwise, gradually pressure the pressure pump until the balloon disappears (at the maximum)

**Table 1. Comparison of baseline data between groups A and B (n = 34).**

| | Group A (n = 17) | Group B (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Age (year) | 63.235 ± 5.245 | 61.824 ± 6.199 | 0.368 | 0.715 |
| Gender | - | - | 0.654 | 0.419 |
| Male (%) | 12 (70.6) | 14 (82.4) | - | - |
| Female (%) | 5 (29.4) | 3 (17.6) | - | - |
| Basic disease | - | - | 3.294 | 0.51 |
| Glomerular nephritis (%) | 7 (41.2) | 4 (23.5) | - | - |
| Diabetes (%) | 5 (29.4) | 9 (52.9) | - | - |
| Hypertension (%) | 3 (17.6) | 1 (5.9) | - | - |
| Polycystic kidney (%) | 1 (5.9) | 1 (5.9) | - | - |
| Transplant kidney failure (%) | 1 (5.9) | 2 (11.8) | - | - |
| History of hemodialysis (month) | 49.529 ± 21.444 | 28.562 ± 22.176 | 1.445 | 0.158 |

**Table 2. Comparison of basic data of AVF between groups A and B.**

| | Group A (n = 17) | Group B (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Type of fistula | - | - | - | <0.001 |
| AVF (%) | 17 (100) | 17 (100) | - | - |
| Location of anastomosis | - | - | - | <0.001 |
| End-to-side anastomosis (%) | 17 (100) | 17 (100) | - | - |
| The site of AVF | - | - | 4.154 | 0.386 |
| Left forearm (%) | 14 (82.4) | 12 (70.6) | - | - |
| Left upper arm (%) | 1 (5.9) | 0 (0) | - | - |
| Right forearm (%) | 2 (11.8) | 2 (11.8) | - | - |
| Left forearm wrist (%) | 0 (0) | 2 (11.8) | - | - |
| Middle left forearm (%) | 0 (0) | 1 (5.9) | - | - |
| Duration of use (month) | 42.118 ± 21.456 | 22.25 ± 22.22 | 1.367 | 0.181 |
| Time of PTA treatment | 0.529 ± 0.368 | 0.25 ± 0.238 | 1.332 | 0.192 |
| Type of stenosis | - | - | 0.654 | 0.419 |
| Type I (%) | 14 (82.4) | 12 (70.6) | - | - |
| Type II (%) | 3 (17.6) | 5 (29.4) | - | - |
| Type III (%) | 0 (0) | 0 (0) | - | - |
| Type IV (%) | 0 (0) | 0 (0) | - | - |

PTA, percutaneous transluminal angioplasty.

to maintain the pressure for one minute; press the trigger to release the pressure quickly, pull the piston handle back, repeat the operation once after a 1 minute interval if there is still residual stenosis. The process of dilating the narrowed blood vessel occurs from the proximal to the distal end, focusing on the stenosis, and eliminating the stenosis as much as possible. During the expansion process, ultrasound was used to monitor the vessels in real time. After a successful dilatation, the color of blood flow changed from gentle monochrome to alternating red and blue turbulence by Doppler ultrasound, and the residual stenosis at the lumen was <30%. If bleeding occurs after dilation due to a tear in the lumen, balloon inflation to 6–8 atm pressure was used to obtain hemostasis. Ultrasound images were retained during the operation. After successful dilation, the balloon catheter and traction guidewire were removed, and following confirmation that there were no complications, the vascular sheath was removed, and a purse-string suture was placed or the puncture site was compressed for 15 minutes.

Postoperative. Patients received two tablets of Papaverine HCl (H63020199, Qinghai Pharmaceutical Factory Co., Ltd., Xining,China) orally twice daily to prevent thrombosis in the surgical area. The images were retained by ultrasound B mode, to measure the brachial artery flow and vessel diameter, and calculate the rate of stenosis. Freehand 3D images were generated from the retained images to determine the degree of stenosis and the occurrence of any complications (Fig. 3).

## *Observation Indicators*

### Clinical Data Collection

General patient information included age, gender, primary disease, duration of hemodialysis, method of fistula anastomosis, location of fistula anastomosis, type of fistula stenosis, duration of fistula use, and the number of PTA procedures.

**Table 3. Comparison of measurement data between group A and B.**

| | Group A (n = 17) | Group B (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Diameter of AVF stenosis (mm) | 2.015 ± 0.27 | 1.765 ± 0.196 | 1.589 | 0.122 |
| Length of AVF stenosis (cm) | 1.746 ± 0.436 | 1.538 ± 0.724 | 0.523 | 0.605 |
| Stenosis rate (%) | 59.859 ± 4.377 | 61.029 ± 3.81 | –0.427 | 0.672 |
| Brachial artery flow rate (mL/min) | 393.059 ± 85.513 | 358.5 ± 48.508 | 0.745 | 0.462 |
| PSVR | 3.053 ± 0.335 | 3.241 ± 0.624 | –0.562 | 0.578 |

### PTA-Related Data Collection

Data included ultrasound images, diameter at the stenosis, diameter of the normal vessel segment, stenosis rate, PSVR, brachial artery flow; puncture time, guidewire passage time, operation duration, and surgical complications.

### Follow-Up Data Collection

Data included technical success rate, first-time patency rate, primary patency rates at 1, 3, 6, and 9 months post-surgery (Where technical success meets the PTA success criteria; first-time patency refers to completing an effective and adequate hemodialysis treatment post-surgery, with dialysis blood flow >200 mL/min; primary patency is defined as maintaining an open vascular pathway until the need for further intervention).

### *Statistical Methods*

SPSS 26.0 statistical software (IBM Corp., Armonk, NY, USA) was used. The measurement data conforming to normal distribution were described as mean ± standard deviation ($\bar{x}$ ± s), and the *t*-test was used for comparison between the two groups. Count data were expressed in numbers (n) and percentages (%), and the chi-square test ($\chi^2$) was used for comparison between groups. Paired *t*-tests (paired-*t*) were used for preoperative and postoperative comparisons within the same group of patients, and a *p*-value $< 0.05$ was considered statistically significant.

## Results

### *Comparison of Baseline Data Between Groups A and B*

There was no significant statistical difference when comparing age, gender, history of base disease, history of hemodialysis, type of fistula, method and location of the anastomosis, duration of use, type of stenosis, history of PTA treatment, diameter of AVF stenosis, length, stenosis rate, and brachial artery flow rate, and PSVR between the two groups of patients ($p > 0.05$) (Tables 1,2,3).

### *Intraoperative Indicators: Comparison Between Groups A and B*

No significant statistical difference was found between the two groups in terms of time for puncture and sheath placement, and the number of balloons used during surgery ($p > 0.05$). However, differences in guidewire passage time (4.647 ± 1.347 min *vs.* 2.824 ± 0.326 min, t = 2.788) and total operation time (75.941 ± 7.557 min *vs.* 59.824 ± 8.175 min, t = 3.069) were statistically significant ($p < 0.01$) (Table 4).

### *Preoperative and Postoperative Data Comparison of the Freehand 3D Ultrasound Group*

Comparisons of the diameter of stenosis, stenosis rate, brachial artery flow, and PSVR before and after PTA treatment in the 3D ultrasound group showed statistically significant differences ($p < 0.001$) (Table 5).

### *Comparison of Technical Success Rate, First-Time Patency Rate, and Incidence of Surgery-Related Complications Between Groups A and B*

In group A, one patient experienced a surgical failure post-PTA due to the % stenosis (47.9%) and brachial artery flow (386 mL/min) not meeting standards, while the remaining 16 cases in group A and all 17 cases in group B had the "waist sign" resolved (Fig. 3G), with enhanced blood flow signals indicating successful surgery. The technical success rate was 94.1% *vs.* 100% between groups A and B, with no significant difference (t = 1.03, $p > 0.05$). No surgery-related complications occurred in the 17 patients with AVF stenosis in group A, while one case of postoperative hematoma leading to thrombosis and fistula occlusion occurred in group B. The fistula became patent after vascular reconstruction. There was no significant statistical difference in the incidence of surgical complications between the two groups ($p > 0.05$) (see Table 6).

### *Comparison of Primary Patency Rates at 1, 3, 6, and 9 Months Post-Surgery between Groups A and B*

The first-time patency rate and the primary patency rates at 1, 3, 6, and 9 months post-surgery were followed for both groups. The first-time patency rate was 88.2% (15/17) in group A, with one surgical failure and one case of elasticity recoil causing dialysis failure on the second day

**Table 4. Comparison of intraoperative related indicators between group A and B.**

| | Group A (n = 17) | Group B (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Puncture time (min) | 1.706 ± 0.242 | 1.765 ± 0.387 | –0.273 | 0.786 |
| Guidewire passage time (min) | 4.647 ± 1.347 | 2.824 ± 0.326 | 2.788 | 0.009 |
| Operation duration (min) | 75.941 ± 7.557 | 59.824 ± 8.175 | 3.069 | 0.004 |
| The number of balloon | 1.235 ± 0.225 | 1.176 ± 0.202 | 0.413 | 0.683 |

**Table 5. Comparison of measurement data before and after PTA treatment in group B (*n = 17*).**

| | Preoperative (n = 17) | Postoperative (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Diameter of AVF stenosis (mm) | 1.765 ± 0.196 | 3.646 ± 0.266 | –15.59 | <0.001 |
| Stenosis rate (%) | 61.029 ± 3.81 | 21.135 ± 2.746 | 18.226 | <0.001 |
| Brachial artery flow rate (mL/min) | 358.5 ± 48.508 | 767.912 ± 84.589 | –9.497 | <0.001 |
| PSVR | 3.241 ± 0.624 | 1.437 ± 0.109 | 5.838 | <0.001 |

PSVR, peak systolic velocity ratio.

post-surgery. The first-time patency rate in group B was 94.1% (16/17), with one case of postoperative hematoma compressing the fistula leading to AVF embolism, which was resolved after AVF reconstruction and thrombectomy. There was no significant difference when comparing both groups (t = 0.366, $p$ = 0.545). The primary patency rates at 1, 3, 6, and 9 months post-surgery were 94.1%, 82.4%, 82.4%, and 82.4% for the 3D ultrasound group, compared to 88.2%, 82.4%, 76.5%, and 76.5% for the Doppler ultrasound group. Despite higher patency rates at each time point for the 3D ultrasound group, the difference was not statistically significant ($p > 0.05$) (see Table 7).

### *Follow-up Data Collection*

Technical success rate, first-time patency rate, primary patency rates at 1, 3, 6, and 9 months post-surgery were determined for each group. Technical success was measured by PTA success criteria; first-time patency was defined as completing an effective and adequate hemodialysis treatment post-surgery, with dialysis blood flow >200 mL/min; primary patency was defined as an open vascular anastomosis.

## Discussion

Maximal protection of vascular access is essential for hemodialysis patients. When treating arteriovenous fistula stenosis, the ultimate goal of PTA is not only to expand the stenosis, but also to prolong the postoperative patency time as long as possible. Therefore, a precise assessment of the stenosis before the interventional surgery is essential. Ultrasound is not only easy to operate, is safe, inexpensive, and avoids the risk of radiation, but can also directly measure blood flow. During PTA surgery, ultrasound can show the position of the guidewire and balloon in real time to determine is relationship to the blood vessels. Cho *et al.* [11] found that the success rate of PTA under ultrasound guidance was 96.2% (51/53). In this study, the technical success rate of ordinary ultrasound-guided PTA treatment was 94.1% (16/17), which is consistent with the results of previous studies and demonstrates that ultrasound-guided PTA is highly effective. Our study found that the postoperative vascular murmur was increased in AVF stenosis; and that the diameter, brachial artery flow, stenosis rate and PSRV improved ($p < 0.001$). The technical success rate of the freehand 3D ultrasound group reached 100%, and although the difference was not statistically significant compared with the conventional ultrasound group (t = 1.03, $p > 0.05$), the success rate was significantly higher. In terms of complications, there was no significant difference between the two groups. Our study also found that in the three-dimensional ultrasound group, the guidewire passage time and total surgical time were significantly better than the conventional ultrasound group. Relying on free-arm three-dimensional ultrasound imaging can provide more intuitive, high-resolution and high-definition three-dimensional stereo images, which can accurately demonstrate the morphology and stenosis of blood vessels. It is not only helpful to accurately locate and handle the diseased area during the operation, improve the accuracy and success rate of the operation, reduce the occurrence of complications, but also significantly increase the rate of the guide wire passage through the narrow segment, shorten the total operation time, reduce the postoperative rehabilitation time and relieve the psychological burden of patients concerning the risk of surgery. From the patient's perspective, three-dimensional ultrasound can provide more intuitive and powerful images evidence to inform the patient of their condition. Patients' understanding of their own condition and their satisfaction with the surgical outcome are also greatly improved.

In terms of the evaluation of postoperative efficacy, guidelines [1] requires that 50% of access should still be available 6 months after surgery. A study published by Wakabayashi *et al.* [12] on 4414 patients with AVF stenosis treated with ultrasound-guided PTA found an early postoperative success rate of 97.1% (4288/4414), with a primary

**Table 6. Comparison of technical success rates, first-pass success rates, and incidence of surgical complications in groups A and B.**

| | Group A (n = 17) | Group B (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Technical success rate (%) | 16 (94.1) | 17 (100) | 1.03 | 0.31 |
| First-time patency rate (%) | 15 (88.2) | 16 (94.1) | 0.366 | 0.545 |
| Surgical complications | - | - | 1.03 | 0.31 |
| Complications (%) | 17 (100) | 16 (94.1) | - | - |
| Vascular tear (%) | 0 (0) | 0 (0) | - | - |
| Thrombosed (%) | 0 (0) | 0 (0) | - | - |
| Hematoma (%) | 0 (0) | 1 (5.9) | - | - |
| Infection of arteriovenous fistula (%) | 0 (0) | 0 (0) | - | - |

**Table 7. Comparison of primary patency rates between two groups at 1, 3, 6, and 9 months post-surgery.**

| | Group A (n = 17) | Group B (n = 17) | $\chi^2/t$ | *p-value* |
|---|---|---|---|---|
| Primary patency rates-1 month (%) | 15 (88.2) | 16 (94.1) | 0.366 | 0.545 |
| Primary patency rates-3 month (%) | 14 (82.4) | 14 (82.4) | 0 | 1 |
| Primary patency rates-6 month (%) | 13 (76.5) | 14 (82.4) | 0.18 | 0.671 |
| Primary patency rates-9 month (%) | 13 (76.5) | 14 (82.4) | 0.18 | 0.671 |

patency rate of 94.4% after one month. Granata *et al.* [13] showed that out of 162 patients with AVF stenosis treated with ultrasound-guided PTA, the first-time patency rate was 95.6% (154/162), with primary patency rates at 6 and 12 months of 84% and 69.8%, respectively. So far, there are no reports of applying freehand 3D ultrasound for the treatment of AVF stenosis using PTA. Our study showed first-time patency and primary patency rates in 1, 3, 6, and 9 in both the conventional ultrasound group (88.2%, 82.4%, 76.5%, 76.5%) and freehand 3D ultrasound group (94.1%, 82.4%, 82.4%, and 82.4%). Both groups were higher than the 50% patency rate required by the guidelines and showed a gradual decline with time, consistent with previous studies. There was no significant difference between the two groups ($p > 0.05$); however, we found that the patency rate at each time point in the freehand 3D ultrasound group was higher than that in the conventional ultrasound group.

During the procedure, in order to observe the progress of PTA treatment, doctors need to observe it from exactly the same perspective as the previous ultrasound examination, and plan the next step of treatment. In the traditional two-dimensional ultrasound imaging, the image is a two-dimensional structure, and the section image of a certain angle can be obtained directly. A single cross-section slice does not adequately represent the entire structure. Even if the sensor is placed in a similar position, the resulting images and data are also different. The operator could not directly perform the evaluation for the diagnosis. It is necessary to infer the 3D overall structure of blood vessels based on the information contained in the 2D images and draw conclusions accordingly. This mainly depends on doctors' clinical experience and interpretation, and affects the accuracy and objectivity of diagnostic results. At the same time, AVF vessels are relatively small, and venous segment compression due to the pressure of ultrasound probe may occur resulting in artificial pseudo stenosis, which affects the accuracy of the evaluation of the AVF stenosis. Using a freehand 3D ultrasound examination, the 3D images were reconstructed by collecting 2D images, significantly facilitating the evaluation of AVF stenotic lesions. It can more intuitively reflect the real structure of blood vessels, measure it, and improve the accuracy of the results. Freehand 3D ultrasound imaging also enables doctors to review the intraoperative images and data collected from different perspectives after surgery, or to share them with other experts.

The concept of three-dimensional ultrasound imaging technology was first proposed by Baum and Greenwood in 1961 [14]. With improvements in equipment and algorithms, the practicality of 3D ultrasound imaging technology has been clinically proven to play a significant role in medical imaging and diagnostics [15,16]. Studies have shown [17,18] that it is significantly superior to conventional ultrasound in assessing the structure and irregularity of carotid artery plaques. It has no statistical difference from magnetic resonance imaging (MRI) in evaluating plaque characteristics [19] and surpasses magnetic resonance angiography (MRA) in detecting vascular stenosis and plaque ulceration [20]. Rogers *et al.* [21,22] were the first to apply three-dimensional ultrasound to the assessment of arteriovenous fistula stenosis, and studies have shown no statistical difference in the detection of AVF complications using 3D ultrasound compared to conventional ultrasound. The ultimate goal of all interventions is to prioritize patient care, and apply the most cost-effective measures to maintain effective and safe hemodialysis treatment. The advantages of 3D imaging technology in surgical operations are becoming increasingly evident [23]. Freehand 3D ultrasound imaging is convenient for the assessment and guidance of PTA treatment of arteriovenous fistula stenosis.

This study demonstrated to potential of freehand 3D ultrasound imaging technology to guide PTA for autologous arteriovenous fistula stenosis. Although the results show that the proposed freehand 3D ultrasound is highly accurate and intuitive in measuring vascular stenosis, there are still several limitations:

(1) Ultrasound has an advantage in exploring the peripheral vessels, which is not applicable for patients with central venous stenosis.

(2) This study had a limited sample size and the average follow-up time was short. With the addition of new samples and the longer follow-up time, it will provide a stronger basis to support the conclusions of the study.

(3) The image of freehand 3D ultrasound reconstruction is stereoscopic and intuitive, but its volume measurements still depends on 2D image data, so the reliability of volume measurement is insufficient.

(4) Although freehand 3D ultrasound imaging can quickly and intuitively display vascular lesions, the imaging process still takes a few seconds and cannot yet achieve real-time imaging.

## Conclusion

In summary, freehand 3D ultrasound imaging-guided PTA treatment for arteriovenous fistula stenosis is effective and can serve as a new method for the diagnosis, treatment, and follow-up of AVF stenosis. But there are still some shortcomings with this technology and more clinical studies are needed to verify its clinical value, safety, and efficacy.

## Availability of Data and Materials

The datasets generated and analyzed during the current study are not publicly available due to sign the agreement with the patient but are available from the corresponding author on reasonable request.

## Author Contributions

GG provided funding support, reviewed and edited the manuscript. GG, XZ and QH designed the research study. HL guided the research. GG, KZ and BZ performed the research. BL and HL provided help and advice on the 3D ultrasound examination techniques. GG analyzed the data. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

## Ethics Approval and Consent to Participate

This study was approved by the medical ethics review of the 903RD Hospital of the PLA Joint Logistics Support Force (the approval number:20210722/08/01/008). A signed preoperative informed consent to inform the patient of the operation to be performed, and the relevant data will be collected from each patient in the study.


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## Conflict of Interest

The authors declare no conflict of interest.

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