



Accuracy of 3.0T magnetic resonance angiography for the detection of arteriovenous fistula dysfunction in hemodialysis patients requiring interventional therapy: a prospective study

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Background: Color Doppler ultrasonography (CDUS) is feasible to detect arteriovenous fistula (AVF) dysfunction in hemodialysis patients but is not sufficient to map the structure of fistula required for interventions. This study is designed to evaluate the diagnostic accuracy of three-dimensional time-of-flight magnetic resonance angiography (TOF-MRA) at 3.0T versus CDUS for AVF dysfunction, by using digital subtraction angiography (DSA) as reference.

Methods: This prospective study enrolled 68 consecutive patients with dysfunctional AVF who underwent both CDUS and TOF-MRA at Shanghai Sixth People's Hospital affiliated to Shanghai Jiao Tong University School of Medicine. The analysis of the dysfunctional AVFs was divided into three regions: the feeding artery, fistula and draining veins. In the whole- and per-regional-based analyses, two observers who were blinded to the clinical and DSA results independently analyzed all CDUS and TOF-MRA datasets. The image quality and stenosis severity of the lesions on TOF-MRA were evaluated. A receiver operating characteristic curve was applied to analyze the detection of AVF dysfunction with TOF-MRA.

Results: A total of 204 vessel regions were evaluated. The whole-region-based image quality of TOF-MRA was poorer in patients with a total occlusion (1.8 ± 0.8) than in those with stenosis (2.7 ± 0.6 , $P < 0.001$). In the whole-region analyses, TOF-MRA had higher sensitivity [99.1% (94.6–100.0%) vs. 82.9% (74.6–89.0%), $P < 0.001$] and similar specificity [93.1% (85.0–97.1%) vs. 94.3% (86.5–97.9%), $P = 0.755$] than CDUS. The per-region-based analyses showed that TOF-MRA yielded higher sensitivity [fistula region, 98.1% (88.4–99.9%) vs. 80.8% (67.0–89.9%); $P = 0.004$; draining vein region, 100.0% (92.5–100.0%) vs. 85.0% (72.9–2.5%); $P = 0.003$] and similar specificity [fistula region, 88.2% (62.3–97.8%) vs. 88.2% (62.3–97.9%); $P > 0.99$; draining vein region, 100.0% (59.8–100.0%) vs. 87.5% (46.7–99.3%); $P > 0.99$] than CDUS. Sensitivity and specificity of TOF-MRA were comparable to those of CDUS in feeding artery region.

Conclusions: TOF-MRA is a feasible and accurate method to display AVF dysfunction in hemodialysis patients, and this method might fulfill the endovascular treatment planning requirements.

Keywords: Hemodialysis; time of flight (TOF); magnetic resonance angiography (MRA); arteriovenous fistula (AVF); intervention

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Introduction

The maintenance of good hemodialysis access to upper limb arteriovenous fistula (AVF) is the basis of treatment for patients with end-stage renal failure (1). In hemodialysis patients with long-term dialysis treatment, due to the existence of vascular arteriosclerosis, repeated puncture, compression, infection, and other factors, vascular intimal hyperplasia and thrombosis, upper limb dialysis pathway stenosis eventually develops (2,3). Non-invasive imaging methods are often required to determine vascular lesions. Color Doppler ultrasonography (CDUS) is widely applied as a convenient, real-time imaging method to display stenotic lesions, and measure the hemodynamic parameters, and show the thrombi (4). However, sonography has certain limitations, including a possible overestimation of the degree of AVF stenosis, poor accuracy in detecting nonthrombotic venous outflow occlusions and the variability in the diagnostic quality depending on the ultrasonographer experiences (5). More importantly, CDUS is difficult to use as a guide for endovascular treatment plans due to its inability to display vascular access (6). In addition to ultrasound, enhanced imaging modalities, including computer tomography angiography (CTA) or magnetic resonance angiography (MRA), show more accurately the AVF dysfunction lesion than CDUS, with sensitivity ranging between 90.2–98.7% and specificity between 92.2–98.0% (7-12), however contrast-enhanced examination may run the risk of nephrotoxicity and nephrogenic systemic fibrosis (13,14). Digital subtraction angiography (DSA) is the “gold standard” for the diagnosis of vascular diseases and can provide dynamic flow images for further interventional therapy, but it is invasive, involves X-ray radiation exposure and uses contrast agents. Therefore, a safe and reliable imaging method is urgently needed for the accurate detection of AVF dysfunction in hemodialysis patients who may need further interventional treatment.

As a contrast-free method, time-of-flight magnetic resonance angiography (TOF-MRA), based on the “flow effect” of MR, has generated promising results for the diagnosis of intracranial artery diseases, such as aneurysm, atherosclerotic stenosis and arteriovenous shunt (15-18). In this way, a clear difference is formed between the saturated quiescent tissue and the unsaturated flowing blood to

display the blood vessels (19). However, conventional TOF-MRA can only display unidirectional blood flow signals and is seldom used for displaying venous vessels. The vascular imaging with the use of AVF needs to show the involved arterial blood inflow, anastomosis and venous outflow, which may present a greater challenge for TOF MRA imaging. Gonzalez *et al.* reported TOF-MRA can be employed to evaluate non-maturing AVFs, however, the study did not evaluate for dysfunctional AVF and the number of subjects in that study was small (20). In this study, the pre-saturated sequence in the venous direction of the conventional TOF-MRA sequence was removed so that all the blood flow signals in the arterial and venous directions could be acquired. This study aims to apply this improved TOF-MRA to diagnose stenotic or occluded vascular lesions of dialysis access, to provide a safe and effective vascular imaging method for endovascular treatment planning for patients with dysfunctional AVFs. We present this article in accordance with the STARD reporting checklist (available at <https://qims.amegroups.com/article/view/10.21037/qims-23-1505/rc>).

Methods

Study design and patient population

The study was approved by the Institutional Review Board of Shanghai Sixth People’s Hospital affiliated to Shanghai Jiao Tong University School of Medicine (No. 2018-11-12) and was conducted in accordance with the Declaration of Helsinki (as revised in 2013). All patients provided written informed consent. This prospective study included individuals receiving maintenance dialysis in the nephrology unit at Shanghai Sixth People’s Hospital who were suspected of having dysfunctional AVFs, from June 2018 to March 2021 (Clinical trial No. NCT04312711). The following were the inclusion criteria for patients with dysfunctional hemodialysis access: (I) swelling in the limbs, reduction of pulsation and tremor at the anastomotic site, and reduction of the murmur; (II) both the venous pressure and the negative pressure in the arteries increased, resulting in a decrease in the blood flow through the fistula to less than 500 mL/min; (III) during dialysis, it was challenging to puncture the hemodialysis site. The exclusion

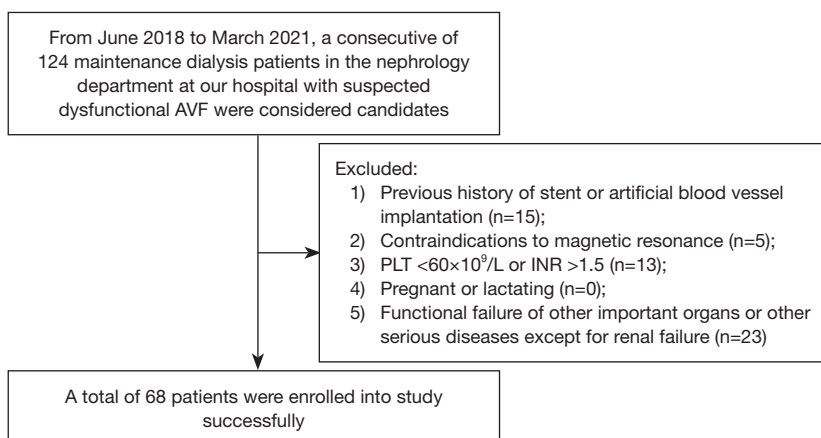


Figure 1 Flowchart showing the recruitment of patients in this study. AVF, arteriovenous fistula; PLT, platelet; INR, international normalized ratio.

criteria included: (I) prior stent or artificial blood vessel implantation; (II) contraindications to magnetic resonance; (III) platelet (PLT) level $<60 \times 10^9/\text{L}$ or international normalized ratio (INR) >1.5 ; (IV) pregnancy or lactation; and (V) functional failure of important organs or other serious diseases, excluding renal failure. *Figure 1* presents a comprehensive flowchart outlining the process of selecting patients in details.

Imaging protocol

CDUS

Two sonographers of 12 and 8 years of experience independently conducted ultrasonography studies in the Department of Ultrasonography. Using 5- and 7-MHz linear array scanners (Aspen Advanced; Siemens Healthcare, Erlangen, Germany), the complete assessment of the hemodialysis access fistula was conducted, starting from the feeding artery at the axillary artery level and extending to the draining vein at the subclavian vein level. The tests were conducted in both vertical and horizontal directions. At every examination level, spectral waveforms were acquired, and color Doppler interrogation was employed during the examinations. The calculation and recording of peak systolic velocity (PSV) and the position of any constricted regions were performed. The criteria for PSV were identical for the inflow, shunt proper (such as anastomotic sites), and outflow tract. Whenever feasible, measurements were acquired from waveforms with an insonation angle below 60° . The narrowing was deemed substantial if the PSV exceeded 375 cm/s or if there was a reduction of 50% or more on the

grayscale imaging. The localizations of the stenoses were drawn on a form where all data were recorded.

MRA

A superficial body array matrix coil was used to perform MRA on a 3-T system (Skyra, Siemens Healthcare, Erlangen, Germany). The imaging was conducted while the patient was in a supine position, ensuring that the target arm, which held the fistula, was positioned as close to the center of the examination bed as feasible. The TOF-MRA scan lasted approximately 5 minutes and covered a transverse slab from the elbow joint to 5 cm below the anastomosis. It utilized acquisition parameters including a repetition time of 23 ms, an echo time of 3.5 ms, a flip angle of 70° , a volume of interest measuring $200 \times 200 \times 200 \text{ mm}^3$, a section thickness of 2 mm, an acquisition matrix of $1,024 \times 1,024$, and consisted of 180 slices. Using the TOF images, two highly experienced radiologists made an initial assessment of the stenosis location. Using an automated subtraction technique, maximum intensity projection (MIP) images were reconstructed for all three stations in the coronal orientation. These images were then combined into a single image using a specialized workstation called Syngo[®] MR from Siemens Healthcare. The schematic illustration of the TOF-MRA scan protocol is present in *Figure 2*.

Interventional radiologists (with 17 and 15 years of expertise, respectively) performed the DSAs using the digital angiography unit (Artis zee; Siemens Medical Solutions), within an average of 10 [1–14] days following the ultrasonography and MRA. A method of entry was utilized on either the venous or brachial artery. A catheter

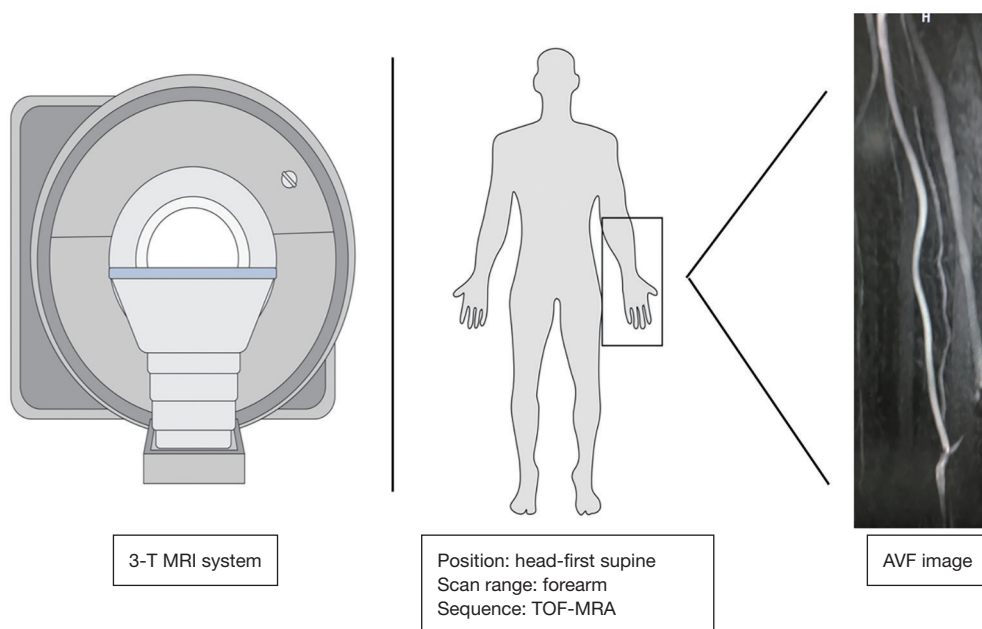


Figure 2 Schematic illustration of the TOF-MRA scan protocol. MRI, magnetic resonance imaging; TOF-MRA, time-of-flight magnetic resonance angiography; AVF, arteriovenous fistula.

with a diameter of 5-French (1.70 mm) was used to inject an iodine-based contrast agent (Imeron 350; Bracco Imaging, Shanghai, China). The interventional radiologist selected the anteroposterior views based on their own judgment. Pictures of feeding artery, fistula and distal venous outflow were obtained. Following the angiogram, PTA was conducted on the regions with stenoses exceeding 50% or experiencing complete occlusion.

Image analysis

The MRA and DSA images were evaluated by two experienced radiologists, one with 10 years of experience and the other with 15 years of experience in assessing vascular images. They conducted the evaluations without knowledge of the patient's identity, medical history, or symptoms. The MRA data sets were assessed using a specialized computer (Syngo[®] MR, Siemens Healthcare), while the DSA images were analyzed on a different computer (SyngoXWP; Siemens Healthcare).

All regions were assessed for the diagnostic performance and image quality of TOF-MRA. The AVF architecture was divided into three regions for all participants: arterial inflow, anastomosis (including 1 cm length of vessel on both sides of the anastomosis), and venous outflow. In this

study, the analysis did not include the proximal half of the brachiocephalic vein and superior caval vein, which are the main part of the venous outflow, as they were not visible in the TOF-MRA imaging.

The image quality of the pictures acquired at each of the three areas was assessed on a scale of 0–4 using the Likert rating system. 0 for an image that is considered ‘nondiagnostic’; 1 for “poor” quality, due to severe image artifacts, significant venous contamination, and/or inadequate vascular signals, which makes the observer lack confidence; 2 for “fair” quality, and the observer has slight confidence due to small imperfections, mild to moderate interference from veins, and/or a reasonably consistent signal from blood vessels; 3 for “good” quality, with the observer can be assured of a high standard of quality; 4 for an “excellent” quality, which is given for a superior quality scan that is free from or has minimal presence of venous contamination, lacks any artifacts, and exhibits consistent vascular signals, thus instilling a strong sense of confidence in the observer.

An electronic caliper was utilized to grade the stenosis of lesions on CDUS, MRA, and DSA. In all regions (*Figures 3-5*), the sonographer or radiologist ascertained the presence of stenosis or occlusion. The level of narrowing was evaluated using a visual scale where 0 represents a fully unobstructed vessel wall, 1 indicates less than 50%

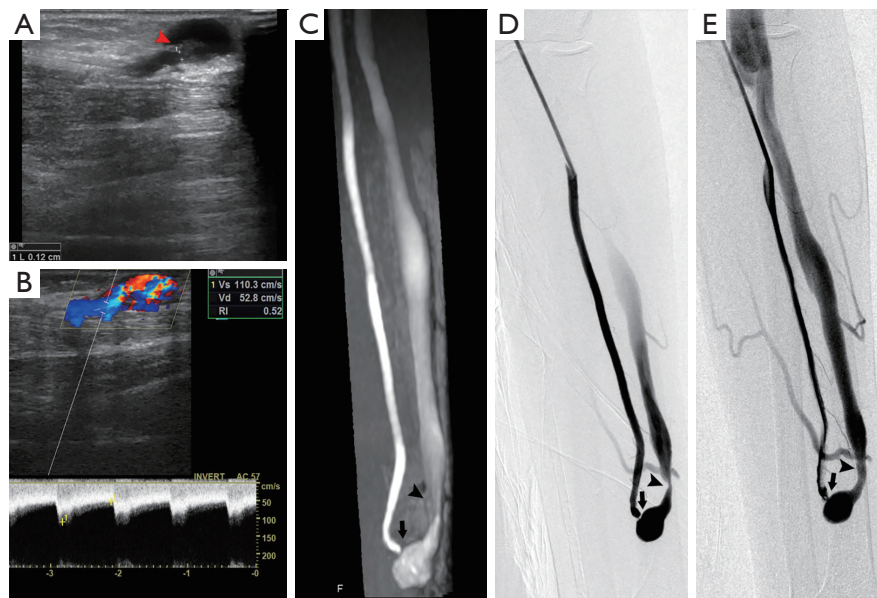


Figure 3 A 49-year-old man of diabetic nephropathy has been on dialysis for 8.5 years with suspected dysfunctional AVF access. (A,B) CDUS showed thrombus in the adjacent draining vein region (red arrowhead) and the flow velocity in the fistula region increased (110.3 cm/s). (C) However, besides the stenosis in the adjacent draining vein region as CDUS showed (arrowhead), TOF-MRA also revealed another severe stenosis in the fistula region (arrow). (D) DSA demonstrated similar results to that of TOF-MRA (arrow and arrowhead). (E) DSA showed all stenosis was recanalized successfully after percutaneous transluminal angioplasty (arrow and arrowhead). Vs, systolic velocity; Vd, diastolic velocity; RI, resistance index; AVF, arteriovenous fistula; CDUS, color doppler ultrasonography; TOF-MRA, time-of-flight magnetic resonance angiography; DSA, digital subtraction angiography.

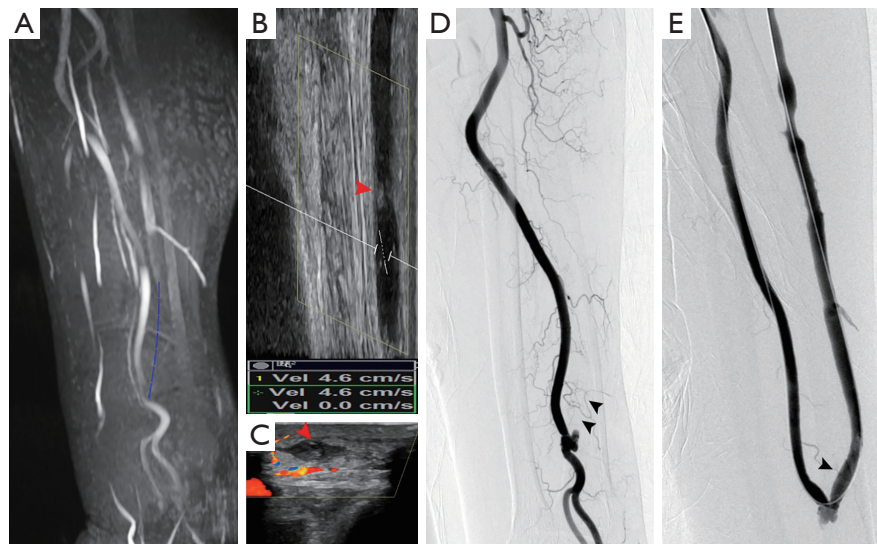


Figure 4 A 59-year-old man of glomerulonephritis has been on dialysis for 4 months with suspected dysfunctional AVF access. (A) TOF-MRA revealed a total occlusion in the fistula and adjacent draining vein regions (blue dot-line), and the distal vessel was unobstructed. (B) CDUS showed a thrombus in the draining vein region (red arrowhead) and the flow velocity was slow (4.6 cm/s). (C) A thrombus in the fistula region was present by CDUS (red arrowhead). (D) DSA demonstrated similar results to that of TOF-MRA (arrowheads). (E) DSA showed occlusion segment was recanalized successfully after percutaneous transluminal angioplasty (arrowhead). AVF, arteriovenous fistula; TOF-MRA, time-of-flight magnetic resonance angiography; CDUS, color doppler ultrasonography; DSA, digital subtraction angiography.

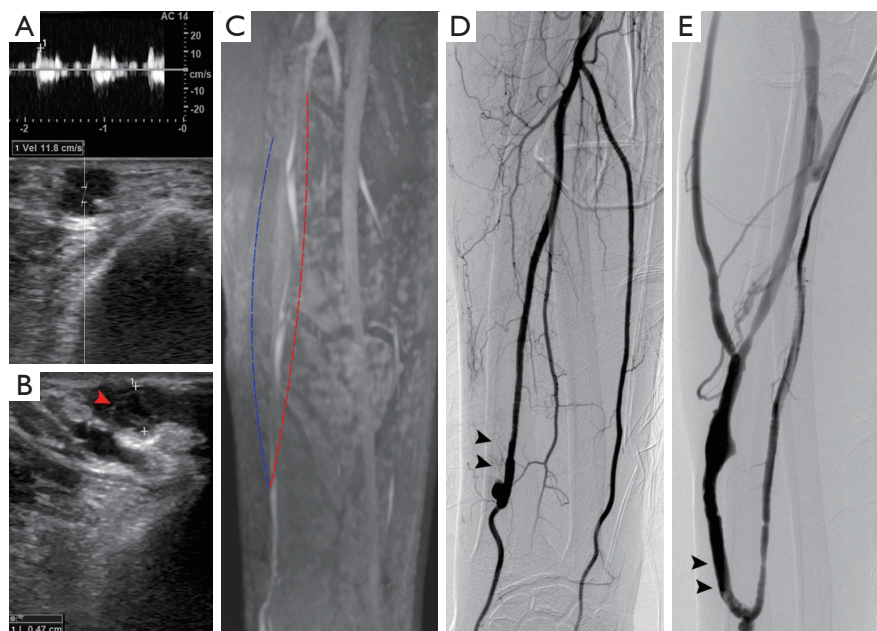


Figure 5 A 53-year-old man of diabetic nephropathy has been on dialysis for 12 months with suspected dysfunctional AVF access. (A) CDUS showed the flow velocity was slow in the draining vein region (11.8 cm/s). (B) A thrombus in the fistula region was present by CDUS (red arrowhead). (C) TOF-MRA revealed total occlusion in the feeding artery, fistula and draining vein regions (red and blue dot-lines). (D) however, DSA demonstrated the feeding artery region was unobstructed, and fistula and draining vein regions were occluded (arrowheads). (E) DSA showed all occlusions was recanalized successfully after percutaneous transluminal angioplasty (arrowheads). AVF, arteriovenous fistula; CDUS, color doppler ultrasonography; TOF-MRA, time-of-flight magnetic resonance angiography; DSA, digital subtraction angiography.

narrowing, 2 signifies 50–75% narrowing, 3 denotes 75–99% narrowing, and 4 represents complete blockage (segmental and total). Only the most critical narrowing per region was assessed for analysis purposes. Stenoses that had a luminal constriction greater than 50% were deemed to be clinically significant in terms of blood flow. If the stenosis score on TOF-MRA and CDUS was higher than that on DSA, it was deemed as an overestimation; otherwise, it was considered an underestimation (*Figure 6*).

Statistical analysis

The mean \pm standard deviation was used to report the Likert scores for the diagnostic image quality, and they were compared using the paired *t*-test. DSA was regarded as the benchmark. Proportions of sensitivities, specificities, positive predictive values (PPVs), and negative predictive values (NPVs) for detecting significant (50–100%) stenosis were displayed as both whole-region and per-region. The corresponding 95% confidence intervals (CIs) were also included for each estimate. The level of agreement between

observers in determining significant stenosis was assessed by computing the κ statistic. The Cohen's kappa coefficient (κ) was computed, where $\kappa > 0.80$ was considered as 'almost perfect', values between 0.61 and 0.80 were considered 'substantial', and values between 0.41 and 0.60 were considered 'moderate'. Significance was attributed to values with a two-sided *P* value less than 0.05. SPSS v19.0 (IBM, Armonk, NY, USA) was utilized for the statistical analyses.

Results

Between June 2018 and March 2021, a total of 68 patients with 204 vessel segments who underwent TOF-MRA, CDUS and DSA examinations and met the inclusion criteria were prospectively included in our study, and their clinical baseline characteristics are listed in *Table 1*. The technique success for TOF-MRA scan was 100%. The mean acquisition time of TOF-MRA was 5.4 ± 0.9 minutes, and the mean examination time of CDUS was 12.5 ± 4.6 minutes. Imaging parameters for TOF-MRA, CDUS, and DSA are listed in *Table 2*.

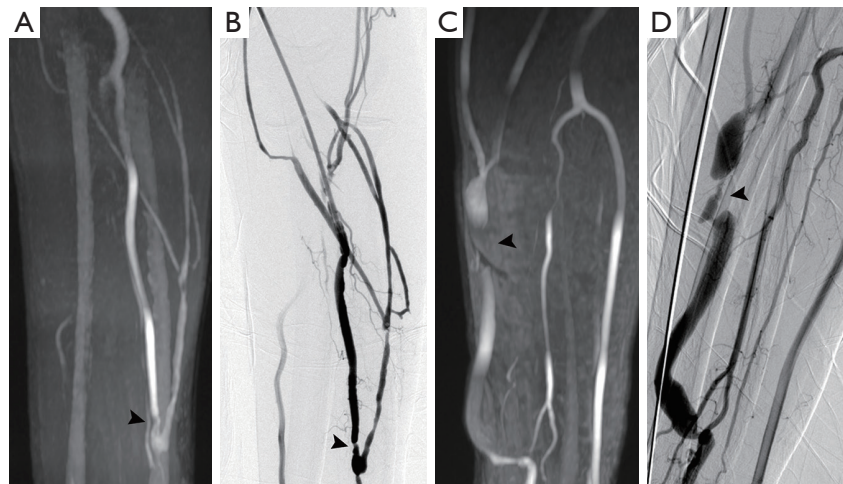


Figure 6 Exemplary pictures of images-cases of underestimation (A,B) and overestimation (C,D) between the TOF-MRA and DSA. (A,B) TOF-MRA revealed less than 50% narrowing in the feeding artery, which was diagnosed as 50–75% narrowing by DSA (arrowheads); (C,D) TOF-MRA showed total occlusion in the feeding artery, which was diagnosed as 75–99% narrowing by DSA (arrowheads). TOF-MRA, time-of-flight magnetic resonance angiography; DSA, digital subtraction angiography.

Table 1 Baseline characteristics of the 68 study participants

Characteristic	Participants
Age (years)	61.4±12.2
Sex (male)	47 (69.1)
Hypertension	59 (86.8)
Hyperlipidemia	3 (4.4)
Smoking	13 (19.1)
Cause of end-stage kidney disease	
Diabetes	14 (20.6)
Glomerulonephritis	20 (29.4)
Both diabetes and glomerulonephritis	21 (30.9)
Polycystic kidney disease	2 (2.9)
Other*	2 (2.9)
Unknown	9 (13.2)
Usable time of AVF (months)	21.2±20.7

Unless otherwise indicated, the data are expressed as the number of patients, and the data in parentheses are percentages. The data are expressed as the mean ± standard deviation. *, nephropathy of amyloidosis (n=1), renal carcinoma (n=1). AVF, arteriovenous fistula.

Image quality analysis

The patient-based analysis of image quality of TOF-MRA revealed that 2 patients were scored as grade 2, 44 patients as grade 3 and 22 patients as grade 4. The per-region-

based analysis found that the average image quality score was 2.5 ± 0.8 , with 129 regions (63.2%) shows good quality, and only 3 regions (1.5%) considered nondiagnostic by TOF-MRA. On the basis of the lesion type, a significant difference of image quality was found between the patients with and the patients without total occlusive segments (1.8 ± 0.8 vs. 2.7 ± 0.6 , $P < 0.001$). However, between lesions with different stenotic types, the image quality analysis did not reveal any significant difference (grade 2, 3.0 ± 0.3 vs. grade 3 2.8 ± 0.6 , $P = 0.576$). Further region-based analyses indicated that the image quality of TOF-MRA showed no significant difference at the different sites (feeding artery, 2.5 ± 0.7 ; fistula, 2.5 ± 0.8 ; draining veins, 2.5 ± 0.8 ; $P > 0.99$).

Diagnostic performance comparison of TOF-MRA and CDUS

Regarding the lesion location classification based on DSA, a total of 122 segments with >50% stenosis or occlusion were confirmed. Feeding arteries were involved in 2 patients, fistulas in 4 patients, draining veins in 14 patients, both feeding arteries and fistulas in 2 patients, both fistulas and draining veins in 40 patients and whole regions in 6 patients. Taking DSA as a reference standard, the stenosis severity was overestimated in 15 segments on TOF-MRA and in 8 segments on CDUS. The stenosis severity was underestimated in 4 segments using TOF-MRA and in 27 segments using CDUS (Figure 5). The whole-region

Table 2 Imaging parameters for TOF-MRA, CDUS, and DSA

TOF-MRA	CDUS	DSA
Repetition time (23 ms)	Scanner (linear array)	Tube voltage (69 KV)
Echo time (3.5 ms)	Frequency (5- and 7-mHz)	Tube current (37 mA)
Flip angle (70°)		Pulse width (4.8 ms)
Volume of interest (200×200×200 mm ³)		Frequency (7.5 f/s)
Section thickness (2 mm)		Image pixel spacing (0.75×0.75)
Acquisition matrix (1,024×1,024)		
Slices (180)		

TOF-MRA, time-of-flight magnetic resonance angiography; CDUS, color Doppler ultrasonography; DSA, digital subtraction angiography.

comparison of the lesion stenosis between TOF-MRA and CDUS indicated a significant difference in the sensitivity [99.1% (116 of 117) *vs.* 82.9% (97 of 117), $P < 0.001$] and NPV [98.8% (81 of 82) *vs.* 80.4% (82 of 102), $P < 0.001$], but they had similar specificity [93.1% (81 of 87) *vs.* 94.3% (82 of 87), $P = 0.755$] and PPV [95.1% (116 of 122) *vs.* 95.1% (97 of 102); $P = 0.996$]. In the per-region-based analyses, compared to CDUS, TOF-MRA yielded higher sensitivity in the fistula region [98.1% (51 of 52) *vs.* 80.8% (42 of 52), $P = 0.004$] and in the draining vein region [100.0% (60 of 60) *vs.* 85.0% (51 of 60), $P = 0.003$], but this was not seen in the feeding artery region due to the relatively small number of involved regions (5 cases) (Table 3).

Interobserver agreement

The κ values of the diagnostic performance and image quality indicated good agreement between both readers. With regard to the diagnostic performance, the κ value for TOF-MRA was 0.975 and for CDUS, it was 0.964. With respect to the image quality of TOF-MRA, the κ value was 0.866.

Discussion

In the present study, TOF-MRA was a feasible technique in patients with suspected hemodialysis access stenosis for subsequent angioplasty treatment plans. Using DSA as the reference standard, the diagnostic accuracy of TOF-MRA was high (sensitivity of 98.3–99.1% and specificity of 93.1–95.4%), which was superior to CDUS. The image quality of TOF-MRA was also satisfactory, with a score of 2.5 ± 0.8 .

When AVF dysfunction is present, precise imaging of the entire hemodialysis access and identifying the

specific stenosis lesions play an important role. CDUS has proven to be a valuable and reliable screening tool in managing clinically suspected hemodialysis access stenosis. The results of CDUS in this study were similar to those reported in previous literature (21), and we found an 82.9% sensitivity and a 94.3% specificity. However, when further endovascular treatment is required, CDUS has limitations with respect to the depiction of vascular tree vessels for definitive therapy planning. Consequently, CTA or contrast enhanced MRA (CE-MRA) showed a better performance than CDUS for this purpose. Doelman *et al.* reported that the sensitivity and specificity of CE-MRA with DSA for the detection of significant (>50%) stenoses in a failing dialysis accesses were 96% and 98%, respectively (7), which indicated that CE-MRA can be used for the evaluation of a failing AVF access. CTA also demonstrated a sensitivity ranging between 90.2–98.7% and a specificity between 92.2–97.5% (8–12). Nonetheless, what cannot be ignored is that the contrast-enhanced MR technique requires venous puncture, whereas the Dialysis Outcome Quality Initiative guidelines indicate that puncture of peripheral veins should be avoided for venous preservation (22). In addition, gadolinium or iodine contrast medium may have some nephrotoxicity properties in patients with residual renal function (14,23,24); therefore, the routine use of CE-MRA or CTA is restricted in the clinical setting for symptomatic AVF evaluation.

TOF-MRA, as a nonenhanced MR angiography technique, has been carried out for the assessment of cerebrovascular disease (25,26) and is seldom used for hemodialysis access since TOF-MRA is unable to adequately depict the venous vessels. When TOF-MRA was applied for cerebrovasculature, a presaturation pulse was used inferior to the slice to suppress the signal from venous

Table 3 Diagnostic performance of TOF-MRA and CDUS for detection of the 50–100% stenosis of AVF using DSA as the standard reference

Parameter	TOF-MRA vs. DSA	CDUS vs. DSA	P
Whole-region			
Sensitivity	99.1% (94.6–100.0%)	82.9% (74.6–89.0%)	<0.001*
Specificity	93.1% (85.0–97.1%)	94.3% (86.5–97.9%)	0.755
PPV	95.1% (89.2–98.0%)	95.1% (88.4–98.2%)	0.996
NPV	98.8% (92.5–99.9%)	80.4% (71.1–87.3%)	<0.001*
Per region			
Feeding artery			
Sensitivity	100.0% (46.3–100.0%)	80.0% (29.9–98.9%)	>0.99
Specificity	93.5% (83.5–97.9%)	96.8% (87.8–99.4%)	0.68
PPV	55.6% (22.7–84.7%)	66.7% (24.1–94.0%)	>0.99
NPV	100.0% (92.3–100.0%)	98.4% (90.0–99.9%)	>0.99
Fistula			
Sensitivity	98.1% (88.4–99.9%)	80.8% (67.0–89.9%)	0.004*
Specificity	88.2% (62.3–97.8%)	88.2% (62.3–97.9%)	>0.99
PPV	96.2% (85.9–99.3%)	95.5% (83.3–99.2%)	>0.99
NPV	93.8% (67.7–99.7%)	60.0% (38.9–78.2%)	0.028*
Draining vein			
Sensitivity	100.0% (92.5–100.0%)	85.0% (72.9–92.5%)	0.003*
Specificity	100.0% (59.8–100.0%)	87.5% (46.7–99.3%)	>0.99
PPV	100.0% (92.5–100.0%)	98.1% (88.4–99.9%)	0.464
NPV	100.0% (59.8–100.0%)	43.8% (20.1–69.4%)	0.009*

Data are expressed as the diagnostic performance of TOF-MRA and CDUS using DSA as the reference standard with the 95% confidence intervals in parentheses. *, represents significant difference. TOF-MRA, time-of-flight magnetic resonance angiography; CDUS, color Doppler ultrasonography; AVF, arteriovenous fistula; DSA, digital subtraction angiography; PPV, positive predictive value; NPV, negative predictive value.

blood, and the presaturation bands were omitted in our study to allow simultaneous visualization of both arterial and venous blood flow. Jin *et al.* assessed the diagnostic value of TOF-MRA in comparison to multidetector CTA, and the study yielded a 96.4% sensitivity and a 94.3–97.1% specificity (27). In our study, the region-based analyses of significant stenosis (50–100%) for TOF-MRA showed a 99.1% sensitivity and a 93.1% specificity, which is consistent with the previous study. The stenosis severity of 15 segments using TOF-MRA was overestimated in our study, and in contrast, CDUS overestimated the stenosis severity in only 8 segments. The reason for the TOF-MRA overestimation in the stenosis of AVF was attributed to the flow voids caused by poststenotic intravoxel phase

dispersion. Interestingly, due to the relatively lower sensitivity of CDUS compared with TOF-MRA (82.9% *vs.* 99.1%, $P < 0.001$), the stenosis severity was underestimated in 27 segments by CDUS, and only 4 segments by TOF-MRA were underestimated. Taken together, these above results confirmed the notion that TOF-MRA is a promising method for the assessment of dysfunctional AVF before further endovascular treatment.

However, challenges of TOF-MRA for AVF evaluation still exist. The patients with total occlusive AVF segments showed significantly lower image quality scores than those without total occlusive AVF segments (1.8 ± 0.8 *vs.* 2.7 ± 0.6 , $P < 0.001$) in this study. As a potential mechanism, there is two-way blood flow in the vessels if the AVF is completely

occlusive, which leads to the confusion of determining the blood signals; moreover, as an essential pitfall of TOF-MRA, it is insensitive to slow blood flow, which becomes desaturated similar to stationary tissue, resulting in a signal loss from the vessel (28). Therefore, since the flow rate of blood is slowed down in the occlusive AVF and the hemodynamic signals are too sluggish to be detected within the occlusive vessels, a poor image quality might be the result. Since black-blood T1WI, also known as vessel wall enhancement (VWE), is a reliable examination method to enable analysis of vessel wall, it might be an alternative method for detecting total occlusive AVF (29). Although VWE has been used widely in the evaluation of intracranial vasculopathies, it requires a relatively long examination time and gadolinium-based contrast media, limiting its practical applications for patients with end-stage renal failure. Another challenge of TOF-MRA is its relatively long acquisition time. The TOF-MRA examination time was approximately 5 minutes at our center, sometimes it was difficult for the patients with end-stage renal disease to maintain long periods of immobility, which may result in a decrease in the image quality. Moreover, the MR scan area included only the elbow joint to 5 cm below the anastomosis and the remaining AVF access was not included. As we consider that the majority of stenoses of dysfunctional AVFs were located in a forearm vessel, and only one patient who had a brachiocephalic vein occlusion with a temporary dialysis cannulation history was excluded from the analysis.

Our study had limitations. The single-center experience with a limited number of included patients may not be able to investigate the feasibility and accuracy of TOF-MRA for the diagnosis of AVF dysfunction fully. Moreover, further studies are required to investigate whether TOF-MRA may improve the performance of subsequent endovascular treatment. Finally, patients with arteriovenous grafts, which are commonly seen in clinical practice, were not enrolled in this study.

Conclusions

In conclusion, by using DSA as reference, this study showed that TOF-MRA was superior to CDUS in accurately diagnosing dysfunctional AVFs in hemodialysis patients, which may facilitate subsequent endovascular interventions.

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Footnote

Reporting Checklist: The authors have completed the STARD reporting checklist. Available at <https://qims.amegroups.com/article/view/10.21037/qims-23-1505/rc>

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at <https://qims.amegroups.com/article/view/10.21037/qims-23-1505/coif>). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Review Board of Shanghai Sixth People’s Hospital affiliated to Shanghai Jiao Tong University School of Medicine (No. 2018-11-12), and all patients provided written informed consent.

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