Health-care Professionals' Perspectives on Ultrasound Evaluation of Arteriovenous Hemodialysis Fistula: A Narrative Review

CME Credits

Chung-Ming Fu[1], Foong-Fah Leong[1], Sheng-Ying Chung[2], Wen-Chin Lee[1]*

[1]Division of Nephrology, Department of Internal Medicine, Kaohsiung Chang Gung Memorial Hospital, Chang Gung University, College of Medicine, Kaohsiung, Taiwan, [2]Division of Cardiology, Department of Internal Medicine, Kaohsiung Chang Gung Memorial Hospital and Chang Gung University, College of Medicine, Kaohsiung, Taiwan

Abstract

Arteriovenous hemodialysis fistulas play a critical role in maintaining life on hemodialysis. With the growing use of Doppler ultrasound in nephrology, its utility has expanded to improve the prognosis and quality of life of patients receiving hemodialysis. On a fistula care team, different health-care professionals, including nephrologists, dialysis technicians, and surgeons or vascular interventionalists, require different information. This review article comprehensively explains how Doppler ultrasound evaluation can be beneficial in the management of arteriovenous fistulas from different perspectives of health-care professionals. The article also introduces the pathophysiology of arteriovenous fistula disease and provides a thorough introduction to the use of Doppler ultrasound for the evaluation of arteriovenous fistulas and their associated diseases, addressing the need for a comprehensive understanding among ultrasound practitioners.

Keywords: Arteriovenous fistula, dialysis vascular access, Doppler ultrasound, hemodialysis

Introduction

The incidence and prevalence of end-stage kidney disease is increasing worldwide.[1,2] Dialysis vascular access (DVA), including autogenous arteriovenous fistula (AVF), arteriovenous graft (AVG), and tunneled dialysis catheter, plays the most important role in preserving the lives of patients receiving hemodialysis. The integration of ultrasound into the care of DVA can be very helpful. However, existing review articles on the management of AVFs are predominantly from the perspective of vascular interventionalists. Other professionals on the dialysis care team, such as nephrologists and dialysis technicians, are underrepresented. This article provides a comprehensive review of Doppler ultrasound assessment and common clinical problems in AVFs from different professional perspectives.

Pathophysiology of Arteriovenous Fistula Disease

In a successful AVF, the vein receives a large volume of blood flow with shear pressure from the artery after the creation of the fistula, resulting in lumen dilation of the drainage vein. This change is called arterialization or outward-remodeling of the AVF drainage vein, and is the essential process of fistula maturation [Figure 1a].[3] However, the wall shear stress of blood flow also induces damage to the vessel, leading to cellular activation of endothelial cells and smooth muscle cells, which causes intimal hyperplasia [Figure 1b].[4] If the intimal hyperplasia outweighs the outward remodeling in the fistula vessel, the result may be a stenosis or immaturity of the fistula. Moreover, thrombosis formation may occur when the intimal layer of the drainage vein becomes de-endothelialized and adherent to platelets and monocytes.[3] In addition, patients with chronic kidney disease (CKD) typically have abnormal bone remodeling and calcium-phosphate imbalances that lead to diffuse vascular calcification.[5,6] This unique change in medial

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Address for correspondence: Prof. Wen-Chin Lee, Division of Nephrology, Department of Internal Medicine, Kaohsiung Chang Gung Memorial Hospital, 123 Dabi Rd, Kaohsiung 83301, Taiwan. E-mail: leewc@cgmh.org.tw

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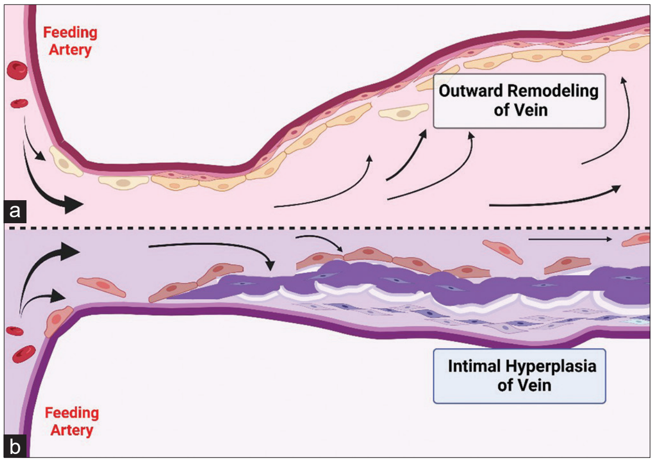

Figure 1: After the arteriovenous anastomosis is created, the vein may exhibit either outward remodeling (a) or intimal hyperplasia with thickening of the vessel wall (b). In most cases, the two conditions coexist and outweigh each other during fistula maturation

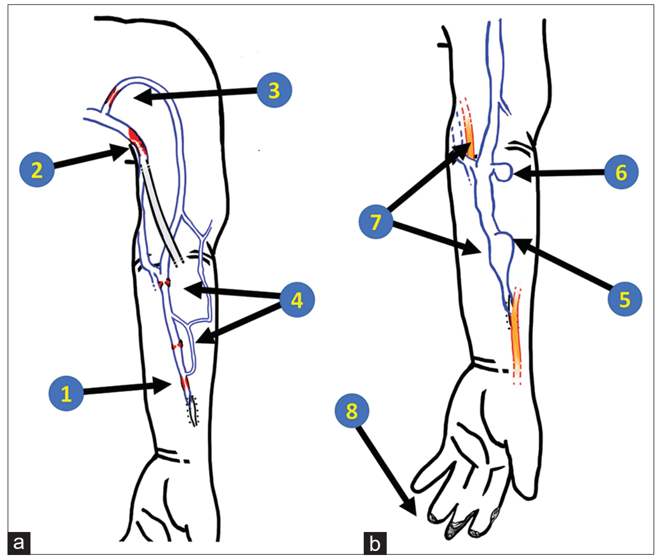

Figure 2: (a) Common stenotic sites of the arteriovenous (AV) fistula vessel – 1: Juxta-anastomotic stenosis, 2: Proximal swing stenosis (usually in patients with brachiobasilic fistula), 3: Cephalic arch stenosis (usually in brachiocephalic fistula), (4): Stenosis at the sites of repeated punctures, (b) Common AV fistula diseases include – 5: Aneurysm, 6: Pseudoaneurysm, 7: High-output heart failure (should alert if high blood flow or diffusely engorged outflow vessel is noted), 8: Steal phenomenon

calcification in patients with CKD causes vascular stiffness, leading to delayed maturation or dysfunction of the AVF.

All AVF disorders can be divided into two main groups: Inflow insufficiency and impaired outflow return, and both can lead to recirculation during hemodialysis and subsequently decreased dialysis adequacy.[7] In addition, localized hematoma or stenosis due to repeated punctures is a common cause of fistula dysfunction, which often results in aspiration of blood clots during puncture or difficulty in hemostasis at the end of dialysis. Figure 2a and b illustrates the potential disorders of the AVF and the common sites of these disorders.

Table 1: Roles of Doppler ultrasound in the management of autogenous arteriovenous fistula in end-stage kidney disease patients

Blood flow (Qa) measurement
Diagnosis of AVF stenosis
AVF maturation assessment
Pre-AVF creation evaluation
Diagnosis of other AVF disorders
Vascular mapping of the AVF system
Regular AVF surveillance

AVF: Autogenous arteriovenous fistula

Doppler Ultrasound Evaluation of Arteriovenous Fistula

Compared to angiography, Doppler ultrasound is noninvasive, readily available and very useful for AVF management.[8] The use of a linear transducer is recommended for ultrasound evaluation of AVFs, which are mostly located superficially beneath the skin.[9] By using different modes, duplex ultrasound can provide different perspectives of vascular information.[10] The Brightness mode (B-mode) of ultrasound can precisely depict the diameter, depth, and the morphology of the vessels.[11,12] The Color Doppler mode (CD-mode) can determine the presence of flow and its direction, and the Pulse Wave Doppler mode (PW-mode, or the so-called spectral Doppler mode) can provide other functional data, such as blood flow volume and velocity in the fistula or around the stenotic lesions [Figure 3]. A decrease in blood flow or change in waveform may be a sign of stenosis.[13] The main roles of Doppler ultrasound in the management of AVF are listed in Table 1.

Different Professional Perspectives on Ultrasound Evaluation of Arteriovenous Fistula

Maintaining DVA is achieved with good teamwork, as it is not only a nurse's or technician's responsibility. The responsibility is also shared among nephrologists, surgeons, and vascular interventionalists. On a fistula care team, different positions may require different information. Table 2 summarizes different health-care professionals' concerns regarding AVF, as well as how ultrasound can assist. The following sections describe how ultrasound can improve the morbidity and outcome associated with AVF from different perspectives.

Blood flow (Qa) measurement

When the AVF has stenosis or even obstruction, the blood flow (Qa) usually decreases.[14] Therefore, the measurement of blood flow (Qa) of AVFs can predict the stenosis of AVFs, and is one of the best means for monitoring the function of DVA. It is very helpful for physicians and dialysis technicians in predicting a smooth dialysis course and adequate dialysis adequacy.[15,16]

Most ultrasound software equipped with PW- or spectral-Doppler mode is capable of measuring the flow volume of the

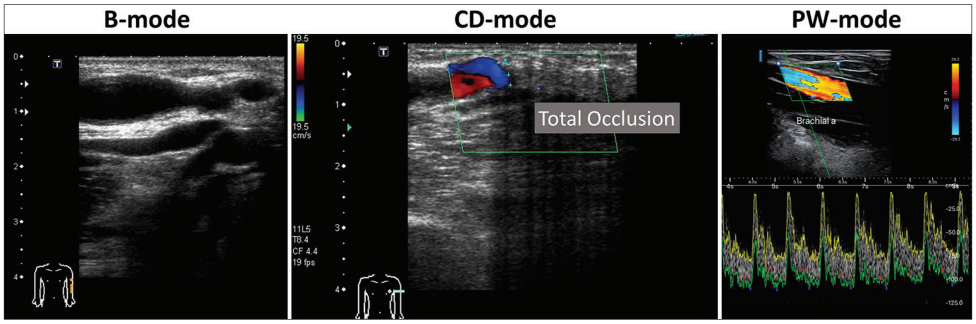

Figure 3: B-mode can be used to depict the diameter and depth, or morphological lesions (e.g. stenosis, thrombosis…) of the arteriovenous fistula vessels. CD-mode can be used to detect the blood flow. PW-mode allows the measurement of blood flow velocity, waveform, and volume. B-mode: Brightness mode, CD-mode: Color Doppler mode, PW-mode: Pulse Wave mode

Table 2: Different professional perspectives on Doppler ultrasound evaluation of autogenous arteriovenous fistula

Different professional perspectives	Expected benefits of Doppler ultrasound	How Doppler ultrasound can help
Dialysis technician	Knowing when to start cannulating after AVF creation	AVF maturation assessment
	Easy puncture of the AVF	Vascular mapping of the AVF system
	Smooth dialysis course and good hemostasis	Blood flow (Qa) measurement
Nephrologist or internal physician	Smooth dialysis course and good hemostasis	Diagnosis of AVF stenosis
	Adequate dialysis clearance	
	Knowing when to refer patient to a surgeon	Diagnosis of AVF stenosis
Surgeon or vascular interventionalist	The indication of vascular intervention	(determination of the severity of stenosis)
	Lesion description before angioplasty	Diagnosis of AVF stenosis
		Vascular mapping of the AVF system
	Good selection of candidates for AVF creation	Pre-AVF creation evaluation
		Vascular mapping of the AVF system
All	Find out underlying AVF disorders	Diagnosis of other AVF disorders

AVF: Autogenous arteriovenous fistula

blood vessel. The value of the blood flow volume is derived from the product of the time-averaged mean velocity (TAMV) and the cross-sectional area [Figure 3, PW-mode].[17,18] Some ultrasound software can automatically detect and calculate the cross-sectional area of the lumen, while others require the operator to confirm its radius accurately. The operator should obtain several pulse cycles to calculate the TAMV using the Doppler mode.[18,19] If the pulse cycles are not clearly discernible due to turbulent flow or other reasons, the operator should be skeptical of the generated blood flow values. Some authors recommend measuring Qa at least three times and using the average value. It is recommended to set the insonation angle to <60° because the insonation angle can affect the ultrasound assessment of blood flow velocity.[10]

A well-functioning AVF or AVG usually has a blood flow between 700 and 1300 ml/min.[16] If the blood flow is <500 ml/min in an AVF, <600 ml/min in an AVG, or if a reduction in usual blood flow of >25% is noted, stenosis of the outflow vessel should be suspected.[16,20,21] For autogenous AVF, it is most advisable to measure flow volume (Qa) at the brachial artery close to the elbow. Measuring via the outflow vein has several drawbacks because the outflow vein often has an irregular wall and diameter, accessory branches, and is easily compressed by the ultrasound transducer. All this may result in an inaccurate calculation of flow volume. However, if the outflow vein or the so-called "stick zone" of the fistula is straight and singular without branches, and if a discernible pulse cycle is obtained, measuring blood flow at the outflow vein may be acceptable. When assessing Qa for an implanted graft (AVG), direct measurement at the graft vessel is recommended.[17,22]

Measurement of Qa has limitations in some clinical practices and settings. The irregular vessels and turbulent flow of outflow vessels can make each measurement differ. In addition, if there is a collateral vein distal to the narrowed vein, or if the location of the stenosis is more proximal (e.g., central vein stenosis), normal blood flow measured in the brachial artery cannot exclude these stenotic lesions.[17]

Diagnosis of arteriovenous fistula stenosis

Exclusion of AVF vessels stenosis ensures smooth hemodialysis course and good hemostasis, and that's what dialysis technicians look for most. Knowing the exact location and severity of the AVF lesion is also very helpful to surgeons before vascular intervention. An ultrasound beginner can easily identify a stenosis or thrombosis and accurately locate the lesion.

Diagnosis of the stenosis and determination of severity

In most situations, a stenosis can be determined in B-mode if the vessel diameter is <2–3 mm, or if the vessel lumen is significantly reduced by more than 50%.[9] However, because the diameter of the fistula outflow vessel usually varies widely (or dilates at puncture sites due to repeated cannulation), calculating the diameter or lumen reduction by B-mode alone may not accurately determine the severity of each stenosis. Therefore, it is better to check the functional information of the fistula vessel, peak systolic velocity (PSV), or PSV ratio with CD- or PW-mode simultaneously.

As the diameter of a blood vessel narrows, the velocity of blood flow accelerates, making PSV a diagnostic tool of detecting stenosis. In general, it may be a sign of stenosis if the PSV of the AVF outflow vein or graft is >300–400 cm/s.[9] Some operators use CD-mode and determine vessel stenosis by observing the presence of the "aliasing phenomenon," an apparent change in the direction of flow color in areas of high velocity, producing a color that appears to be backward in direction or a color bruit artifact [Figure 4].[23]

However, the blood flow velocities and PSV in the outflow vein naturally increase as the feeding artery flow is higher.[9] Therefore, it is more accurate to use the PSV ratio rather than PSV alone to facilitate the diagnosis of stenosis. The PSV ratio can be obtained by dividing the PSV within the stenotic segment by the value at prestenotic segment. A PSV ratio >2.0 may indicate that the vessel is more than 50% stenosis, and a PSV ratio >3.0 may suggest more than 75% stenosis.[24]

It is important to note that the use of PSV or PSV ratio alone to diagnose stenosis may be inappropriate as flow velocity may be inherently accelerated in curved or kinked portions of the outflow vessel tree. Morphologic changes and functional information obtained from Doppler ultrasound must be mutually corroborated in the diagnosis of vascular stenosis.[25]

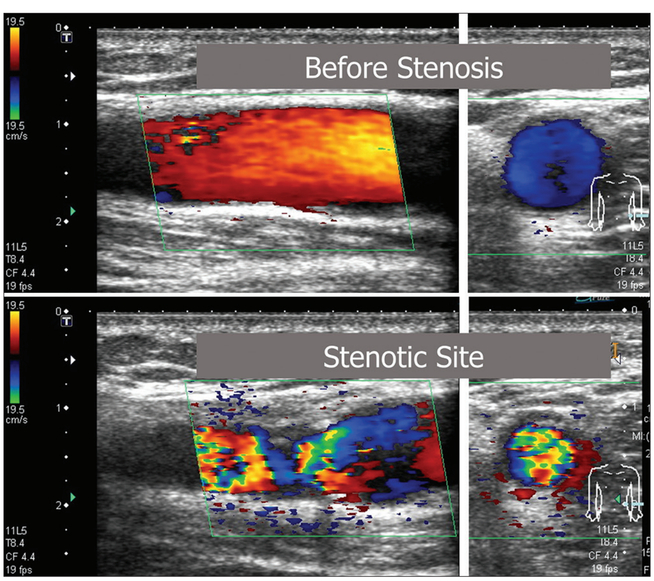

Figure 4: The lower part of the figure shows an "aliasing phenomenon" at the stenotic site. A bruit artifact is produced, indicating that the blood flow velocity increased significantly and exceeded the maximum velocity scale of the color Doppler-mode

The common sites of stenosis

Different types of DVA are predisposed to different locations of stenosis. Knowing this before an ultrasound exam can make the exam more efficient. Figure 2a shows the common sites of stenosis in different locations of an AVF system. In general, forearm access is more likely to produce a stenosis adjacent to the anastomosis (usually within 4 cm of the anastomosis), known as a "juxta-anastomotic stenosis."[16] Upper arm access is more likely to produce a stenosis in the proximal part of the outflow vessel or in the axillary area. Cephalic arch stenosis is relatively common in patients with brachiocephalic fistula, and proximal swing stenosis is more common in brachiobasilic fistula.[26,27] In patients with AVGs, stenoses frequently affect the venous anastomosis or the adjacent outflow vein segment.[28] The presence of central venous stenosis can be one of the complications after previous central venous catheter implantation. In addition, stenosis is also very common at the sites of repeated punctures.

Arteriovenous fistula maturation assessment

It is very important for the dialysis technician to know when to begin cannulation of the AVF after the creation. However, nearly 50% of autogenous AVFs fail to reach maturity and require intervention.[29,30] During maturation assessment, sonographers can assess whether the patient's vessels are too small or too deep to puncture, and measure flow volume to check for insufficient blood flow in the fistula system. Large accessory branches or significant stenosis may also contribute to the immature fistula vessel and must be identified by ultrasound. The 2019 K-DOQI Clinical Practice Guidelines recommend that sonographers use the "six rules" to assess the maturity and suitability of dialysis fistulas. These rules are as follows: Assess the fistula 6 weeks after fistula creation; vessel diameter should be >6 mm, vessel depth should be <6 mm, blood flow should be >600 mL/min, and segment length for venipuncture should be <6 cm.[21] Another study group, the Hemodialysis Fistula Maturation Study Group, defines the suitability of hemodialysis fistula as a condition where the minimum diameter of the outflow vessel is >4 mm and the blood flow rate is >500 mL/min.[31,32] The above two methods of determining fistula maturity are summarized in Table 3.

Prearteriovenous fistula creation evaluation

The presence of vascular abnormalities prior to creation surgery may decrease the likelihood of unsuccessful AVF maturation. If the candidate vein is found to be too small or has too many accessory branches, the likelihood of an unsuccessful anastomosis or an immature AVF is increased. Almost all guidelines consistently recommend appropriate evaluation and vascular mapping before fistula creation.[16,21] A proper candidate vein for cannulation should not be too small in diameter (preferably larger than 2.0–2.5 mm before surgery),[33,34] not be too deep (<6 mm in depth), have a linear, noncurved course, and preferably should not have an accessory branch within 5 cm of the expected anastomosis site.[21,35]

Table 3: Two assessment methods to determine autogenous arteriovenous fistula maturity

	Rules of six	HFM clinical maturation criteria
Source	From the 2019 K-DOQI clinical practice guideline[21]	From HFM study group[31,32]
Timing of investigation	6 weeks after fistula creation	1 day, 2, and 6 weeks after fistula creation
Criteria of suitability	Vessel diameter >6 mm	Minimum vessel diameter ≧4 mm
	Vessel depth <6 mm	Blood flow rate ≧500 mL/min
	Blood flow ≧600 mL/min	
	Segment length for punctures >6 cm	

HFM: Hemodialysis fistula maturation, K-DOQI: Kidney Disease Outcomes Quality Initiative

Diagnosis of other arteriovenous fistula disorders

Aneurysm and pseudoaneurysm

Aneurysm of the AVF or AVG is the dilation of the vessel itself into a bulbous protrusion, whereas pseudoaneurysm is the formation of a space with blood flow secondary to extravasation after perforation of the vessel. Possible causes of aneurysms and pseudoaneurysms are wall degeneration due to high blood flow, repeated punctures (especially buttonhole punctures), stenosis downstream of the vessel, or high venous pressure.[36]

Aneurysms and pseudoaneurysms can be easily identified using the B-mode of ultrasound. A "yin-yang sign" or "Korean flag sign" [Figure 5] can be observed in the aneurysm or pseudoaneurysm using the CD-mode because the blood flow is constantly swirling in the spherical structure. Using the CD- or PW-mode, a pseudoaneurysm can be observed to have a flow connection to the main stem of the vessel.[37]

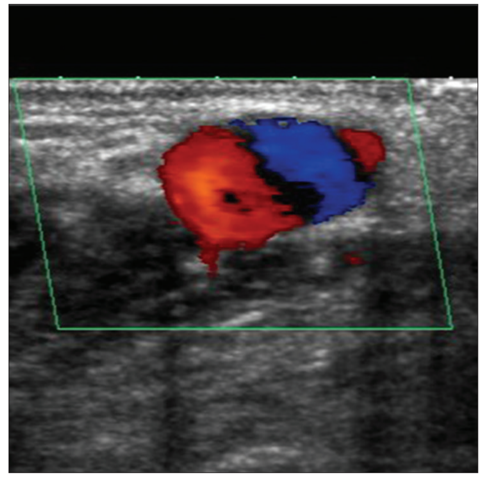

Figure 5: A "Korean flag sign" is observed in color Doppler-mode in an aneurysm of the forearm cephalic vein of a hemodialysis patient

High-output heart failure

An AVF generates a left-to-right shunt that contributes to a decrease in systemic resistance and an increase in venous return and preload. These changes further trigger an increase in cardiac output, and the long-term consequences could be high-output heart failure (HOHF).[38] Definitive diagnosis of HOHF requires right heart catheterization. To recognize HOHF, clinicians must be alert to potential symptoms and physical findings related to the heart and AVF, including tachycardia, wide pulse pressure, and jugular vein engorgement. Some patients with HOHF present with steal phenomenon syndrome over the distal limb of the same side of the AVF.[39] By applying brief manual compression to the arteriovenous anastomotic site, temporary occlusion of the high-flow fistula may restore normal blood flow to the systemic circulation, resulting in a decrease in pulse rate, and increase in blood pressure.[40] The left ventricular ejection fraction on the echocardiogram may be normal or high. During AVF ultrasound examination, a sonographer should be alert for HOHF if a Qa >1.5–2.0 L/min is detected in an AVF, and refer the patient to a specialist or consider flow reduction surgery.[18]

Dialysis access-associated steal syndrome

Dialysis access-associated steal syndrome (DASS) is an uncommon but serious complication following AVF creation. When an autogenous AVF or AVG is created, the pressure gradient created by the anastomosis may cause arterial supply from the distal hand (e.g., from an ulnar artery or collateral flow) to be "stolen" to the anastomotic site via retrograde flow. This steal phenomenon is physiologically present in 80%–94% of arteriovenous accesses without symptoms or clinical significance.[41,42] However, when inherent compensatory mechanisms are insufficient to maintain distal arterial perfusion, acute or chronic ischemic insults develop.

Symptoms of DASS include nail changes, tingling, and numbness during hemodialysis, and moderate symptoms include cyanotic fingers, rest pain, sensory or motor dysfunction, ulcerations, or even tissue loss at the fingertips. If acute and severe hypoxemic symptoms such as acute-severe pain and cyanotic fingers are observed, urgent surgical ligation of the fistula should be considered.[43,44] The diagnosis of DASS should be based on reduced or absent perfusion of the digital artery. Retrograde or bidirectional flow in the artery distal to the anastomosis can be detected with Doppler ultrasound. Manual compression of the AVF can be performed during ultrasound examination, and restoration of antegrade flow or an increase in digital perfusion may be observed after manual occlusion of the fistula.[45] The sonographer should also be alert to other possible vascular conditions that may exacerbate the steal phenomenon, such as inflow stenosis and distal arteriopathy. This information is essential for the surgeon to determine the interventions of DASS.

Vascular mapping of the arteriovenous fistula system

A formal vascular ultrasound or angiogram report is usually filled with text and numerous values or complex images that are difficult for other health-care professionals to understand. At this point, the surgeon, vascular interventionalist, and sonographer can create a vascular map with a simple image to the patient or hemodialysis unit. The vascular map can be a personalized as a "vessel passport" for each patient and shows the course of the fistula vessel, blood flow and direction, recommended cannulation sites, and vascular lesions. The dialysis technician can perform a puncture based on the vascular map. Once AVF dysfunction is noted, vascular interventionalists can determine the appropriate treatment plan in advance based on each patient's vascular map.

Regular surveillance of arteriovenous fistula

Numerous clinical studies have investigated whether regular surveillance has a beneficial effect on dialysis access. Regular monitoring of the AVF theoretically enables early detection of AVF dysfunction, allowing early intervention to improve access lifespan and reduce the use of double-lumen catheters.[46] However, the results of regular surveillance by Doppler ultrasound in recent studies remain conflicting, especially for AVG surveillance.[47-49]

Aggressive clinical monitoring of the AVF remains critical. The National Kidney Foundation's K/DOQI guideline recommends careful inspection of the vascular access before each dialysis session as well as monthly monitoring of flow volume and other parameters of the dialysis access.[21]

Conclusions and Perspectives

Ultrasound is already an indispensable tool in today's health-care environment and can help patients receiving dialysis in a variety of ways. Of course, Doppler ultrasound has some limitations. Performing an AV fistula assessment using Doppler ultrasound is challenging and requires considerable training, and the accuracy of ultrasound findings is operator-dependent. Moreover, most ultrasound reports may not fully reflect the true hemodynamic changes in the fistula vessel during hemodialysis treatment because it is difficult to perform a real-time AVF study while the patient is receiving hemodialysis.

Nonetheless, the benefits of Doppler ultrasound greatly outweigh these limitations. Doppler ultrasound can help physicians to evaluate the comprehensive function of an AVF. A simple ultrasound evaluation of the AVF and vascular mapping can guide the dialysis technician to the proper vessel cannulation sites and provide the surgeon with more precise information before intervention. Although not mentioned in this review, the use of Doppler ultrasound can also improve the safety and efficacy of vascular procedures such as vascular puncture, angioplasty, and brachial plexus blocks. All these contributions can lead to improved quality of life and better outcomes for patients receiving dialysis.

Declaration of patient consent

The ultrasound figures used in this article were obtained with the explicit consent of the patients. All identifying information has been removed to protect patient confidentiality.

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Conflicts of interest

There are no conflicts of interest.

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