

Doppler Ultrasound in Vascular Access care: the pearls and pitfalls of flow volume measurement

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ABSTRACT

Vascular access (VA) care is a critical part of the management of end-stage renal disease. Optimal care is necessary to avoid underdialysis and VA loss, leading to increased morbidity, mortality, and health-care-associated costs. The cornerstone of VA surveillance is flow volume (Qa) measurement. One of the most common ways to quantify Qa in clinical practice is by using duplex ultrasound (DUS), which is based on the Doppler method. DUS is a cheap and non-invasive technology that allows direct Qa measurement and the simultaneous visualization of the VA morphology, which allows the diagnosis of underlying lesions. In addition, DUS has a similar precision to Ultrasound Dilution (UD) methods. On the other hand, DUS is an operator-dependent technique, has more potential measurement errors, is time-consuming, and also loses accuracy in higher Qa. This narrative review aims to discuss the theory and technical considerations behind DUS, as well as its advantages, disadvantages, and pitfalls. We also review the reliability of DUS measurement and its correlation with UD methods. Finally, we reflect on the role of DUS Qa measurements in arteriovenous fistula maturation and surveillance. Despite the overall quality of data regarding VA surveillance not being high, we believe that DUS will remain one of the most important tools at our disposal in every step of VA care.

Keywords: Arteriovenous Fistula, Blood Flow Volume, Doppler Ultrasonography, Hemodialysis, Vascular Access

INTRODUCTION

Vascular access (VA), often labeled the lifeline of the hemodialysis patient, is a critical part of the management of end-stage renal disease (ESRD)¹. Optimal VA care is necessary to avoid underdialysis and VA loss, undoubtedly leading to increased morbidity, mortality, and health-care-associated costs^{2,3}. VA monitoring was defined by the National Kidney Foundation Kidney Disease Outcomes Quality Initiative (KDOQI) as the examination and evaluation of the VA using the physical examination to detect signs that suggest the presence of dysfunction². On the other hand, surveillance consists of periodic evaluation through the use of one or more tests that may require special instrumentation and for which an abnormal result suggests the presence of dysfunction².

The cornerstone of VA surveillance is VA flow volume (Qa) measurement. In the presence of significant arteriovenous fistula (AVF) stenosis, there is almost always a reduction of the Qa, independent of the kind of arteriovenous shunt, anatomical location, or stenosis topography^{4,5}. Ultrasound dilution (UD) is often referenced as the gold-standard, but unfortunately, a true gold-standard for *in vivo* non-invasive Qa measurement does not exist^{6,7}. UD methods are highly reproducible but also suffer from potential measurement errors mainly related to inadequate mixing of the indicator solution, for example, due to aneurysmatic outflow veins or needle orientation and position^{8,9}. Nowadays, one of the most common ways to quantify Qa in clinical practice is by duplex ultrasound (DUS)¹⁰. DUS also enables the

direct visualization of the VA morphology, which allows the diagnosis of underlying lesions and contributes to the therapeutic decisions made by the VA team.

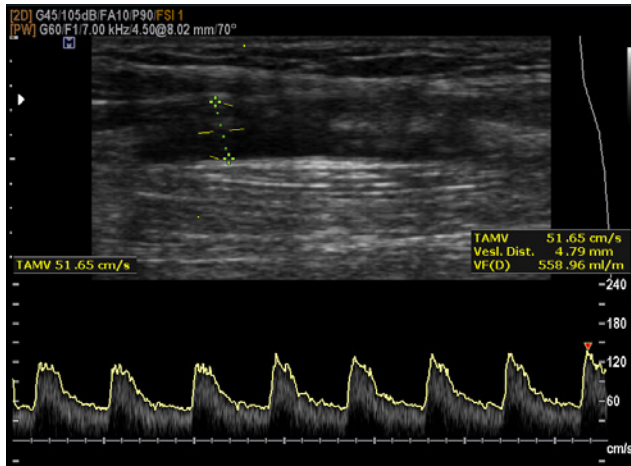
Recently, the European Renal Best Practice (ERBP) clinical practice guidelines on hemodialysis VA stated that the evidence for surveillance in addition to clinical monitoring is inconclusive¹¹. Still, DUS Qa measurement is a very useful tool in vascular access care that is being increasingly adopted by nephrologists in their daily clinical practice. All the clinicians involved in VA care should be familiar with its advantages, disadvantages, and potential pitfalls, as well as its reliability and correlation with other methods in chronic kidney disease patients.

DUPLEX ULTRASOUND – THEORY AND TECHNICAL CONSIDERATIONS

Ultrasound is an imaging technique that allows the investigation of the VA through the use of a transducer capable of emitting and receiving ultrasounds and converting them to an electrical signal. This signal is analyzed by a processor and, based on the amplitude of the signal received, a gray-scale image is displayed on the screen of the ultrasound machine¹². The use of Doppler ultrasound for the detection of blood flow in the hemodialysis VA was reported for the first time in 1971, following the increasing use of the Doppler ultrasonic flowmeter as an adjuvant in the diagnosis and management of vascular disease at the time¹³. The simplest and most widely available method

Figure 1

Doppler Ultrasound blood flow measurement. A multifrequency linear probe is placed in a longitudinal view across the centerline of the brachial artery, in a straight portion, free of calcifications and stenosis. Pulsed wave sample volume should encompass the whole lumen, using an insonation angle of $\leq 60^\circ$, and without overlapping the vessel walls. The direction of the cursor should be parallel to the blood flow. Once the velocity spectrum is obtained, mean velocity and the diameter of the vessel are measured, and flow volume is calculated by the Q formula [see text].



for Qa estimation using DUS is based on the single-point Doppler method¹⁴.

The Austrian physicist Christian Doppler described the Doppler effect in 1842¹⁵. The Doppler effect is defined as the change in frequency of a sound wave due to a reflector moving towards or away from an object. This phenomenon is common in our everyday life, for example, when an ambulance approaches and goes away while the listener stands in the same position. The pitch of sound increases when the ambulance approaches, and then suddenly, the sound pitch decreases as the vehicle moves away from the listener. Applying the Doppler effect in a blood vessel allows us to accurately measure the movement of red blood cells as their movement creates a change in the frequency of the sound wave coming from the transducer¹⁶.

The measurement of Qa should be done using a multifrequency linear probe and an adequate preset for high-velocity measurement¹⁰. In a longitudinal scan, the peak velocity is estimated using pulsed-wave Doppler at a straight location along the presumed centerline of a vessel, using an insonation angle of $\leq 60^\circ$ (Figure 1). The correct way to measure blood velocity is still a matter of debate. Some authors advise placing the sample volume encompassing the whole lumen, to include the high central velocities and slower peripheral velocities^{17,18}. Other authors prefer to insert the sample volume encompassing only 50–70% of the vessel lumen, stating that it reduces the interferences due to the vibration of the vessel walls^{19,20}. Because blood velocity changes during the cardiac cycle, it is mandatory to obtain an average velocity. Once the velocity spectrum is obtained, flow volume is calculated by the following formula²¹:

$$Q = \text{average velocity (cm/s)} \times \text{cross-sectional area of the vessel (mm}^2) \times 60 \text{ (seconds)}, \text{ where the cross-sectional area is given by } A = \pi \times d^2 \text{ (mm)} / 4.$$

For the calculation of the luminal cross-sectional area, the diameter is measured in the same longitudinal plane used for velocity interrogation, making a 90° angle with the sample volume gate.

In DUS flow volume measurement, it is assumed that the flow is minimally disturbed, the vessel is circular and that a parabolic velocity profile across the lumen is present, based on the Poiseuille flow theory²¹. The brachial artery is more likely to be circular and have a long straight segment, and is less susceptible to compression than the outflow vein²². For this reason, the site for Qa measurement should be the brachial artery, whether the AVF is radial or brachial artery-based, even knowing that part of the blood flow will not enter the VA system^{10,23}. It is also important to note that up to a third of the blood flow of a radiocephalic AVF comes from the cubital artery through the palmar arch²⁴, and measurement in the brachial artery prevents the underestimation of the Qa in this kind of AVF. If possible, Qa should be measured at least 5 cm proximal to the anastomosis, in a straight part, free of calcifications or stenosis²³. In case of high bifurcation of the brachial artery, the Qa should be measured in the segment before the bifurcation. If it is not possible, the axillary artery should be considered²⁵. In polytetrafluoroethylene (PTFE) grafts, Qa should be measured in the venous segment of the graft, if there is a place where it can be accurately measured (e.g. straight and non-punctured site, without intragraft stenosis), as it correlates better with the UD methods²⁶. Otherwise, the brachial artery should be used.

Copious ultrasound gel, image optimization with the adjustment of the focus, zoom, and grayscale, as well as careful attention to limit pressure applied by the transducer, will minimize the deformity of the vessel, which may affect measurements of the diameter. Evaluation of inflow, outflow, turbulent or stenotic flow, identification of large competing vein branches, aneurysms, assessment of the depth from the skin surface, and the relationship with the surrounding structures are the basics of the remaining hemodialysis access DUS examination. Finally, before the Qa measurement is started, the patient should be comfortable in the supine position, and at rest for at least 3 minutes. The examination should be performed at room temperature and preferably before the hemodialysis session, as the Qa will tend to be lower after the treatment^{17,25}.

■ DUPLEX ULTRASOUND – ADVANTAGES, LIMITATIONS, AND PITFALLS

At present, DUS is the first-line imaging modality to assess the VA. It is a cheap, easily available, non-invasive, non-ionizing imaging method that allows not only the hemodynamic investigation of the access but also the direct visualization of the VA morphology and its surrounding structures²⁷. It also permits the investigation of other dysfunctions not related to stenosis and thrombosis, such as aneurysms or hematomas, and can be used in the pre-dialysis period²⁸. Moreover, portable ultrasound machines can be used at the point-of-care by the nephrologists in the dialysis unit or outpatient clinic for

the immediate detection of VA pathology or by the dialysis staff for ultrasound-guided cannulation²⁹.

The major limitation of DUS is that it is an operator-dependent technique that needs a substantial period of learning to achieve proficiency³⁰, even more for VA due to its unusual hemodynamics and anatomical variations. Also, DUS's ability to evaluate central vessels is limited due to the location of the vessels inside the thorax and is mostly confined to indirect information from Doppler interrogation, which can raise the suspicion of central stenosis³¹. Other potential limitations on performing this examination are recent surgery, severe edema, immobilization of the member, presence of bandages or bleeding wounds³².

The accuracy of Qa strongly depends on the accuracy of the diameter measurement (Table 1). The diameter measurement should make a 90° angle with the sample volume gate. Since any error in the determination of the diameter will introduce a fractional error in the calculation, Qa should be measured at least three times and averaged. Color Doppler should only be used to determine the direction of flow and should be turned off to avoid the overestimation of the vessel diameter³³. Excessive transducer pressure over the brachial artery is associated with a decrease in the cross-sectional area measured in the longitudinal view and consequent underestimation of the Qa³⁴. A technical error in determining the correct center of the vessel will also reduce the cross-sectional area, reducing the calculated Qa⁶. Also, the cross-sectional blood vessel area is often elliptical rather than circular, for example, due to plaque accumulation. The necessary assumption of a circular vessel area will result in an underestimation of the "real" Qa¹⁴. Even small curvatures can lead to a focal increase in velocity that will increase the derived flow and should be avoided by the operator³⁵.

The diameter of the brachial artery varies during the different phases of the heart cycle. The same phase of the cardiac cycle should be considered to reduce the potential measurement error caused by this variability. Some authors advocate measuring the Qa during the systolic phase^{18,36}, while others recommend the end-diastolic phase³⁷.

In the presence of an arrhythmia, there are beat-to-beat variations in the blood velocity, which will influence the Qa calculation. An average of three consecutive heart cycles should be used to reduce this effect³⁸.

The sample volume should include at least 70% of the vessel lumen. Incomplete insonation will lead to an overestimation of the mean blood velocity^{18,38}. The spectrum should only display a signal from the artery. Inadequate pulse repetition frequency will lead to aliasing and errors in velocity measurement and should be adjusted by the sonographer²⁰. Over-gaining the Doppler signal will overestimate the Qa measurement as it introduces noise that is incorporated in the Doppler waveform. Also, under-gain will reduce the Doppler signal and cause a significant underestimation of the mean velocity³⁹. The presence of plaques and calcifications may lead to a posterior acoustic window or decrease in the Doppler signal, underestimating the velocity measurement⁴⁰.

Although modern-day ultrasound machines incorporate an electronic Doppler angle correction, the operator still has to place the pulsed-wave cursor parallel to the direction of the flow. Flow direction is not always parallel to the vessel wall, even in normal vessels. Incorrectly identifying the direction of flow will lead to an error in the calculated velocity³⁹.

■ RELIABILITY OF DUPLEX ULTRASOUND FLOW VOLUME MEASUREMENTS

In a recent in vitro experimental study on a phantom model with three different operators and five different commercially available ultrasound machines, no significant intraobserver or interobserver differences were found in Qa measurement⁴¹. This shows the good test-retest and inter-method reliability of modern scanners, which is reassuring for the clinicians.

In an experimental study in PTFE grafts in dogs, DUS showed a reasonable agreement ($r = 0.73$) in Qa measurement compared to

Table 1

Tips to avoid potential Qa measurement errors with Duplex Ultrasound.

Duplex Ultrasound	
Diameter assessment	<ul style="list-style-type: none"> • Qa should be measured multiple times and averaged; • Color-Doppler should be turned off to avoid overestimation of the diameter³³; • Apply the least amount of pressure possible to avoid a decrease in the cross-sectional area³⁴; • Use the transverse view to confirm that Qa is measured in the center of the vessel⁶.
Cardiac cycle	<ul style="list-style-type: none"> • Use the same phase of the cardiac cycle; • In the case of arrhythmia, calculate mean velocity using 3 heart cycles³⁸.
Spectral Doppler-related	<ul style="list-style-type: none"> • Sample volume should encompass the whole lumen of the vessel^{10,23}; • Qa should be measured in a straight part of the brachial artery, free of calcifications or stenosis^{17,23}; • Only the velocity above the baseline should be considered in the calculation of the mean velocity; • Pulse repetition frequency and the Doppler signal should be optimized^{20,50}.
Insonation angle	<ul style="list-style-type: none"> • Keep the insonation angle $\leq 60^\circ$¹⁷; • Place the pulsed-wave cursor parallel to the direction of the flow⁵⁰.
Other	<ul style="list-style-type: none"> • The examination should be done at room temperature; • The patient should be comfortable and at rest for, at least 3 minutes¹⁷.

electromagnetically measured flow-rates over a range of up to 1400 ml/min⁴². An improved correlation was obtained when flow ranged up to 900 ml/min ($r = 0.989$). This is related to the DUS flow volume equation, as small changes in the diameter measurement or mean velocity will cause a disproportionately higher error in Qa^{6,9,41}. There was also an improvement in accuracy when the flow was measured in the venous segment of the graft ($r = 0.92$), due to a reduction of turbulence in that segment.

He *et al.* compared Qa measured by DUS and MRI and reported a significant correlation between methods, when Qa was measured in the proximal artery 2 cm proximal to the anastomosis ($r = 0.89$) or in the outflow vein, 10 cm distal to the anastomosis ($r = 0.92$)⁶. DUS also shows excellent inter-method reliability with MRI. However, the proximal artery measurement showed more data points within the 95% limit of agreement, providing evidence to support the recommendation that Qa should be measured in the brachial artery.

Chowdhury and colleagues evaluated DUS Qa analysis before and after hemodialysis in a population with brachio-cephalic AVF and concluded that there is a significant reduction in Qa of 105 mL/min (-6.9%) post-hemodialysis²⁵. A similar reduction of Qa was reported with UD methods⁴³. This reduction can be explained by an increase in blood viscosity due to ultrafiltration⁴⁴ that reduces the overall blood flow rate and effective circulating volume⁴⁵. However, Bland-Altman analysis of the study data revealed a high variability of Qa measurements with limits of agreement from -599 mL/min to +810 mL/min between pre and post hemodialysis Qa measurement. Interestingly, less than 30% of the patients had a variation of Qa > 25%, and all of them had a pre-hemodialysis Qa > 1000 ml/min. This results highly suggest that the variability of Qa is due to errors in measuring the mean velocity or diameter (Table 1).

CORRELATION BETWEEN DUPLEX ULTRASOUND AND ULTRASOUND DILUTION METHODS

Following the first clinical trial of ultrasound dilution methods in 1995⁴⁶, Sands *et al.* compared the Qa measurement by UD and DUS⁴⁷. They performed 66 measurements in 9 AVFs and 10 PTFE grafts, using

the Transonic hemodialysis monitor (HD01, Transonic Systems, Ithaca, NY). A linear relationship between the two measurements with a correlation coefficient (r) of 0.83 was reported. In the next years, other studies followed (Table 2).

Schwarz and colleagues⁴⁸ evaluated 59 hemodialysis patients with forearm AVF and compared the performance characteristics of UD and DUS in the detection of stenosis. They reported similar performance characteristics between UD and DUS for the detection of stenosis (receiver operating characteristic of 0.79 and 0.8, respectively). Qa determined by DUS was lower than those obtained by UD. Huisman *et al.*⁹ reported a reasonable correlation between UD and DUS ($r = 0.69$). In their study, DUS Qa measurements were also significantly lower than UD. Moreover, Weitzel *et al.* reported a better correlation between UD and a Doppler ultrasound-based Qa measurement with lower Qa (< 1600 ml/min, $r = 0.91$)⁴⁹.

Lin *et al.*⁵⁰ reported the use of a variable pump flow-based Doppler ultrasound method for Qa measurement. In their work, they assessed the Qa with this new technique in 55 patients and compared it with both UD and conventional DUS. In a sub-analysis of this population, UD and DUS had an r of 0.94 and an intraclass correlation coefficient (ICC) of 0.86.

Although the Qa measurement was not taken in the brachial artery and the DUS technique was not consistent across these observational studies, they support that DUS and UD Qa measurements have a good correlation. They also show us that DUS measurements are consistently lower than those from UD. Taking this into account, we believe that the correlation coefficient is not a good metric for Qa measurement because it does not quantify the difference between tests. Knowing the difference between measurements, for example, using a Bland-Altman plot, is much more important from the clinician's point of view as it allows a better interpretation of both tests when performed in the same individual. Surprisingly, only Schwarz *et al.*⁴⁸ reported a Bland-Altman plot mean difference of 212 ml/min (95% CI, -778 to 1,202). We think that a mean difference of approximately 200 ml/min would be acceptable for clinical purposes in a normal-flow VA, but should be lower in VA with significant stenosis and reduced Qa, as it will influence treatment decisions.

Table 2

Studies comparing ultrasound dilution and duplex ultrasound Qa measurements in the same individual.

Study	UD System	DUS Machine	Methods	DUS Qa Measurement	Results
Sands <i>et al.</i> ⁴⁶	Transonic HD01 hemodialysis monitor	Phillips P700 CVI	9 AVFs and 10 PTFE grafts	Not reported	$r = 0.83$
Schwarz <i>et al.</i> ⁴⁸	Transonic hemodialysis monitor	Acuson-128 ultrasound machine	59 hemodialysis patients with forearm AVF	Outflow vein, within one week of the UD measurement	UD ROC 0.79; DUS ROC 0.8
Lin <i>et al.</i> ⁵⁰	Transonic HD02 hemodialysis monitor	Toshiba Model SSA 340A	55 patients, 53 AVFs and 2 grafts	During the HD session, with the transducer placed in the outflow vein	$r = 0.94$; ICC = 0.86
Huisman <i>et al.</i> ⁹	Transonic HD01 hemodialysis monitor	Siemens Sonoline Antares	24 patients with 3 PTFE grafts and 21 AVFs	Shortly before the HD session, in the outflow vein between usual arterial and venous puncture sites	$r = 0.69$

AVF – arteriovenous fistula; PTFE – polytetrafluoroethylene; r – correlation coefficient; UD – ultrasound dilution; DUS – duplex ultrasound; ROC – receiving operator characteristics; ICC – intraclass correlation coefficient.

■ THE ROLE OF DUPLEX ULTRASOUND FLOW VOLUME IN AVF MATURATION AND SURVEILLANCE

Failure to mature is a frequent complication of AVFs⁵¹. Achieving an adequate Qa is one of the key factors for a fistula to be used for hemodialysis. The other is an outflow vein with adequate development for cannulation. In general, a Qa of 500 mL/min and a venous diameter of at least 4 mm are required for a radiocephalic AVF to be suitable for hemodialysis⁵² and are usually achieved by 4 to 6 weeks. Usually, failure to mature is due to either a stenosis and/or the presence of a significant accessory vein, which causes a diversion of the flow to other venous systems.

In our opinion, a DUS evaluation is mandatory, at least once in the first 4 to 6 weeks after AVF creation. Early monitoring with DUS not only allows the measurement of the Qa but can also identify the problem leading to primary failure. The stenotic lesions present in the AVF circuit are usually progressive and will lead to thrombosis and VA loss over time. DUS can also measure the Qa of an individual accessory vein and attest to its importance in the underdevelopment of the AVF. Early therapy after DUS evaluation, in cases of impaired AVF maturation, has been shown to increase the likelihood of achieving a VA suitable for hemodialysis in approximately 50%⁵³.

The development of stenosis is the main enemy of AVF longevity. The diagnosis of stenosis requires a reduction > 50% of the vessel lumen (morphological criteria) and a ratio > 2 of the peak systolic velocity (PSV) between the stenosis area and the pre-stenotic area or a PSV > 400 cm/s in a non-anastomosis zone (functional criteria). For the stenosis to be hemodynamically significant, the presence of at least one additional criterion is required. It can either be a residual vessel diameter < 2 mm, or a Qa < 500 ml/min in AVFs (< 600 ml/min in AVGs), or a > 25% reduction in Qa if the Qa < 1000 ml/min¹⁰. In the absence of these additional criteria, the stenosis is considered borderline⁵⁴.

The early detection of significant stenosis allows angioplasty or surgical correction to be performed and decreases the incidence of thrombosis, thus improving patency access rates. A recent meta-analysis reported that the risk of thrombosis was significantly decreased by 43.8% with the use of access flow surveillance, but no benefit was noted in AVGs⁵⁵. The absence of benefit from surveillance in AVGs is consistent across the literature^{56,57}.

The last version of the ERBP clinical practice guidelines on hemodialysis states that caution is required in interpreting both the relative and absolute effect sizes obtained by the meta-analysis¹¹. This moderate-quality evidence also needs to be weighed against the increased number of diagnostic angiographies, which may ultimately not change the number of invasive procedures a person needs to undergo in their lifetime. Because of uncertainties around the absolute reduction in risk of AV fistula failure, which needs to be weighed against an increased number of diagnostic angiograms, the ERBP group felt that more research is needed before any specific recommendation can be made.

■ FUTURE DIRECTIONS

New ultrasound-based technologies for measuring flow are emerging. Transverse oscillation ultrasound is a vector-based technique

where the blood velocities of both the axial and the transverse directions are obtained, and the complexity of blood flow can be visualized and quantified⁵⁸. Ultrasound imaging velocimetry is a non-Doppler method, that tracks speckles scattered from within blood by micro-bubbles, providing a new tool to measure blood flow accurately⁵⁹. Without some of the limitations of conventional DUS for VA assessment, they could improve the accuracy of Qa measurements and increase the strength of VA surveillance. Further clinical research of these technologies in the VA field is required.

■ CONCLUSION

DUS is a cheap and non-invasive technology that allows Qa measurement and the direct visualization of the VA morphology. DUS has similar precision as UD methods but is operator-dependent and with more potential measurement errors (Table 1). It also loses accuracy in higher Qa, and clinicians should keep in mind that its Qa measurements are usually lower than UD.

More research is needed to standardize the DUS operator technique and quantify the difference in Qa measurements with other methods, which would allow a better clinical interpretation of Qa measurement tests and a higher quality of research in this area. Unfortunately, the overall quality of data regarding VA surveillance is not high and robust guideline statements cannot be made, in part because in the randomized clinical trials not enough attention was paid to the Qa measurement itself.

We hope that better data regarding VA surveillance will soon be available. Still, we believe that DUS will remain one of the most important tools at our disposal in every step of VA care.

Disclosure of potential conflicts of interest: none declared

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