CHAPTER 30

Ultrasound in Vascular Access

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Hemodialysis is the most prevalent renal replacement therapy for patients developing end-stage renal disease (ESRD). Survival on dialysis is directly related to the adequacy of dialysis, which, in turn, substantially relies on the nature of dialysis access. Arteriovenous fistula (AVF), with superior long-term outcomes, is considered the preferred access for long-term hemodialysis (HD).[1] Compared with other industrialized countries, the prevalence rate of AVF is lowest amongst ESRD patients who are dialysis dependent in the United States.[2,3] In an attempt to increase AVF prevalence, Centers for Medicare and Medicaid Services (CMS) launched the Fistula First initiative in 2004. As a result, the incidence of AVF in the United States has risen from 27% in 2003 to over 50% and continues to increase.[4] Preoperative vessel mapping ranks high among the "change concepts" advocated by Fistula First that have contributed to this increase in AVF constructions.[5] Currently the use of ultrasound has evolved as a preferred technique for vascular mapping in planning for AVF. Besides vessel mapping, real-time ultrasound also can play an important role in other aspects of vascular access management. This chapter will discuss the use of ultrasound in planning and management of vascular access in ESRD patients.

Ultrasound

Ultrasound is the term used to describe sound waves with a frequency greater than that of audible sound. Audible sound has a frequency range of 8 to 20 kilohertz (KHz). The range of frequency of sound waves used in medical applications is from 2 to 20 megahertz (MHz). The present generation of ultrasound transducer probes, used in vascular access, has multiple piezoelectric crystals capable of emitting ultrasound waves when stimulated by electrical energy and are called linear array transducers.[6] Assuming that the sound waves travel through soft tissue at a constant speed, variable amounts of sound waves are reflected back (*echo*) at the interface between different soft tissues (e.g., subcutaneous tissue and muscle interface) and have different acoustic impedance (tissue density that affects sound wave propagation). Assuming that sound waves travel in a straight line, the crystals that emit these waves in the transducer also sense the reflected waves and convert the sound energy back to electrical energy. Cleverly engineered handheld probes utilize computer capabilities to process the information transduced, based on the distance traveled by the wave that was emitted before it was reflected, and presents this information in a two-dimensional spatial manner on a television screen, thereby producing an image in grey scale (B mode). The speed at which the sound pulses can be generated depends on the frequency of the ultrasound. Present transducer probes have the capacity to generate and gather return-wave information at rapid rates (e.g., 5,000 times per second). This rapid change in picture frames enables the machines to scan in real time. Real-time scanners can generate images at rapid sequence and show the motion of the transducer or the tissue as it is being scanned (real-time ultrasound).[6,7]

Doppler Ultrasound

The frequency of ultrasound waves stays constant when reflected by a stationary object. On the other hand, the frequency of the waves increases or decreases if the waves are reflected by a moving object (just as the sound of a police alarm gets louder as the vehicle approaches a listener). The relationship between this alteration of frequency was first summarized and mathematically explained by Christian Doppler in 1842.[8] Early clinical application of the Doppler effect was in the evaluation of blood flow. Early-generation Doppler probes used two crystals, one continually producing the ultrasound and the other continually receiving the reflected waves (*continuous wave Doppler*) that are converted to audio signals. More advanced probes have crystals that can generate sound waves in short pulses and compute the reflected shifts (*pulse wave Doppler*). These probes can provide good depth resolution.[7,9]

Duplex Doppler is the term used for a combination of the B mode for imaging and Doppler for flow evaluation. The B mode provides imaging for accurate focusing of the Doppler to assess flows in specific locations. This is the most useful imaging modality for the functional evaluation of a vascular access. Most Duplex Doppler machines are capable of color flow that adds color to a two-dimensional image based on direction or volume of the blood flow.

Ultrasound with duplex Doppler capability can be used in various facets of arteriovenous access planning and management. The utility of this modality in preoperative vascular access planning is well established.[4,5] Intraoperatively, it can be used to image the vessels to select ideal sites for vascular anastomosis and plan precise incisions to expose vessels for access surgery.[10] Postoperatively, the duplex Doppler is an excellent tool for vascular access maturation evaluation. It helps to plan for elective interventions to facilitate early access maturation. It is also useful in evaluating access procedures with long-term problems such as stenosis, aneurismal dilations, and low fistula blood flow states.[11]

Ultrasound for Vascular Access Planning

A careful history and physical examination capturing data relevant to the success of an AVF, such as history of central and peripheral vein abuse, coagulation disorders, anatomy, and quality of available arteries and veins, continues to be the mainstay of vascular access evaluation.[12,13] However, clinical examination is of limited value in patients who are overweight and obese. Clinical examination is also not very reliable in identifying the quality of the vessel wall—and especially the amount of calcification and consequently the luminal diameter of the arteries. Ultrasound vessel mapping should always complement thorough clinical evaluation.[14] Such an approach has shown to increase the incidence of AVF placement and maturation.

Vessel Mapping

Vessel mapping is the term used for a combination of vein and arterial mapping.[15,16] This should be ideally performed or viewed in real time by the operating surgeon and should complement a thorough clinical examination. B mode ultrasonographic imaging using probes with variable frequencies from 5 to 13 MHz generally provide excellent delineation of vascular anatomy. Lowering the frequency provides better penetrance. Hence, lower frequency probes are often used to visualize deeper structures. However, as depth increases, the clarity of the images is compromised. The majority of primary fistulae utilize superficial veins (cephalic in the forearm or in the upper arm) for their outflow. They also rely on brachial or radial artery for the inflow. Both the artery and the vein are superficial structures and are easy to visualize with a linear array transducer at higher frequencies with remarkable clarity. AU1

The technique of vein mapping has been eloquently outlined in many publications, including the guidelines from the Fistula First initiative.[4,17] Results of vein mapping rely significantly on vein distention techniques. Without proper distension, a vein that is well suited for AVF creation is easily missed during the vein mapping. Applying double tourniquets (one below the elbow to occlude the superficial veins and one below the axilla to occlude the deeper vein) provides a better opportunity to maximize venous distention (Fig. 30.1). Use of gravity by leaving the extremity in dependent position (we prefer the subject sitting on a chair with arms rested on the examination couch at a lower elevation to use gravity for vein distention) and gentle tapping on the vein helps break venous spasm and dilate the veins. Similarly, the use of exercise with a tourniquet and warming the extremity can help in vein distension.[4,18] During mapping, it is important to note the size and continuity of the outflow vein. It is also important to note the relation of the vein to the artery. In the lower third of the forearm, it is not unusual for the cephalic vein to distance itself from the artery near the wrist and take a more dorsal course

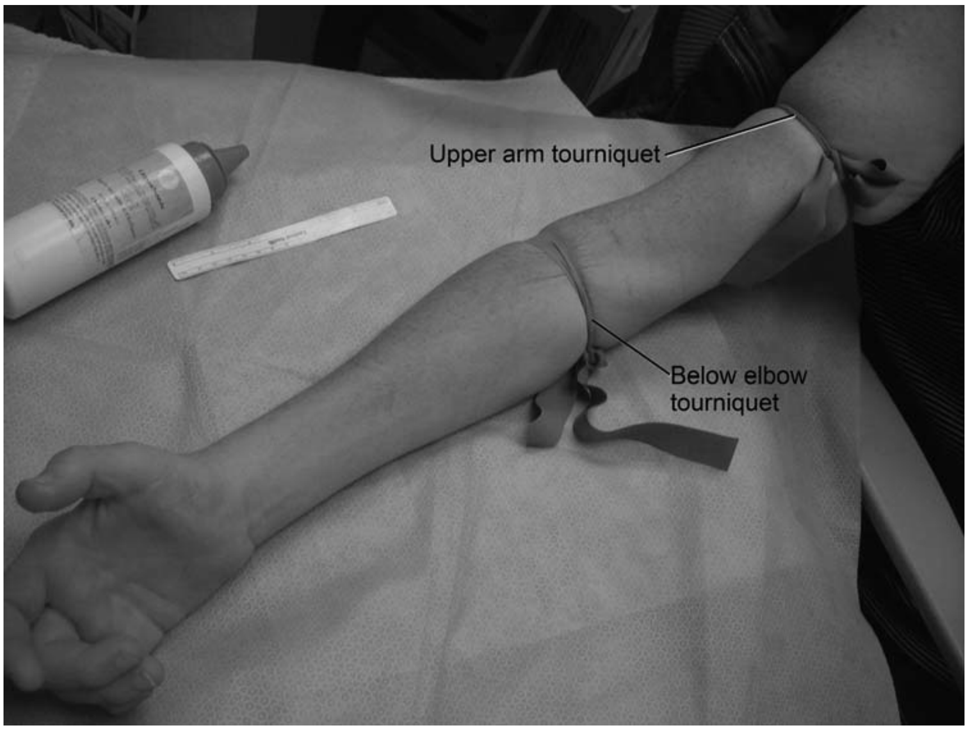

Figure 30-1.
Use of double tourniquets for vein distension.

(Fig. 30.2a). Such anatomic variations play a key role in planning incisions to identify, dissect, and mobilize veins to create a successful arteriovenous anastomosis. Ultrasound vein mapping to assess the diameter and quality of veins has shown to increase the success of fistula maturation.[5]

Arterial evaluation should include measurement of the size of the lumen and also the quality of the vessel wall. Studies have suggested that the preexisting arterial wall disease as measured by intima-media thickness could play an important role in access patency and maturation.[19] This is also evident from successful AVF established in children with soft, healthy, thin-walled arteries that are often <2 mm in diameter.[20] It is the quality of the arterial wall that determines the capacity of the artery to dilate and accommodate

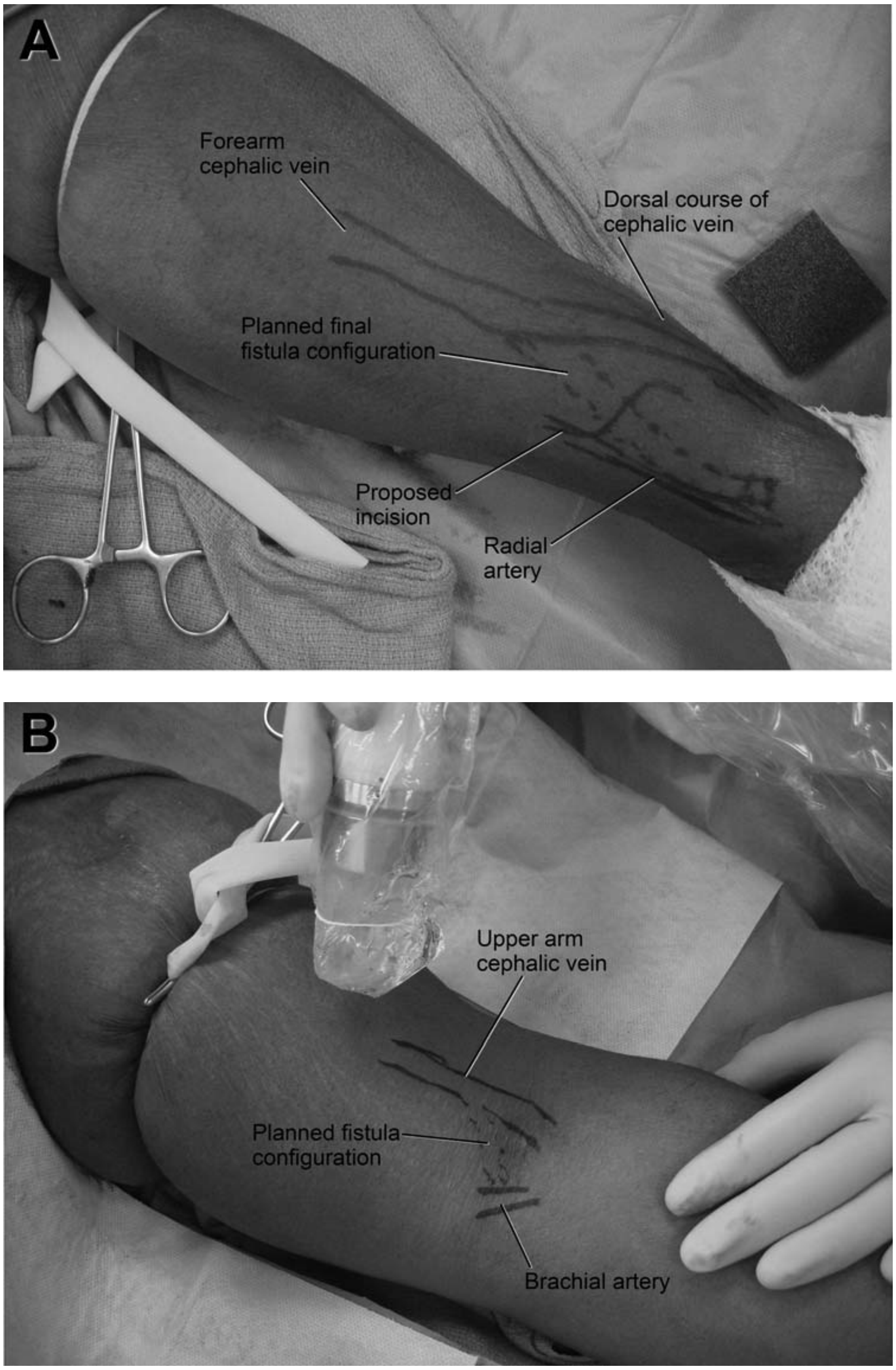

Figure 30-2.
Intraoperative vessel mapping and procedure planning using ultrasound.

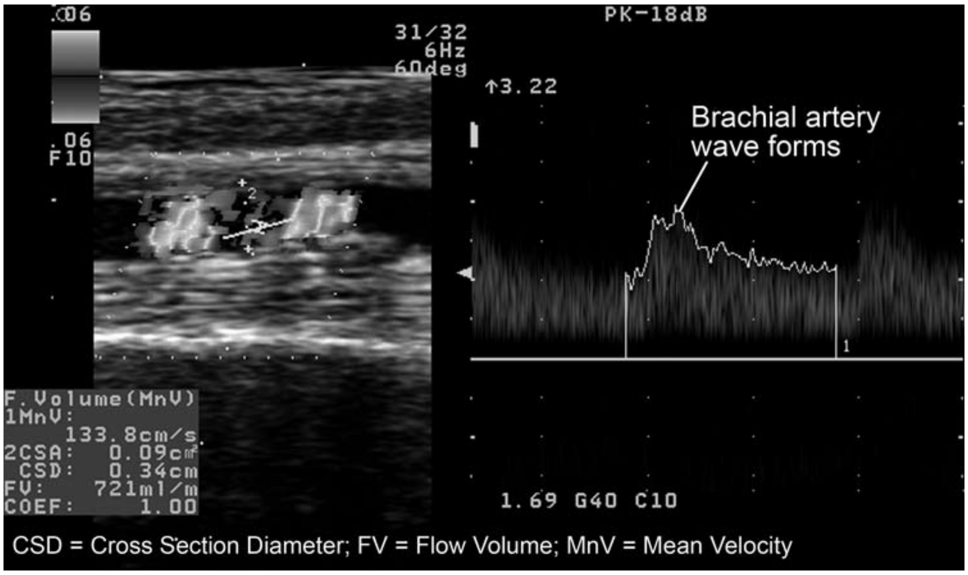

Figure 30-3.
A thick-walled narrow-caliber (3.4 mm) brachial artery with flow of 721 ml/min in a basilic transposition fistula with a 6 mm anastomosis.

the increased flow that is necessary to overcome the acute loss of resistance produced by the creation of an AVF. The wall of an artery with arteriosclerotic or atherosclerotic changes often has a limited capacity to dilate depending on the extent of the disease. In these situations, the increase in flow volumes tends to depend more on the diameter of the vessel (Fig. 30.3). Hence, larger caliber vessels with significant wall disease that are not capable of significant dilation can still provide sufficient flows necessary for dialysis. B mode ultrasound permits the surgeon to visualize the artery, evaluate the extent of calcification and the luminal diameter to make an informed critical decision on the suitability of the site in the artery that could be used for inflow to the AVF (Fig. 30.4 a,b). Besides determining the luminal diameter, ultrasound imaging is very useful in assessing arterial wall calcification and stenosis. Many studies have reported increased success of AVF maturation using inflow arteries with the diameter greater than 2 mm.[21,22] Duplex Doppler evaluation of resistive indices in the artery has also been used for provocative testing (*reactive hyperemia test*) to assess the distensibility of the artery to use it as a predictor of AVF maturation.[11]

The single most important component of vessel mapping includes the appreciation of vascular anatomy in a given individual and comprehension of the spatial relationships of the artery to the vein. This becomes critical as there is often considerable variation in the normal anatomy in any given patient population forcing the surgeon to tailor an incision to achieve necessary dissection and mobilization for AVF creation. This becomes even more important during the evaluation of patients with variations in anatomy or those with multiple previous surgeries. While viewing by real time ultrasound scanning, a vascular access surgeon with the operative and clinical background is often in a position to notice subtle nuances in the surgical anatomy in a given patient. The surgeon is provided with a view of the vascular anatomy that lies beneath the skin, thereby adding an entire new dimension to clinical evaluation while planning a vascular access procedure. In our clinical practice, using real time ultrasound as a complement to the clinical examination in the office has increased the AVF placement rate from 60% to 85% (Table 30.1).

Intraoperative Use of Ultrasound

In addition to those factors discussed above, the success of AVF also relies on surgical technique and experience of the surgeon.[23] This is evidenced by the vast range of AVF maturation failures reported in the literature.[24,25,26] Whereas vessel mapping in the clinic provides the necessary information to plan surgical intervention, the use of real time ultrasound in the operating room provides the surgeon the luxury of confirming findings of the previous assessments and marking the precise location of the artery and vein (Fig. 30.2b). This allows precise incisions and adequate mobilization of the vein to perform the anastomosis at a planned location on the artery (Fig. 30.2a). Using intraoperative ultrasound can thus significantly reduce negative explorations. It is particularly useful in patients who do not have clinically identifiable superficial venous anatomy. Precisely placed small incisions reduce the need for extensive tissue dissection to identify veins and thereby reduce operative time and wound morbidity.

Most operative rooms are equipped with simple ultrasound machines providing a real time image that is often used for intravenous or intra-arterial catheter placements. These transducers can be easily used for vessel mapping, to mark the vessels to be used for AVF creation, and to plan the incision (Fig. 30.2 a,b). Having an ultrasound machine with duplex adds a whole new dimension to intraoperative capabilities. Besides providing better resolution during imaging, these machines help the surgeons in assessing intraoperative arterial flows. The relationship of intraopera-

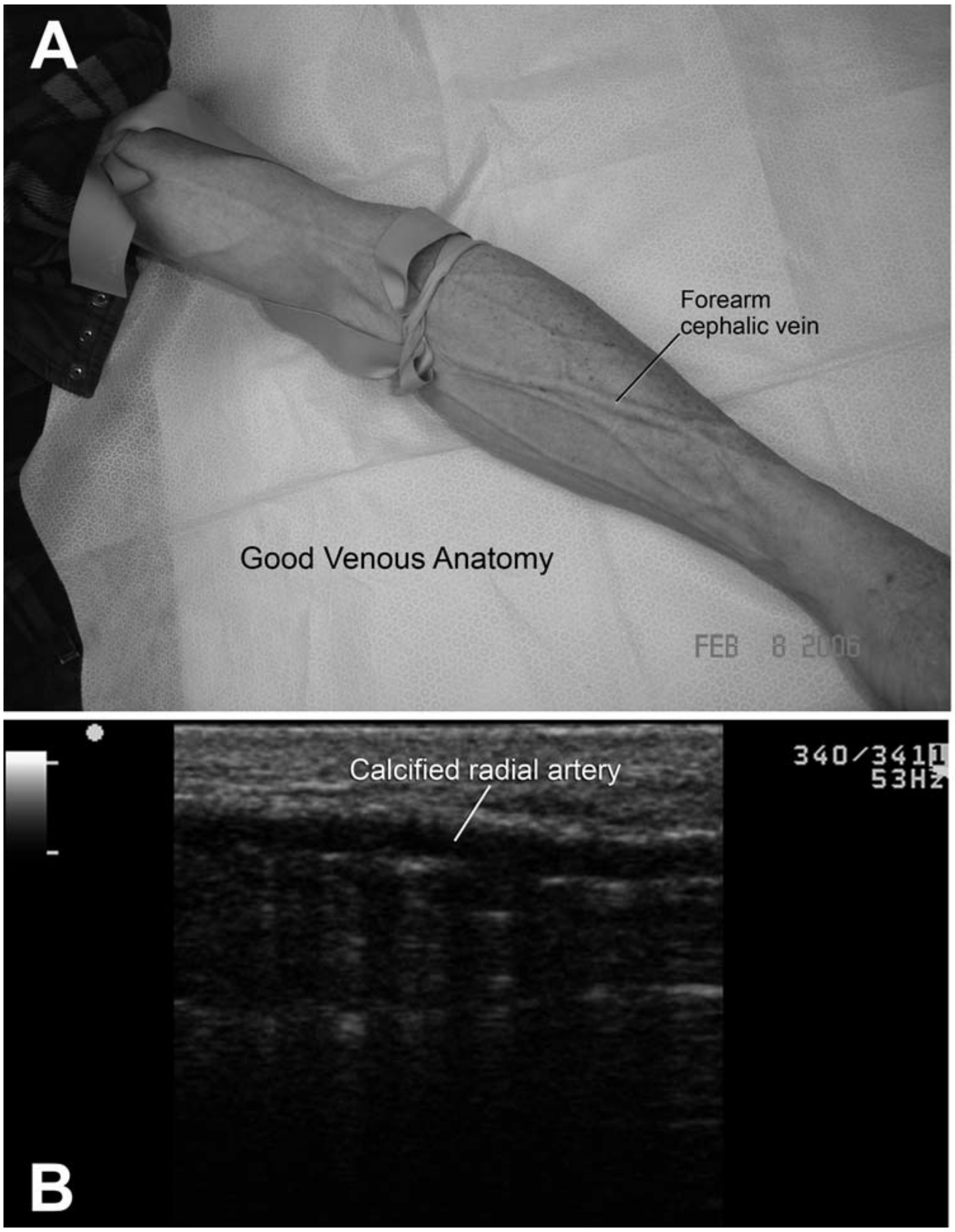

Figure 30-4.
An unexpected extensive radial artery calcification in a patient with good superficial venous anatomy for AVF detected by ultrasound vessel mapping.

tive blood flow to fistula maturation is currently not well evaluated.[27] However, brachial artery flow volume and waveforms are very useful in detecting early access thrombosis.[11] Anecdotally, we had a patient in whom we were able to salvage a fistula that started to thrombose soon after fistula creation. This patient had decreasing flow in the brachial artery that led to re-exploration as the wound was being closed. Platelet aggregates occluding the anastomosis were cleared and the patient was treated with anticoagulants to salvage the fistula. It was later realized that the patient had an underlying hypercoagulable state. Since then, we have used the ultrasound technique to identify and salvage two more fistulae after early postoperative thrombosis.

Postoperative Use of Ultrasound

Ultrasound is a useful tool for identifying some postoperative problems associated with vascular access.[11] Arm edema and wound swelling are commonly encountered. Ultrasound helps differentiate tissue edema from postoperative hematoma or lymphocele. It is also useful for guiding needle aspirations of lymphoceles that occasionally compress outflow. Ultrasound can differentiate a tunnel hematoma from graft needle stick infiltration especially, in early stick situations where patients present with graft swelling. In the AU2 presence of significant edema from venous hypertension, ultrasound often shows increased pulsatility of the outflow vein extending towards central circulation, helping to make

Table 30–1
Effect of Ultrasound Evaluation on AV Access Planning

	Year	New Access	AV Grafts	AV Fistula	AVF %
Pre-DOQI era	1993	65	51	14	22
	1996	71	50	21	30
Clinical evaluation	1998	158	82	76	48
	1999	154	77	77	50
Clinical evaluation ultrasound mapping	2000	125	50	75	60
	2001	104	44	60	58
	2003	83	36	48	57
Clinical evaluation and ultrasound mapping in clinic	2004	106	25	81	77
	2005	179	26	153	86
	2006	129	17	112	87

Note. AV = arteriovenous.

the diagnosis. A surgeon well versed with viewing real-time ultrasound has innumerable opportunities for early use in postoperative evaluation of vascular access to improve patient care.

Atrioventricular Fistula Maturation Evaluation

A mature fistula is defined as a fistula that is capable of delivering flows necessary for adequate dialyses (see Chapter 25). AU3 Establishing objective maturation criteria provides the surgeons with an opportunity to objectively evaluate maturation and electively plan interventions that could help fistulae mature. Duplex Doppler ultrasound is an ideal tool to assess fistula maturation. B mode imaging provides details pertaining to the size, diameter, length, and depth of the outflow vein. Duplex Doppler also provides functional details by evaluating the flow patterns and flow volume. Real-time ultrasound often allows the surgeon to visualize sites of obstruction to the flow, nature of obstruction (e.g., valve hypertrophy, valve dysfunction), and available collateral vessels to plan vein patch venoplasty and vein enhancement (Fig. 30.5). It also provides the surgeon an opportunity to decide if a fistulogram or a venoplasty is necessary for further evaluation and help maturation of the AVF.

Doppler Ultrasound Flow Evaluation

Duplex Doppler ultrasound is routinely used in the functional evaluation of circulation in several vascular beds.

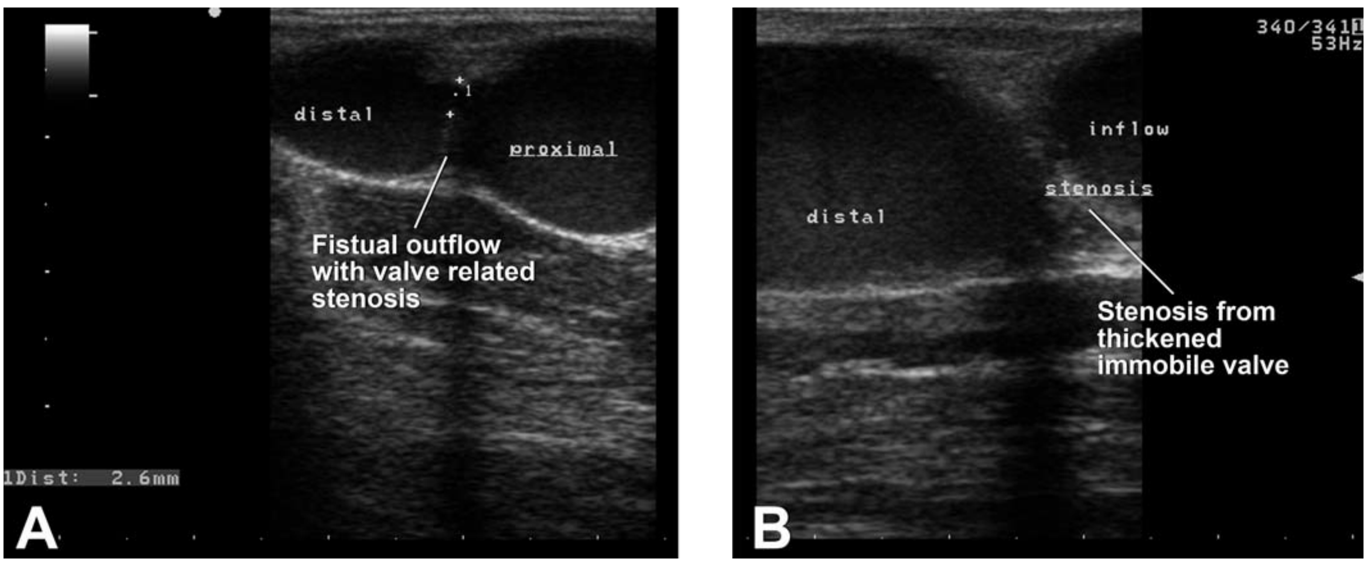

Figure 30-5.
Two longitudinal views of dilated proximal and distal vein with stenosis of lumen caused by valve thickening.

Assessing carotid arterial disease, hepatic artery, portal vein, and hepatic vein flow velocities and volumes are a few examples.[6] Doppler has the capability of assessing the flow velocity. Ultrasound imaging can reliably measure the vascular diameter. Volume flows are derived from these measurements.[10] Most modern ultrasound equipment has volume flow measurements as part of the standard parameters measured during vascular evaluation.[28]

Historically, volume flow has not been a popular parameter for functional evaluation of the vascular system. The AU4 main reason for this is the low reliability and accuracy of testing. Volume flow measurements are significantly dependent on equipment and technique. When compared to segmental pressure measurements, volume flows were not considered useful as an indicator of vascular disease.[29] The source of errors that could lead to inaccuracy in measurement of volume flows have been evaluated and discussed in extensive details in several previous publications.[30] Most new instruments have incorporated several steps to minimize errors in measurement and calculation of flow volumes.[28]

Measuring volume flow in AVF is a unique clinical situation. With the creation of an AVF, flow to the upper extremity bearing a vascular access conduit increases 10 to 20-fold (1000% to 2000%).[31] The observer in this situation is interested in a flow estimate rather than an accurate flow measurement. With volume flow changes of such magnitude, an error of 5 to 10% in flow estimation would be within an acceptable range (e.g., 800 ml/min vs. 720 ml/min or 860 ml/min). Moreover, measuring flow volumes 3 to 5 times and using the average of the measurements is a technique that can be used to further minimize this error. Measuring volume flow with duplex ultrasound has shown good correlation with other accepted methods of access flow measurement.[32]

Volume flow calculations using duplex Doppler rely on vascular diameter. Measuring the flow in an outflow vein of a fistula poses several problems that could account for inaccuracy with this technique. Outflow veins do not have a standard diameter. They are also easily compressible and often pose difficulty for accurate measurement of the diameter. Valves within the veins and the tributaries often produce complex flow patterns. Lastly, fistula outflow veins have markedly turbulent flow. On the other hand, major arteries in the upper limb (axillary/brachial) are most often straight and have uniform diameter. They are more deeply situated and not easily compressible. Measuring blood flow in these arteries is a reliable and reproducible technique (Fig. 30.6). Brachial artery flows in the upper extremity of a renal failure patient is usually less than 100 ml/min.[10,33] Hence the flow measurement in the feeding artery to the limb (brachial or axillary artery) can be used as a reliable indicator of fistula flow.

AVF flow = Brachial artery flow – 75 to 100 ml/min AU5

This is an extremely useful technique to get a reliable functional assessment of AVF to assess maturation. Volume flow measurement in the feeding artery to the limb correlates well with access flow rates and has been recommended as an accurate method to evaluate AVF.[11,33]

Use of Ultrasound for Atriovenous Graft Evaluation

Imaging an **atriovenous graft** (AVG) may be difficult in the early postoperative period until the ePTFE graft is com- AU6 pletely soaked. Following this, real-time ultrasound with duplex Doppler can be a useful tool in evaluating AVG to confirm tissue incorporation. It is very useful for detecting seroma, hematoma, or lymphocele accumulation, which can be subtle and pose problems with needle stick. Duplex Doppler ultrasound can also be used to estimate AVG flows by measuring inflow artery flows. Also, ultrasound is very

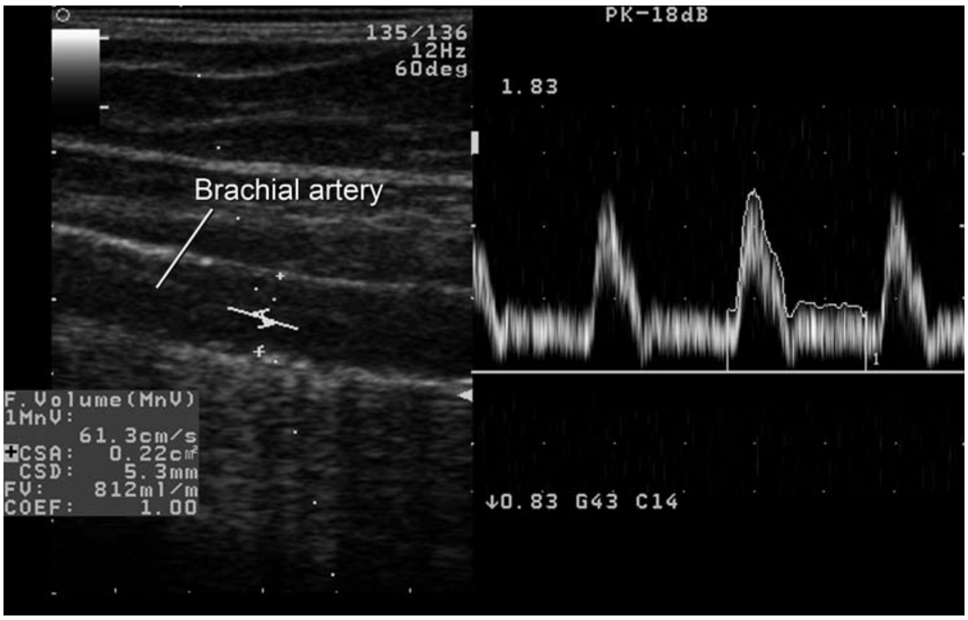

Figure 30-6.
Brachial artery flow measurement in a patient with radiocephalic fistula. AU11

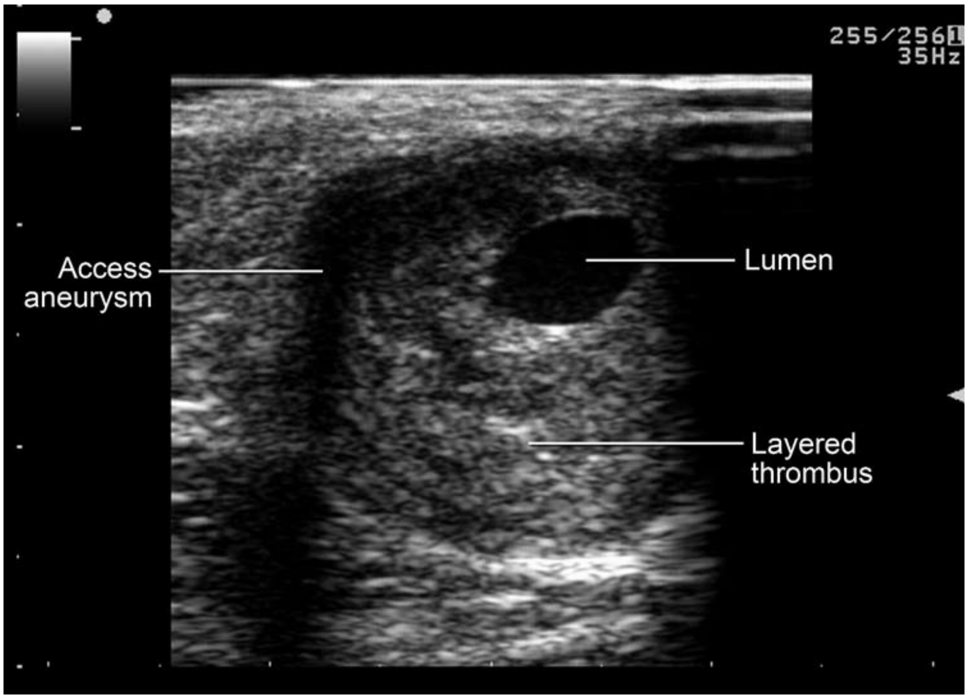

Figure 30-7.
Layered chronic mural thrombus in an aneurysm presenting as needle stick difficulty.

helpful in evaluating large pseudoaneurysms filled with chronic layered thrombi, which often produce problems with needle sticks (Fig. 30.7). These are often not visualized with a contrast study, because the contrast flows only within the lumen. It is also used to look for perigraft collection and needle guided aspiration when graft infections are suspected.

Use of Ultrasound for Detection of Stenosis and Thrombosis

Duplex ultrasound is routinely used to image both the superficial and deep venous systems for evidence of thrombosis. B mode imaging can visualize a thrombus within the lumen of the veins. An acute thrombus tends to produce distention of the vein with an increased luminal diameter resulting from increased venous pressure. Compression techniques can also be used to determine if a venous thrombus is present. As opposed to a normal vein, thrombosed veins fail to collapse with Doppler probe compression.[34,35]

Ultrasound is also reliable in diagnosing stenosis in blood vessels and AV access dysfunction. The feeding artery, the anastomosis, and the entire length of the outflow vein can be scanned with relative ease with B mode scanner. Using duplex and color flow provides the examiner an opportunity for functional evaluation. Increased flow velocities caused by the stenosis are often diagnostic of a functionally significant lesion. Robin et al. showed that AU7 an increase in PSV ratio of 3 correlated with a 25% stenosis, as demonstrated on arteriography.[36] Though clinical examination is reliable in detecting an outflow stenosis in AVF, the ultrasound provides the operator an opportunity to evaluate the nature of stenosis and its extent to make an informed decision on appropriate management. Because of stenosis the intra-access pressure in the segment towards the inflow usually is high and makes the segment more pulsatile. The outflow vein beyond the stenosis tends to be soft and easily compressible and, hence, often difficult to evaluate. In a low-flow state subtle valve related problems can be missed. Similarly, though ultrasound based techniques to evaluate and detect central stenosis have been described, they are not always easy and reproducible. Because central stenosis requires an interventional study for evaluation and management, ultrasound can serve as a preliminary diagnostic tool to raise a suspicion of central problems.

Ultrasound can evaluate the vessel in both longitudinal and transverse axis and also delineate the vessel wall from the subcutaneous tissue and from the vessel lumen. This provides a unique opportunity for the examiner to evaluate the cause for vessel stenosis. The severity (percentage) of stenosis can easily be calculated based on the luminal diameter. Ultrasound can also clearly differentiate between extrinsic compression (such as hematoma or lymphocele) and intramural problems (such as wall thickening or venous intimal hyperplasia) and intraluminal causes (such as thrombus or valve hypertrophy). Using duplex Doppler to measure the inflow arterial flow volume and measuring the flow velocities can provide information on functional significance of the stenosis. Ultrasound also allows the observer to evaluate the state of collateral vessels available to plan for remedial surgeries such as flow diversion or vein patch venoplasty. Thus, the duplex Doppler ultrasound is an ideal tool to complement clinical evaluation of dysfunctional arteriovenous access.

Summary

The field of vascular access is going through a major change in the United States. Arteriovenous fistula is the access of choice. Vessel mapping using ultrasound has become the standard of care for preoperative planning of AV access. Ultrasound is increasingly being utilized in intraoperative planning and evaluation of AV access. Duplex Doppler ultrasound has the capability to provide functional evaluation of vascular access. It has been successfully used for fistula maturation evaluation and to identify maturation failure in AVF thus facilitating early intervention. When used in conjunction with clinical examination, real-time ultrasound scanning adds a new dimension to successful vascular access management.

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AU1: "Penetration"? Penetrance is a term relating to heredity.
AU2: Please clarify "early stick situations." Is hyphenation needed?
AU3: Pls. check cross reference
AU4: Do you mean low "reliability and accuracy of testing"?
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