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Duplex Ultrasonography and Haemodialysis Vascular Access: A Practical Review

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Abstract

Background and Aims: The aim of this review is to discuss the practical use of duplex ultrasonography in the setting of dialysis vascular access, based on the current evidence and own experience. After explaining the necessary tools and practical considerations, the role of ultrasonography in the placement of dialysis catheters will be described. Then we discuss the importance of vascular access selection with vascular mapping, followed by an overview of the most frequent vascular access related complications (thrombosis, stenosis, dysmaturation, access induced ischemia and (pseudo) aneurisms) and their ultrasonographical approach.

Keywords: Haemodialysis, Vascular Access, Duplex Ultrasonography

Introduction

Being their life line, a vascular access (VA) and its long term functioning is of crucial importance to haemodialysis patients. Unfortunately, vascular access procedures and subsequent complications represent a major cause of morbidity, hospitalisation and cost in this patient population. They account for over 20% of hospitalisations of dialysis patients in the United States and Europe and cost about 1 billion dollar annually (1-2). The main options for permanent VA are threefold: A native arteriovenous fistula (AVF), an arteriovenous graft (AVG) and a cuffed tunnelled double lumen catheter. Catheters generally pose most problems and are regarded as inferior to AVFs and AVGs as a long term vascular access modality due to poor blood flows, frequent thrombosis or malfunction, life threatening bacteraemia and the fact that they cause damage to large central veins. For all these reasons, catheters should be avoided if possible, except as a temporary measure. The native AVF is regarded as superior to the AVG, due to its lower complication rate (thrombosis and infection), a lower hospitalisation rate and associated cost and a higher patient survival. Therefore, the K-DOQI guidelines on vascular access recommend a "fistula first" policy with a prevalent functional AVF placement rate of greater than 65% of patients (3). This goal is difficult to achieve in a hemodialysis population that increasingly gets older and has more comorbidities (e.g. diabetes, extensive atherosclerotic disease), associated with poorer vessel quality for construction of native fistulas. A successful vascular

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access program thus demands substantial efforts and requires a multidisciplinary approach where nephrologists, access surgeons, interventional radiologists, dialysis nurses and patients work together in close collaboration. A way to further optimize VA dialysis care, may be the bedside performance of duplex ultrasonography.

Performing Duplex Ultrasound in haemodialysis access: tools and practical considerations

To perform a vascular access DU scan, one needs an ultrasound machine which can combine conventional B mode (black and white brightness) with doppler (colour and spectral analysis) imaging. A 2D linear high frequency transducer (preferably 12 mHz or higher), is ideal to obtain high resolution images of superficial structures. For deeper vessels, a lower frequency probe (5 to 8 mHz) should be used. A sufficient amount of contact gel is applied between the skin and the probe and the examination should be performed in a warm environment to prevent vasoconstriction. Basic knowledge of vascular haemodynamics should be obtained and bed side teaching by an experienced vascular ultrasonographer is recommended in order to master this technique adequately in a reasonable time frame. B Mode provides anatomical information. Internal vessel diameter measurements are done in this mode, anteroposteriorly, in the transverse plane. Minimal amount of pressure on veins is needed in order to keep measurement errors to a minimum. Colour doppler shows, if correctly set, sites with increased blood velocities (suspected stenosis) and the direction of blood flow. Pulsed Doppler spectral examination is performed in the longitudinal plane with the sample volume in the middle of the blood vessel spanning two-third of the blood vessel diameter. It is used to calculate blood volume flow, diagnose stenotic areas (by an increase in peak systolic velocity) and grade the flow into high or low resistance flow.

Blood volume flow is calculated by equipment software, using the following formula:

Time averaged mean velocity (TAMV) x cross-sectional vessel area (π r2) x 60.

It is important to control the angle of the doppler signal and keep it below 60 degrees, in order to achieve the doppler signal of strongest intensity. Due to inherent measurement errors (diameter, sample volume position, doppler angle), the mean of three consecutive measures should be taken. Whereas access blood flow in AVGs can be measured along the entire access, it's recommended to measure flow in native AVFs at the level of the feeding brachial artery, also for radial AVFs. Flow calculations in venous outflow tract of native AVFs are often difficult because of curves, bifurcations, variations in vessel diameter, turbulent flows and should be avoided. For wrist AVFs, measuring the access flow at the level of the radial artery proximal to the anastomosis, leads to an underestimation of flow since a variable portion of the fistula flow is provided by the ulnar artery via the palmar arch (4). Colour-flow doppler ultrasound correlates closely with another measurement of access flow (ultrasound dilution) having a comparable correlation coefficient of 0.83 (5). The advantages of US over phlebography and angiography are the absence of need for contrast agents and thus no risk for allergic reactions, deterioration of residual renal function and phlebitis. It is mobile, painless, non-invasive, less expensive and offers both morphological (direct visual imaging of the access and venous runoff, information about texture of soft tissue and depth of vessels) and functional, haemodynamic (access flow measurement) data. Having outlined this, it is however not the purpose to minimise the role of angiography in the diagnosis and treatment (dilatation and stenting) of vascular access problems. But it is beyond the scope of this review to go further into this matter. Disadvantages of US doppler are the operator dependency, requiring a substantial learning curve, and compared to ultrasound dilution blood flow monitoring, the fact that the examination cannot be performed during a dialysis session.

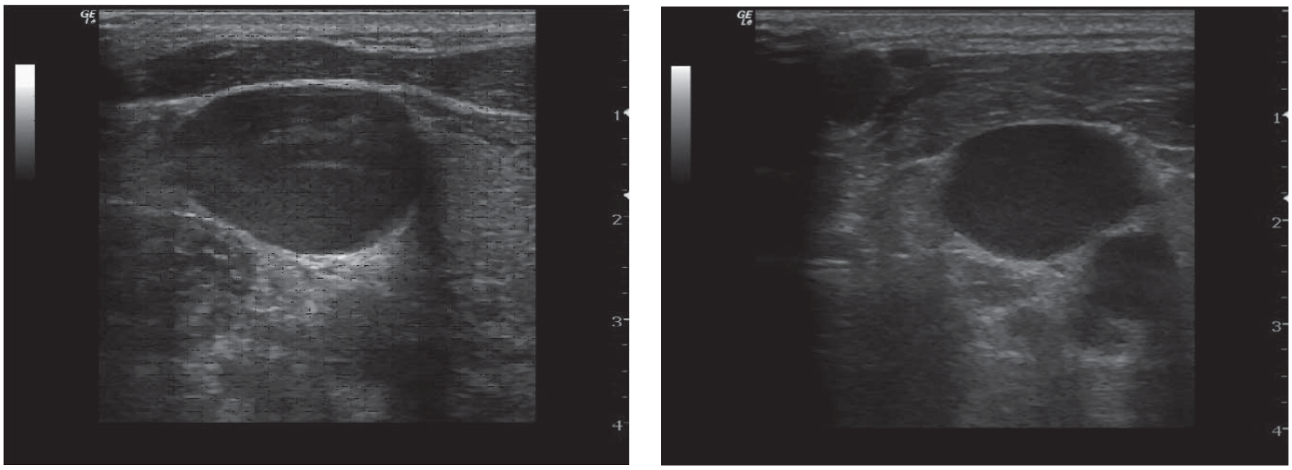

Figure 1. (a) Thin layer of sternocleidomastoid muscle covering the internal jugular vein (caudal part). (b) Thicker layer of sternocleidomastoid muscle in the same patient covering the internal jugular vein (cranial part).

Visualising central veins with US can be challenging and is more easilly done with angiography.

US guided placement of central venous haemodialysis catheter

Although central venous catheterisation (CVC) should be avoided due to the above described disadvantages, this procedure can be necessary in patients who need acute dialysis and do not or cannot have a native AVF or AVG, in patients with a maturing access and those with vascular access failure awaiting interventional radiologic or surgical treatment. The right internal jugular vein is the preferred route for insertion and the subclavian vein should be avoided due to the high risk of central venous stenosis. The subclavian vein is the outflow vein of the arm and any complication in this area could compromise future fistula creation. When it is expected that dialysis will only be necessary for a short time, cannulation of the femoral vein can be considered. Portable ultrasound devices, only offering 2D images, are commonly used for this purpose but the use of more sophisticated US equipment, providing colour and pulsed wave doppler imaging, can be helpful in certain instances such as the diagnosis of vein thrombosis. The European Best Practise Guidelines (EBPG) on VA, stress theneed for ultrasound guided CVC placement because it is superior to and safer than the blind or so called landmark technique (6-7). Relying on external landmarks alone to access the internal jugular vein, is associated with a failure rate between 7 and 19.4%, depending on the experience of the operator (8). Ultrasound guides puncture by locating the target vein more precisely and visualizes anatomical variants and vein thrombosis. This prevents repeated puncture and lowers the rate of complications like pneumothorax and arterial laceration.

US guided CVC placement has some other advantages:

1) Discomfort for the patients can be minimised by easier cannulation resulting in high first attempt cannulation success and by puncturing the vein on a level where the overlying muscle is thinnest (Fig 1).

2) Occasionally, large venous valves can be seen in the internal jugular vein so puncturing them can be avoided (Fig 2).

3) The closer the puncture to the clavicle, the larger the size of the internal jugular vein, so the easier the cannulation. This gives also the advantage that, if a curved catheter is placed, it is more convenient for the patient. The proximal part of the catheter can be directed downwards, over the clavicle, instead of upwards, avoiding an unpractical and unaesthetical antenna-like configuration.

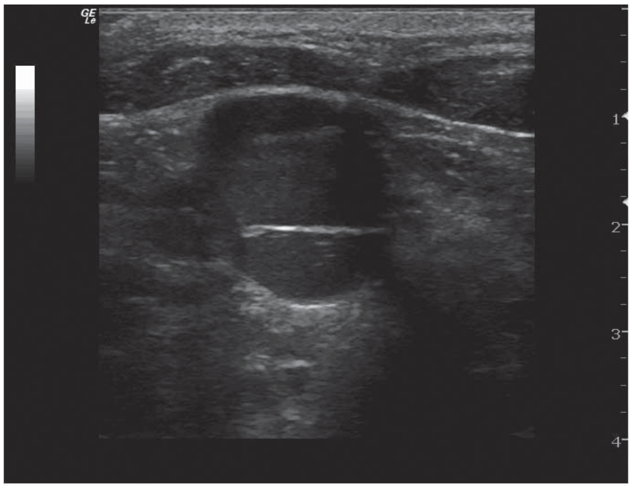

Figure 2. Venous valve in left internal jugular vein

Preoperative vascular mapping

Vascular mapping prior to VA creation has been shown to result in a change in the type and location of access surgery (creation of more native arteriovenous fistulas and less grafts), a decrease in negative exploration rate, an increase in the proportion of patients being dialysed with a fistula and an improvement in the adequacy of fistulas for dialysis, especially in forearm fistulas. (9-13). The increased anatomical knowledge obtained with US mapping, allows the surgeon to select the most appropriate vessels for the VA creation, especially in difficult patients (obese, diabetics, elderly women, previous vascular accesses).The EBPG (6) and the most recently updated K-DOQI guidelines (3) recommend that this procedure should be routinely performed in patients in need for a permanent VA.

Before vascular mapping is performed, a carefully performed history and clinical examination is mandatory. But physical examination alone is insufficient in more than 50% of patients due to obesity and deep lying veins (14). In addition to physical

Table 1. Vascular mapping prior to VA creation with duplex ultrasound

Arterial system
* B Mode
- Inner arterial diameter
- Degree of vessel calcification
* Doppler
- Flow wave form characteristics
- Reactive hyperemia test of the radial artery
Venous system
* B Mode:
- Inner venous diameter
- Vessel wall quality
- Compressibility/distensibility of the vein
* Doppler:
- Detection of flow within vein
- Response to distal compression and respiratory varation of flow: for central veins
Subcutis
* B Mode
- Depth of the vein
- Thickness and echostructure of the subcutaneous adipous tissue
- Relation of the vein to the aponeurosis

examination, duplex ultrasonographic mapping of the upper extremity vessels, will lead to the selection of the most appropriate dialysis access modality, anatomical site and of which particular vessel(s) to use for the vascular access creation. Duplex ultrasound examination should include the vascular structures of both arms, starting with the arm most likely suited for VA creation, based on the prior history and clinical examination. The main features to address are summarised in Table 1.

Although there is no generally accepted "standard" for what constitutes vascular mapping, the following will try to give an overview based on the available literature and our own experience of the procedure. The examination shifts from the arteries to the veins, and ends with an appraisal of the subcutaneous tissue.

The arterial assessment should include the evaluation of the arterial vessels from the axilla to the hand, examining with B mode the inner arterial diameter and degree of vessel wall calcifications at distinct points along the arterial vascular tree. A preoperative internal arterial diameter <= 1.6 mm has been associated with a higher failure rate in arteriovenous fistulas (14), whereas others (9-10, 15) suggested a minimum diameter of 2.0 mm for successful AVF creation. There is no exact consensus in the literature on this issue but one may easily understand that the smaller the arterial diameter and the more calcified the vessel wall, the higher the likelihood of surgical failure, insufficient inflow and non-maturation of the AVF. A high bifurcation of the brachial artery needs to be looked for (occurs in 15 to 20% of the cases), because this results in a deeper and uniformly larger ulnar and a smaller and more superficial radial artery. To prevent the hand from developing steal syndrome, if the cubital region is chosen to create the vascular access, the ulnar artery is recommended for the anastomosis (15). Arterial stenotic regions may be identified. As the feeding artery dilates after VA access creation, it is obvious that not only the initial diameter but also the arterial

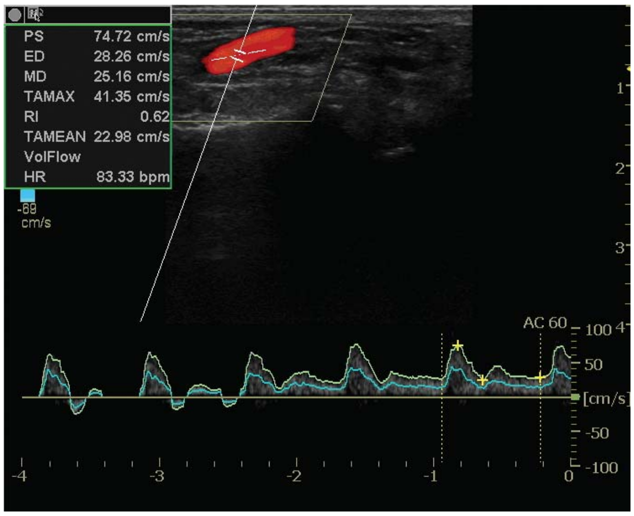

Figure 3. Pulse wave doppler spectrum of a normal left radial artery prior to vascular access construction. Upon opening the clenched fist, the resitive index (RI), decreases from 1 (no end diastolic flow) to 0.62

compliance affects access outcome. Doppler wave forms of upper extremity arteries are characterised by a high resistive flow pattern. After the creation of the vascular access, this pattern changes into a hyperdynamic, low resistive type of wave form, characterised by a pronounced diastolic flow. The arterial compliance can be assessed preoperatively by evaluating the doppler waveform in the radial artery during reactive hyperaemia, induced by reopening a fist that was clenched for 2 minutes (Fig 3). The high resistance triphasic doppler signal with clenched fist, changes normally to a low resistance biphasic waveform after releasing the fist. The resistance index (RI) can be calculated using the following formula (peak systolic flow velocity - end diastolic velocity / peak systolic flow velocity). A preoperative RI <= 0.7 after release of a clenched fist, indicates that arterial flow will increase sufficiently after VA creation and this has been shown to be indicative for arteriovenous fistula success (14). This test is especially helpful in planning the location of the initial operation, i.e. selecting the wrist/forearm or elbow region.

The venous system can be examined before and after application of an upper arm tourniquet, with the arm hanging down and the elbow slightly bent.

.Table 2

Indications for US examination of an established AVF and AVG
1. Decreased or absent thrill over AVF
2.Technical dialysis related problems: cannulation difficulties and other
3. Dysmaturation
4. Routine check: postoperative assessment of baseline anatomy and blood flow
5. Upper limb pain suggestive for hand ischemia
6. Upper limb swelling

Tapping on the forearm superficial veins helps to dilate them. First, the anatomy of the forearm cephalic vein and the antecubital superficial veins (cephalic, basilic and median cubital) is depicted. Although there is much anatomical variation, the typical venous anatomy of the elbow region is characterised by a lateral cephalic vein, a medial basilic vein and median cubital vein connecting both. A communicating vein connects the superficial venous system with the deep brachial veins, which are running paired along the brachial artery. The minimal internal venous diameter for successful VA creation is regarded as 2.5 mm for native AVFs and 4.0 mm for AVGs (9-10, 15). Duplex imaging should document full compressibility and patency of all veins examined with absence of luminal defects and/or stenosis. Vein sclerosis can be detected with a high frequency transducer. Although more difficult to assess, the central veins should not be overlooked prior to VA creation. Flow in the subclavian and brachiocephalic vein is normally phasic with respiration (increases with deep inspiration) and increases with distal compression. Comparison between left and right sides can be useful to detect obstruction. When in doubt, a venography should be performed.

The subcutaneous tissue examination is often overlooked but is important to perform. The superficial vein used for a native AVF should not be too deep because otherwise the venous outflow tract will not be easy to cannulate. A thick subcutaneous fat layer, the presence of liposclerosis and an aponeurotic leaf around the vein, all can be factors prohibiting the vein to come to the surface and limiting its dilatation. In those cases, superficialisation of the vein is advisable.

The role of DU in established vascular access

Once a VA is created, several problems can occur and duplex ultrasonography has a valuable role in diagnosing them. For detecting central venous catheter dysfunction, US has a limited role although this technique can be helpful in diagnosing fluid collections around the catheter in case of tunnelitis and when a haematoma develops due to catheter laceration. The indications for DU in an established AVF or AVG are summarised in Table 2.

Thrombosis

The diagnosis of a thrombosed VA is essentially a clinical one, being an absent thrill on palpation and auscultation. DU can however be useful to confirm the diagnosis and determine the treatment modality (surgical or endovascular), by visualising the location and the extent of the occluded segment. Based on the US findings, the type of surgery can also be influenced (creation of a new, higher located anastomosis at the same site versus creation of a new fistula at another site) (16).

Technical dialysis related problems

Probably most of the benefit of DU in VA lies in this area. In our experience, those problems can be divided into 2 categories: cannulation difficulties and others. The latter category includes a wide range of problems including elevated venous pressures, poor dialysis adequacy, high recirculation, low blood and access flow, aspiration of blood clots, local pain on cannulation and prolonged bleeding after cannulation. Although those problems are often related to stenosis, no pathologic lesion is observed in up to 36% of cases when examined with angiography (17). The encountered problems are in those cases due to an incorrect position of the dialysis needle or incorrect choice of puncture site. DU can then guide the dialysis staff to choose the correct puncture zones. A common encountered problem occurs with an elbow fistula which has its anastomosis between the brachial artery and median cubital vein and where both the cephalic and the basilic outflow veins develop. The cephalic vein is, due to its more superficial course, more easily palpable than the basilic vein who is often not or hardly felt. However, when the latter is the main venous drainage vein, a successful cannulation and dialysis requires puncture of this vein and not the cephalic. In such a case, DU is helpful to take the right decision. We believe that the longevity of a VA is increased by avoiding unnecessary trauma to the newly created and thus fragile fistula or graft. So, it's become routine in our unit that the first puncture(s) of an AVF and AVG are preceded by an ultrasound examination. Visual information on depth and course of the outflow tract are provided to or by the dialysis staff and preferred puncture zones are delineated with a marker on the patient's skin. Besides avoiding local swelling and pain (and prolonged catheter use) due to a failed cannulation, US can detect an underlying problem and suggest a prompt treatment.

Dysmaturation

Maturation is a concept which is not well defined in the literature. In theory, a fistula is dysmature when it can not be cannulated within the expected time frame. In daily practice, fistula maturity is often judged by clinical examination and when done by experienced dialysis staff, it has been shown to be a good predictor of fistula maturity (18). Robbin et al. showed that the following ultrasound criteria for fistula maturation (a diameter of the outflow vein > 4 mm and a blood flow of at least 500 ml/min), are predictive for successful maturation and adequacy for dialysis. The K-DOQI guidelines state that fistula dysmaturation should be evaluated by 6 weeks after construction by physical examination and if needed when clinical doubts, be complemented by ultrasound (3). In our opinion, it's advisable to obtain a baseline set of information on a newly created VA, such as a postoperatively assessment of the anatomy and blood flow. Konner et al. (19) reported an immediate tenfold increase in blood flow rate in the radial artery after fistula creation, which progressively increases during the first 10 days and tapers off later on. However, cannulation 10 days after creation is not recommended as sufficient maturation requires beside sufficient blood flow also an adequately dilated and arteriolised venous vessel wall. Most of the native fistulas can be safely cannulated after 4 to 5 weeks although sometimes, in older, diabetic patients with severe atherosclerosis, it may take longer (up to 3 months) (16). AVGs are generally ready to cannulate after the hematoma and swelling have resolved sufficiently, normally within 2 weeks after creation. DU is able to differentiate between a true delay in maturation and pseudo- dysmaturation, a situation often found in obese patients where the venous outflow is sufficiently dilatated, having a normal blood flow but is lying too deep to be easily palpated and cannulated. This is an indication for superficialisation of the fistula. In cases of true delay in maturation, DU is helpful in determining the cause of the problem: arterial inflow stenosis, anastomotic stenosis, venous outflow tract stenosis (hyperplasia, extrinsic compression by hematoma, seroma or abscess) and the presence of venous draining branches, stealing blood from the main draining vein. The latter can be treated by surgical ligation (20).

Stenosis

Most of the vascular access problems are related

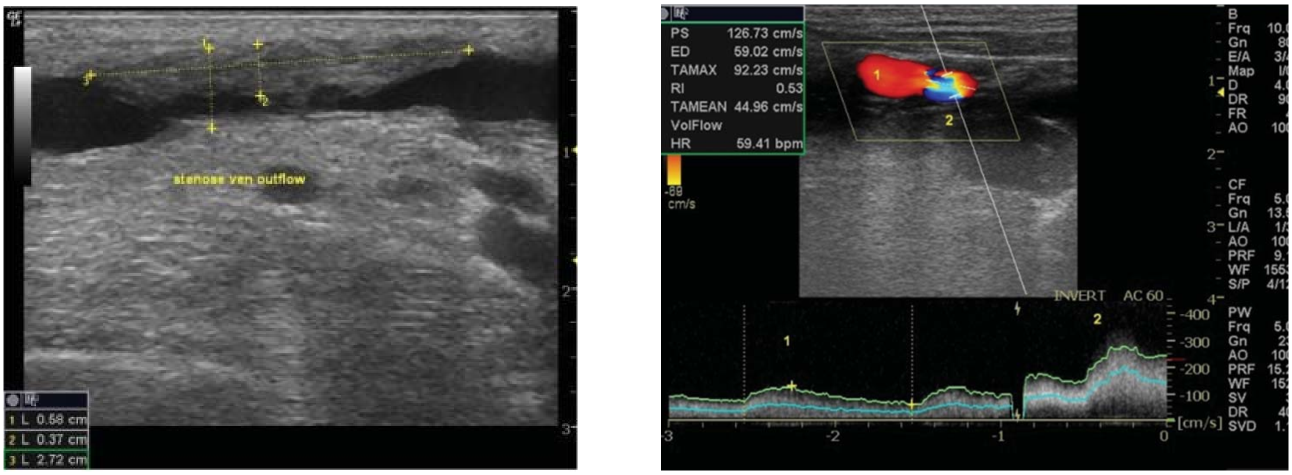

Figure 4. (a) B Mode appearance of high grade stenosis of venous outflow tract. (b) Colour and spectral doppler appearance of high grade stenosis of venous outflow tract, characterised by aliasing and increased blood flow velocities at the site of stenosis.

to stenosis (21). Stenosis in a native AVF tends to occur most frequently at the surgical swing sites and the puncture zone of the vein, whereas AVG stenosis occurs most frequently at the graft-vein anastomosis (3). Predisposing factors for stenosis are surgical injury at the time of creation, neointimal hyperplasia at sites experiencing high shear stress (e.g. anastomosis, bifurcations), scarring at puncture sites, the presence of venous valves and the uraemia per se (22). The US diagnosis of a stenotic lesion is made combining B mode with colour and pulse wave doppler imaging (Fig 4). A stenosis can be quantified morphologically and hemodynamically.

Morphological quantification is done with B mode and Colour Doppler comparing the residual luminal diameter with the original diameter or, when the original lumen cannot be determined adequately, the lumen of a nearby normal segment, using the following formula:

(original lumen - residual lumen)/original lumen x 100 = percent stenosis

Hemodynamical quantification is based on the detection of an increased peak systolic velocity rate (cm/sec) at the site of suspected stenosis, compared to a non stenosed segment.

In the literature, there's no consensus on which threshold to use to define a high grade or significant stenosis in fistulas and grafts (4, 13, 23-24). In our centre, we use as US criterium of hemodynamic significance of a stenosis, a 50% reduction in diameter in B mode in combination with a 2 to 3 fold increase of peak systolic velocity, compared to an unaffected segment. But more important than only grading the stenotic area morphologically or hemodynamically, is to look at the repercussion of the blood vessel narrowing on the access blood flow and the clinical condition during dialysis (ease of cannulation, venous pressures etc). Ultrasonographical signs of impending vascular access thrombosis are a stenotic lesion associated with a low blood flow and detection of a high resistance doppler wave form in the feeding brachial artery (RI> 0.7) (25) So, probably the decision to intervene should rather be based on these findings than upon detection of high grade stenosis per se. Doppler US has been repeatedly shown to be an accurate method for diagnosing vascular access stenosis, when compared to digital substraction angiography (26-29). This finding and the traumatic character of DU, makes it the examination of first choice in case of a clinical suspicion of VA stenosis. Whether ultrasound should also be used as a surveillance technique in screening programs, detecting clinically asymptomatic stenoses, is unclear, as the positive results of initial observational studies could not be confirmed in subsequent randomized trials and meta-analysis (30). Ultrasound dilution based access blood flow screening may prevent access thrombosis in native AVFs but no randomised clinical trials have been performed with doppler US in this setting. There is no evidence that screening with either access blood flow (using ultrasound dilution) or DU is of benefit to patients with AVGs.

Access induced ischemia or steal syndrome

Steal syndrome is an infrequent (ranging from 1.6 to 8%) but often serious VA complication in which a fistula or graft steals blood and thus compromises the perfusion of the distal extremity (31-33). The ischemia can be arterial or venous in origin. The main causes of arterial ischemia are high fistula flow, stenosis of inflow or outflow artery (often diffuse artery disease) or a combination of the previous. DU can be useful to explain the cause of the steal syndrome and to suggest the best treatment option (34). Measuring the fistula flow allows the distinction between a high (> 1000 ml/min) and low/normal flow fistula, with the latter most likely being caused by focal atherosclerotic lesions or diffuse medial calcinosis. With B mode, a thin diffusely calcified distal artery and focal arterial narrowing can be detected, aided by colour, variance and pulse wave doppler modes. Proximal subclavian artery stenosis, however, can not be detected by duplex US. When suspecting such a lesion and in case of a suboptimal duplex US examination, an angiography should be performed. In case of a high fistula flow, the effect of manual compression of the anastomosis, is helpful to predict the effect of future flow reducing interventions (e.g. banding, distal revascularisation and interval ligation, DRILL). Venous ischemia is due to central venous obstruction or stenosis/incompentent valves in the peripheral outflow vein. The latter is typically seen in case of a side to side arteriovenous anastomosis. (35) Both of them can lead to venous hypertension and development of symptoms such as diffuse or localised oedema, pain, discoloration and in advanced cases ulcerations. Venous duplex ultrasound is a reasonable first step diagnostic study to screen patients with arm swelling. It can identify venous stenosis, dilated collateral veins and indirect signs of central venous obstruction. Due to bone superposition and suboptimal imaging quality, the latter should be confirmed by venography.

Aneurisms and pseudoaneurisms

The main mechanisms causing focal dilatation of segments of VA are repetitive injury (needle sticks) and underlying infection (abscess). A distal outflow obstruction may be a factor increasing growth by increasing pressure within the area of concern (36). True aneurisms are found mainly in native AVFs and whereas in AVGs, the majority are pseudoaneurisms. Colour Doppler is useful to distinct a pseudoaneurism from a haematoma, showing in the first case the typical 'to-and-fro' sign, a waveform characterized by the backflow of blood from the aneurismal sac into the vessel lumen during diastole. Indications for examination with ultrasound and repair are: rapid growth, localised pain, persistent bleeding post decannulation and thinning or ulceration of underlying skin. Besides a surgical and an interventional approach, ultrasound can aid in the treatment by guiding thrombin injection in or compression of the pseudoaneurysm (37-38).

Conclusions

Most of the dialysis access problems can be approached by DU. In the great majority of cases, more invasive and expensive investigations should only be made after investigation with this technique. US guided placement of central venous dialysis catheters should become the standard in all facilities treating dialysis patients. The main reason for this is the reduced discomfort for the patient, who is more likely to have difficult vascular anatomy due to previous central venous catheter insertions. Vascular mapping leads to increased creation and use of native AVFs. Preoperative information should be provided to the surgeon concerning the optimal location of the VA. After VA creation, DU is most commonly used to deal with cannulation difficulties, but is useful as first diagnostic tool in other commonly encountered VA problems such as dysmaturation, arm swelling and hand ischemia. However, without being embedded in a multidisciplinary team of doctors, nursing staff and patients who all work together, it probably loses its valuable potential.

Conflict of Interest

None declared.

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