Duplex ultrasound scanning of the autogenous arterio venous hemodialysis fistula: a vascular surgeon's perspective

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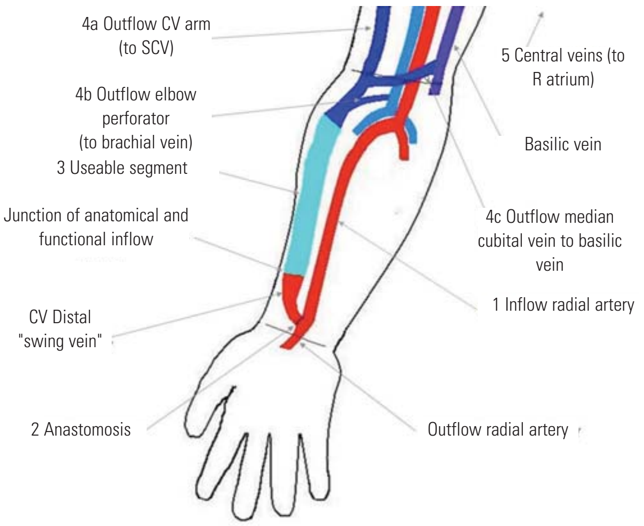

Fig. 1: The standard AAVF.

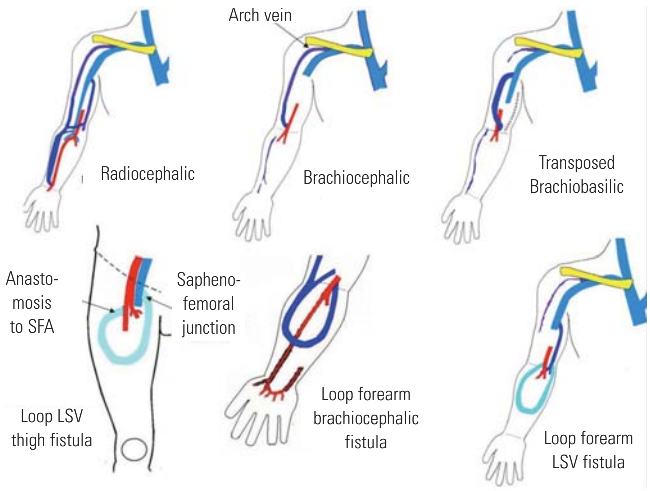

Fig. 2: Common types of AAVF.

Introduction

Duplex ultrasound has become the first line of investigation for the autogenous arterio-venous hemodialysis fistula (aAVF). In recent work published by our group[1], we showed that duplex ultrasound was as accurate as fistulography in the assessment of fistula stenoses. The emergence of duplex ultrasound as the primary tool for examination of the aAVF is the result of better technology, and a better understanding of the anatomy, physiology and pathology of the native fistula circuit.

This article addresses the assessment of the aAVF circuit (native fistula). It is universally accepted that the native fistula is greatly superior to the fistula graft[2,3,4], and construction of a native fistula should be achievable in up to 90% of patients[5].

The autogenous AVF

It is important to note that the aAVF is not a "normal" structure – it is, in fact, a pathology, a "disease" – created surgically for the purposes of hemodialysis access. Furthermore, the aAVF is neither artery, nor vein; it is a hybrid of the two systems, with its own unique anatomy and physiology.

Anatomy of the aAVF

The aAVF can take many different forms, in different anatomical locations, but they all share certain features. All aAVFs have:

1 An inflow artery
2 An anastomosis
3 A useable segment
4 An outflow vein/s
5 Central venous return as illustrated in Fig. 1.

Note the convention in venous and arterial anatomy, which also applies to fistulas: "proximal" means closer to the heart, "distal" means further away from the heart. Around the fistula anastomosis this can become confusing.

For the purposes of this paper, the radio-cephalic aAVF at the wrist is the default setting for all descriptions and discussions. A glossary at the end of this article is provided.

The useable segment is that part of the fistula which receives the dialysis needles. The useable segment needs to have the following characteristics:

Length – sufficient to allow a distance between the arterial and venous needles of more than 8 cm to avoid recirculation.
Diameter – wide enough to allow for ready needling by the patient or dialysis nurse. Adequate diameter ties in with depth.
Depth – the useable segment should be less than 6 mm deep; more than 10 mm deep makes it inaccessible to the dialysis needle.
Straight – a tortuous useable segment is hard to needle.
Arterialised – thick walled enough to allow repeated needle punctures; this develops with time and repeated needling.

An important distinction needs to be made between the anatomical and the functional inflow. The anatomical inflow ends at the anastomosis; the functional inflow ends in the fistula vein about 5 cm past the anastomosis as illustrated in Fig. 1. This difference is very important as about 30% of fistula stenoses occur in this critical 5 cm segment – the so-called "swing vein".

The most widely used (and best) aAVF is the radiocephalic aAVF. In the USA, native fistulas are not as common, and tend to be the generally inferior brachiocephalic aAVF. Other fistula configurations are brachio-basilic, various forms of long saphenous vein based fistulas, and other rarer forms as illustrated in Fig. 2.

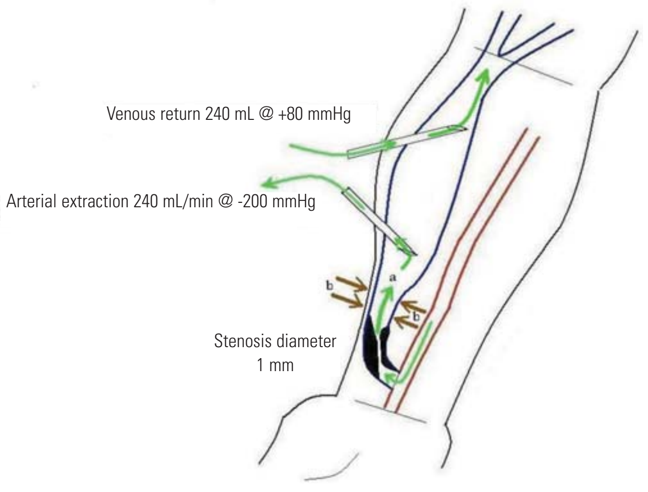

Fig. 3: The hemodynamic effect of a severe inflow stenosis on dialysis.
RC AVF with a critical stenosis in the distal CV (swing vein). The dialysis pump is unable to run at 300 mL/min. Every time the flow is turned up past 240 mL/min, the velocity of the jet of blood (a) coming through the stenosis increases. According to Bernoulli's principle, the pressure at 90 degrees to a stream of flowing blood is inversely proportional to the velocity. Hence, at high jet velocities (a), the pressure at 90 degrees (b) plummets and the CV just past the stenosis collapses and occludes – what is commonly described as "sucking".

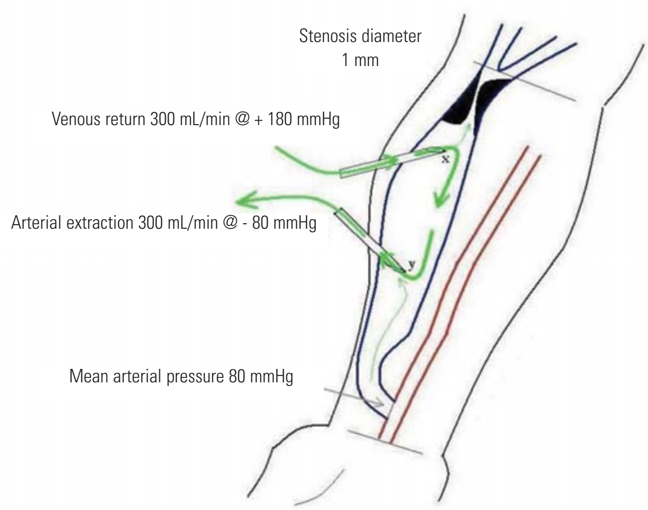

Fig. 4: The hemodynamic effect of a severe outflow stenosis on dialysis.
RC AVF with critical stenosis in outflow cephalic vein at elbow. The dialysis pump can run at 300 mL/min but a high venous return pressure is required to return the blood to the patient (180 mmHg). As a result, a pressure gradient is set up from the venous needle (+180 mmHg) to the arterial needle (-80 mmHg). This results in the blood flowing from the venous needle, not back to the heart, but back to the arterial needle. Little fresh blood is sucked in from the artery, and little dialysed blood is returned to the heart. The upshot of this is recirculation of the blood and ineffective dialysis.

Physiology of the aAVF

The principle of hemodialysis is simple: remove blood from the patient's circulation, filter it in the dialysis machine and then return the dialysed blood to the patient's circulation. In practice however, the difficulty with hemodialysis lies with reliably, safely and repeatedly accessing the patient's circulation. Access can be through an indwelling central line ("vascath"), a synthetic fistula graft, or an aAVF. The aAVF is universally recognised as the best solution.

So that the patient doesn't spend all day attached to the dialysis machine, blood flows through the dialysis system ("pump speed") should not be less than 300 mL/min. The pressure required to extract the blood from the fistula ("arterial pressure") should be around minus 100 mmHg and the pressure required to return the blood to the fistula circuit should be around +100 mmHg. Figs. 3 and 4 illustrate these points.

Pathology of the aAVF

As mentioned, the aAVF is a pathology; accordingly, "normal" refers to what is considered normal for the function of hemodialysis – that is, the requirements of the dialysis pump.

The problems encountered with the dialysis circuit are listed below and their assessment by ultrasound will be discussed.

Stenosis – the most common problem.

Anatomy of the useable segment – size, depth, tortuosity, length, aneurysmal dilation.

Needling site – problems with vessel puncture.

Giant fistula – excessive growth of the fistula circuit. Note that aneurysmal degeneration of the usable segment is not the same as a giant fistula. In a giant fistula, the entire circuit is abnormally large, particularly the feeding artery.

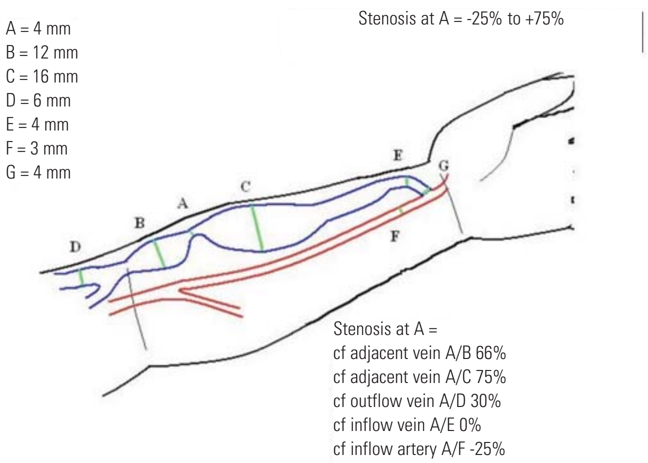

Fig. 5: The problem with the current definition of an aAVF stenosis. Stenosis at A can be defined as anything from -25% to +75% depending on which part of the fistula the diameter of A is compared to. The current convention is to compare A to point B or C, making it a 66–75% stenosis. By that definition however, the "swing" vein (E) and the whole inflow artery (F) should also be considered to be significantly stenosed.
In a sense, the "severity" of the stenosis at point A depends on how narrow A is, and also on how aneurysmal B and C are.

Stenosis in the aAVF

Defining what constitutes a significant stenosis in an aAVF is something our group has been interested in and our research regarding this is due for publication[6].

What constitutes a significant stenosis in an aAVF is not clearly determined. In essence, a stenosis in the dialysis circuit exists when the dialysis machine can no longer dialyse the patient adequately. We believe this stenosis is determined by an absolute minimal luminal diameter –

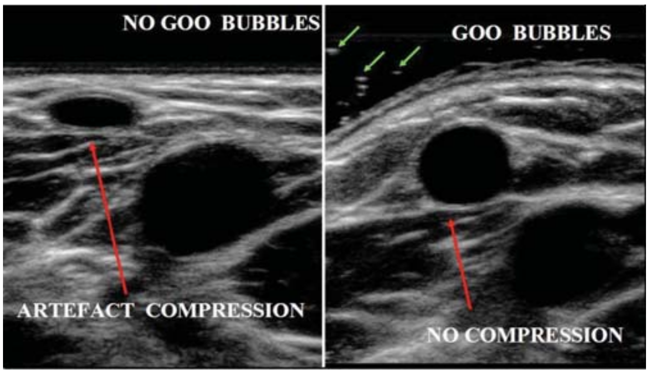

Fig. 6: Gel used as a "standoff" pad. Note bubbles in the gel when not compressing.

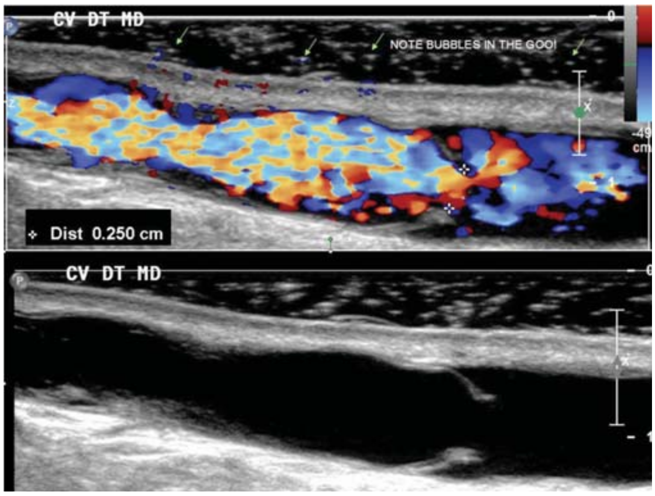

Fig. 7: Valve stenosis in colour and greyscale.

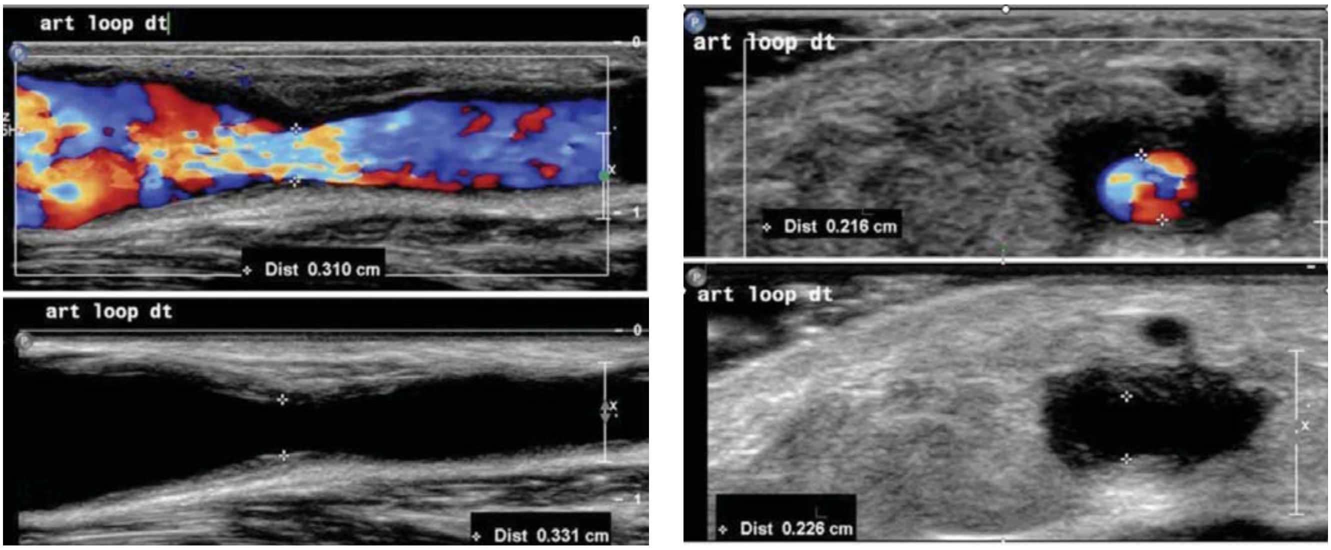

Fig. 8: Assessment of the peri-anastomotic area for endovascular approach.

2.7 mm – although other factors in the dialysis circuit need to be taken into account.

Conventionally, a fistula stenosis is defined, as elsewhere in the vasculature, as a percentage narrowing compared to the adjacent vascular segment. Hence, a 2 mm luminal narrowing in an 8 mm femoral artery is a 75% stenosis. The aAVF circuit however, is a pathology, with no "normal"; hence these grading criteria don't really make sense, as illustrated in Fig. 5.

Furthermore, stenoses in vascular circuits are traditionally determined by velocities, rather than direct measurement of the actual narrowing. One of the reasons for this is technological – in the past, with early ultrasound technology, high quality colour and grey scale definition were not possible. Further, many vascular structures are deep (e.g. iliac vessels) and require low frequency, poor resolution probes to image them. The aAVF on the other hand, is an extremely superficial structure and using modern, high frequency probes, exquisite resolution down to fractions of a millimeter can be achieved in grey scale and colour. Therefore, when determining a fistula stenosis, why measure a surrogate (velocity), when you can measure the real thing (diameter)?

An interesting finding associated with (usually) significant fistula stenoses is what we call the "venturi flap". The fistula vein, immediately past a severe stenosis, is seen to flap open and closed with the cardiac cycle. This relates to the Bernoulli Principle, i.e. the pressure at 90º to a flowing column of liquid is indirectly proportional to the velocity of flow. Hence, during systole, a high-speed systolic jet shoots out of the stenosis and causes collapse of the vein immediately past the stenosis. During diastole, the velocity drops, the pressure at 90º increases and the vein dilates.

Referring to Figs. 3 and 4, it can be seen that, when the fistula diameter drops below a certain value, the dialysis machine can no longer dialyse at flows of 300 mL/min and pressures of 100 mmHg. From our research, the "swing" vein diameter of the radiocephalic fistula should exceed 2.7 mm. Elsewhere in the fistula circuit, and in different fistulas, this figure may vary, but should be broadly similar. Other factors influencing what constitutes an absolute minimum diameter would include any of the following and should be taken into account when judging the significance of a particular stenosis.

1 Length of a given stenosis; remember Poisieulle's Law: flow is proportional to the vessel radius, to the fourth power, and flow is proportional to the length of stenosis to the first power. Hence the influence of the length of the stenosis is far less than the diameter.
2 Number of stenoses in series.
3 Size of the overall fistula. One would expect a given stenosis (e.g. 3 mm) to be more significant in the

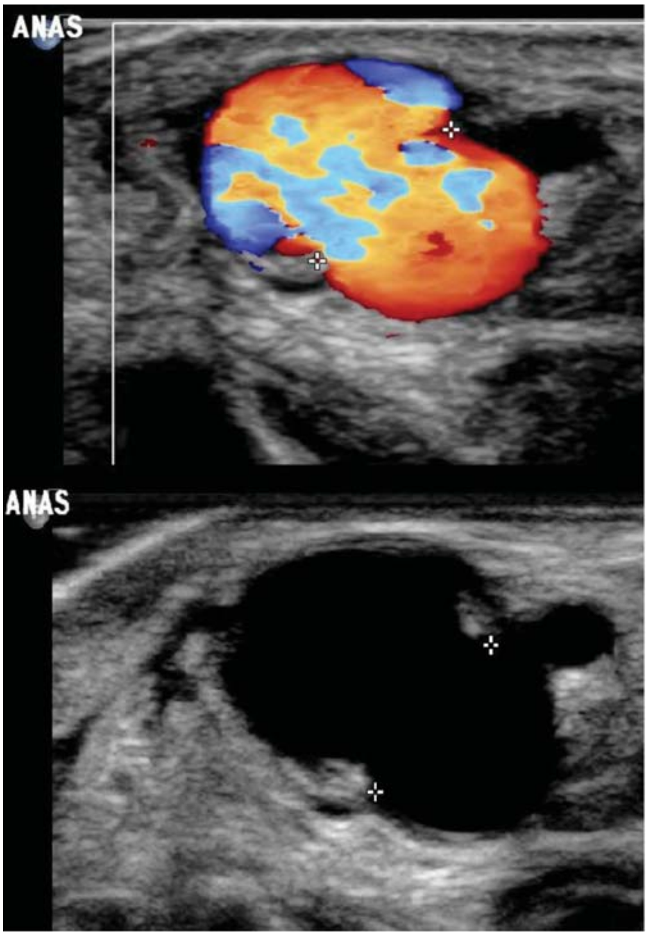

Fig. 9: Assessment of the peri-anastomotic area for endovascular approach.

brachio-cephalic fistula of a large male, than in the radio-cephalic fistula of a small female.

4 Feeding artery diameter. We are trying to factor this into our definition of what constitutes a significant stenosis in an aAVF. As above, a given stenosis will differ in significance in a circuit supplied by a 9 mm brachial artery as opposed to a 3 mm radial artery
5 Combined inflow/outflow problems
6 Other factors – cardiac function, aneurysmal dilation of useable segment etc.

Scanning the aAVF

Set up

A high-end machine (we use a Philips 2000, (Philips, Amsterdam, Holland)) and high frequency linear probe (17-5 MHz) are essential; "second best" is inadequate in fistula scanning. Another useful probe is the 8-5 MHz sector probe, which allows examination of the arch vein in the deltopectoral groove and under the clavicle where it joins the axillo-subclavian vein.

You must use gel. Fistula scanning is one of the few situations where the skinny patient is at a disadvantage. The fistula is too close to the surface and compression artefact is a real danger. Large amounts of gel should be used to create a stand-off pad, and the gel must not be warmed up – it will simply run off the patient's arm.

Both patient and sonographer must be comfortable. The scanner's hand should be in contact with the patient's arm while scanning, to maintain an appropriate distance of the probe with bubbles-in-the-gel as illustrated in Fig. 6.

Assessment

As in all our ultrasound scanning, we aim for a "targeted ultrasound"; rather than a protocol driven general scan, we attempt to answer a specific clinical question with the ultrasound probe. This is particularly important in aAVF scanning as the whole fistula circuit runs from the left ventricle, down the arteries, up the fistula vein and back to the right atrium. Scanning this whole circuit in every patient is unrealistic.

The following information should be obtained by the sonographer prior to the scan to allow for appropriate targeting:

1 Clinical history: Type of fistula, age of fistula, secondary procedures, needling sites.
2 Type of Fistula. In all aAVF work, two types of fistula should be distinguished: aAVF "PF" – problem fistula. This is a mature fistula that is dialysing, but there are problems with the dialysis, flows, pressures, needling etc. aAVF "FTD" – failure to develop. A fistula that is not being used for dialysis yet, it is failing to develop and mature adequately.
3 Dialysis "numbers": dynamic dialysis numbers – flow, arterial pressure and venous pressure as explained above. These are valuable in guiding the sonographer as to the site and type of fistula problem e.g. high arterial pressures suggest an inflow problem. Be aware that the dynamic pressures only make sense in the presence of normal flows; for example, in the presence of an outflow stenosis, the patient might maintain normal venous return pressures (100–120 mmHg) by decreasing the flow down to 250 mL/min.
4 Physical examination:
   - When the fistula vein is occluded, the distal vein should have a strong arterial thump – good inflow.
   - When the arm is elevated, the fistula vein should empty out – good outflow.
   - A thrill felt anywhere in the fistula circuit other than at the anastomosis suggests a stenosis immediately upstream from the thrill.
   - Tortuosity, depth, aneurysmal dilation, accessibility, needling sites, revision scars, nitinol stents should all be noted prior to starting the scan.

Scanning protocol

For the radiocephalic fistula, we start with the inflow artery, then anastomosis, outflow artery, CV distal, CV forearm and outflow at the elbow. Other fistula configurations have a slightly different protocol.

Measuring stenoses

As discussed above, we assess stenosis using absolute minimal diameter measurements in colour and grayscale, as outlined in our previous publication.

Note that in fistulas, dialysis is about flow; hence all measurements concern the luminal diameter, not the outside diameter. Our convention is to take the luminal diameter in systole.

Colour and greyscale pictures allow the definition of the severity and length of the stenosis. Multiple samples of the maximally stenosed area are taken in colour and in greyscale, in both transverse and in longitudinal section, and a final number based on these readings is then recorded. The zoom function on the ultrasound machine is useful and allows for high resolution measurements. Figs. 7 and 8 show the types of images that are routinely obtained.

Inflow artery

Radiocephalic aAVF

Problems proximal to the origin of the radial artery are, in our experience rare. In over 1300 fistula scans, we have only encountered three problems proximal to the radial artery.

The radial artery is a common site of problems, mainly in the diabetic patient with diabetic atherosclerotic disease. The features of the radial artery that need to be commented on are diameter, calcification/disease and tortuosity. Generally, the atherosclerosis is mild in the proximal third of the artery, moderate in the mid third and worst in the distal third.

"Clamp injury" – just before the anastomosis is not uncommon. This stenosis is due to injury from the arterial clamp used to occlude the artery at the time of anastomosis formation. It is typically short, within 5 mm of the anastomosis and can occur in both a healthy and a diseased artery.

It is important to assess the outflow radial artery (see Fig. 1) for two reasons. First, it is an important collateral inflow to the fistula and a small percentage of fistulas actually function adequately on the outflow artery alone through the palmar arch. Second, for endovascular revision of the problematic fistula, a retrograde puncture of the outflow artery can be a good, safe alternative access route if it is long and big enough (see Fig. 9). Note that the direction of flow in the outflow radial artery in the mature fistula is always retrograde i.e. from the wrist to the fistula vein, effectively "stealing" blood from the ulnar artery via the palmar arch.

Other fistulas

Stenosis is rarely a problem in the brachial artery. On the contrary, any fistula supplied by the brachial artery should always have the feeding brachial artery diameter measured because the development of giant fistula with these circuits, especially in men, is not uncommon. Any brachial artery growing beyond 8 or 9 mm should be considered for choke placement on the fistula.

Note that a high bifurcation of the radial artery – often coming off the brachial artery near the axilla – is not uncommon. This can cause some confusion, and the sonographer should be alert to this when the brachial artery is small – < 4 mm.

The outflow brachial artery should be assessed particularly in the presence of a steal problem; if the outflow brachial artery has a stenosis (past the anastomosis), all the blood coming down the brachial artery may be diverted up the low resistance fistula circuit, with too little going to the hand.

Anastomosis

Anastomosis is best assessed in transverse in colour and greyscale. The vibrations at the anastomosis can make colour diameters hard to assess, and greyscale is the best tool. Very helpful are the echogenic stitches in the anastomosis as shown in Fig. 9. The anastomotic area can be very tortuous and the probe must be angled appropriately to define the anastomosis. Velocities at the anastomosis are particularly useless; in a publication by Chao, *et al.*[7], they showed that the average velocity at the anastomosis was 3.75 m/s; therefore, a stenosis of > 75% would require the probe to read a velocity of 13.5 m/s.

CV distal (swing vein)

The swing vein is by far the most common site of problems and it can be difficult to examine as it is very superficial and very tortuous. Nevertheless, as our previous publication[1] indicates, ultrasound is highly accurate in this critical segment.

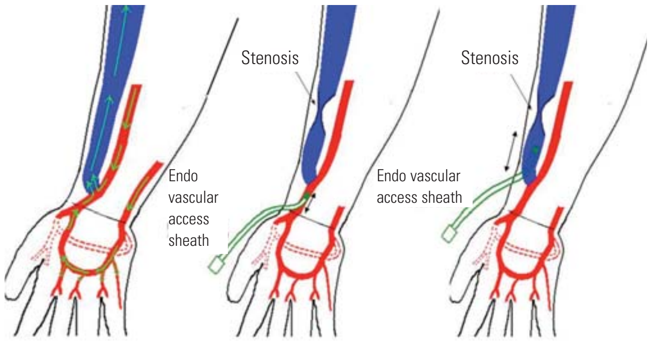

Fig. 10: Assessment of the peri-anastomotic area for endovascular approach.

Another important assessment in the CV distal is the distance of the stenosis from the anastomosis – if this is more than 1 to 1.5 cm, then the endovascular intervention can be performed in an antegrade fashion through the CV hood, an easier and quicker approach than going retrograde through the CV in the forearm (Fig. 10).

Useable segment

The following features need to be assessed. Note particularly the difference between the aAVF FTD and the aAVF PF.

1 Diameter as discussed above. Note that the 2.7 mm minimum luminal diameter does not apply in the useable segment; 2.7 mm may be wide enough to achieve adequate flows through the fistula circuit, but it is not wide enough to allow for reliable needling. The useable segment should be large enough to allow accurate, repeated needling – generally, larger than 5 mm in diameter, although other factors such as depth come into play (see below). This assessment is particularly important in the aAVF FTD.
2 Depth. Again, particularly important in the aAVF FTD. As a rule of thumb, a useable segment deeper than 10 mm cannot be accessed and needs to be made more superficial; if less deep than 5 mm access should be fine; if between 5 and 10 mm deep, other factors come into play, such as size.
3 Tortuosity is a very important issue and can be fixed with a superficialisation operation.
4 Aneurysms are generally of less significance than is thought. Concern should arise if the aneurysm becomes very big (diameter > 2 cm), very thin walled or contains clot. False aneurysms are not a problem of the native AVF.
5 Needling sites, particularly, button holes can be examined to determine if they are placed/orientated correctly.

Outflow

This is where the radiocephalic fistula differs from other fistulas.

Radiocephalic: at the elbow, the radiocephalic fistula typically has three outflow channels, as illustrated in Fig. 1. For this reason, outflow problems with the radiocephalic fistula are uncommon.

1 The CV proper, which joins the deep system at the CV-SCV (subclavian) junction under the clavicle
2 The basilic vein, via the median cubital vein
3 A perforator just distal to the elbow which joins the venae commitantes of the brachial artery.

Table 1: Glossary.

Antegrade	In the same direction as the blood flow
Arch vein	See CVdt
Arterial pressure	The negative pressure the dialysis machine needs to exert to "suck" the blood out of aAVF
AVF	Arteriovenous fistula
aAVF	Autogenous (or native) arteriovenous fistula
aAVF FTD	Failure to develop (or mature)
aAVF PF	Problem fistula – a mature fistula that is not dialysing adequately
Bernoulli	Bernoulli Principle: Pressure at 90^o to a flowing liquid is inversely proportional to the velocity of flow
Choke	A synthetic band placed surgically around the CVdt to prevent progressive enlargement of the fistula
CV	Cephalic vein
CVdt	Cephalic vein distal (also known as the "swing vein"), the 5 cm or so of CV that is mobilised surgically and swung onto the artery for anastomosis
CVpr	CV proximal (also known as the "arch vein"), the part of the CV that courses thru the delto-pectoral groove onto the subclavian vein – a common stenosis site
Distal	Further away from the heart (in veins and arteries)
Dynamic pressures	Pressures in the dialysis circuit during hemodialysis. At flows of 300ml/min, arterial pressure should be about -100 mmHg and venous pressure should be about +100 mmHg
Fistula flow	Flow through the fistula at any one point; calculated from the diameter of the fistula and flow velocity at that point.
Outflow artery	The fistula artery downstream from the anastomosis
Poiseuille's law	$\square\Pi = 8 \square \Lambda \Theta / \pi r^4$ Note flow is related to r^4
Proximal	Closer to the heart (in veins and in arteries)
Pump speed	The rate of blood flow through the dialysis circuit (and dialysis machine) during hemodialysis: target of 300 mL/min
Recirculation	Where blood, returned to the fistula by the venous needle to proceed back to the right atrium, is instead sucked back into the dialysis machine via the arterial needle, resulting in inadequate dialysis. Can occur when needles are too close together or where there is an ouflow stenosis to the fistula
Retrograde	In the opposite direction of the blood flow
Steal	All fistulas "steal" blood from the arterial circulation of the limb. When the amount of blood taken by the fistula causes critical ischemia of the hand (rest pain, gangrene, ulceration) a clinical steal exists
Swing vein	See CVpr
Useable length	That part of the fistula circuit that can be accessed with the hemodialysis needles
Venous return pressure	The positive pressure the dialysis machine needs to exert to return blood to the fistula
Venturi flap	Flapping of the fistula vein with the cardiac cycle, immediately past a severe stenosis (Bernoulli principle)

Brachiocephalic

One of the weaknesses of the brachiocephalic fistula is that it has essentially only one outflow channel – the "arch vein". This is prone to problems and stenoses, and these problems are difficult to fix with open or endovascular techniques.

The arch vein is best examined with the 8-5 MHz sector probe, and usually can be reasonably assessed up to the CV-SCV junction.

Brachiobasilic

Its outflow is directly into the axial deep veins. Again, the sector probe may be needed to assess the outflow in the proximal arm and shoulder.

Central veins

Central venous problems are important in fistula work for two reasons. First, they can interfere with the fistula's venous outflow, and cause high venous return pressures. Second, they are common due to the unfortunate ongoing use of vascaths.

Central venous stenoses and occlusions are of variable functional significance to the fistula function. Collateralisation around the shoulder is very rich, and radiocephalic fistulas with occluded central veins may continue to work satisfactorily.

The severity of the central venous stenosis, the degree of collateralisation and the distance from the anastomosis are all factors.

Generally, central veins are not assessed in the aAVF ultrasound scan for the following reasons.

- Different probes and different patient positioning are required
- Duplex assessment of central venous problems is difficult, often based on indirect evidence such as wave form
- Duplex assessment of central venous problems is of limited accuracy
- Central venous problems both anatomically and physiologically can be accurately and rapidly assessed by conventional antegrade radiography.

Fistula flow

Measurement of fistula flow in mL/min (using diameter + velocity at a given point) is very useful and should be a routine part of every fistula scan. Note that the flow volume (mL/min) derived by this calculation is highly dependent on the value given to the diameter. According to Poiseuille's Law, doubling the radius will increase the flow by the fourth power i.e. flow will increase by a factor of 16.

Ideally, flow measurements should be taken at the point of needling, in the useable segment. Flow of more than 500 mL/min generally indicates adequate fistula function.

Flow measurement is useful in:

- The assessment of the fistula's function
- The change in fistula function over time
- As a surveillance tool
- For research purposes.

Conclusions

aAVF duplex ultrasound is an accurate, safe and reliable modality for investigating the problematic fistula. In the dialysing fistula, it defines the nature, location and severity of the problem and allows for the planning of the endovascular or open surgical treatment. In the predialysis fistula, it determines the cause of non-maturation, which can then usually be corrected. It is a specialised scan that should be done by sonographers with knowledge of the complexities of this unique vascular circuit. Stenoses, the most common problem, should be assessed using colour and grey scale duplex ultrasound measuring luminal diameter. Velocity measurements are of limited value.

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