Vascular imaging for anaesthetists and intensivists, part 1: Basic principles

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Learning objectives

By reading this article, you should be able to:

- Describe the various non-invasive imaging options for peripheral arterial disease, carotid artery stenosis and abdominal aortic aneurysm.
- Discuss the strengths, weaknesses and safety implications of Doppler ultrasound, CT angiography and MR angiography.
- Explain the spectrum of normal vascular appearances for each modality.

In recent decades, advances in CT angiography (CTA), magnetic resonance angiography (MRA) and duplex ultrasound (DUS) have rendered these non-invasive imaging modalities the mainstay of diagnosis and intervention planning for patients with arterial disease. These developments in imaging technology have accompanied a shift away from open surgery towards endovascular treatment for many pathologies.¹

Patients with vascular disease can present unique challenges to anaesthetists and intensivists, especially as multiple morbidity is common and vascular interventions are often complex. Knowledge of the basic principles of vascular imaging provides anaesthetists with greater understanding of their patients and may inform specific management decisions, such as location of BP monitoring and arterial access.

This article covers the basics of CTA, MRA and DUS, with specific reference to their indications, advantages, disadvantages, limitations and safety implications. A systematic approach for reviewing each imaging modality is described in the context of three of the most common vascular pathologies: carotid artery stenosis (CAS), abdominal aortic aneurysm (AAA) and peripheral arterial disease (PAD). In a forthcoming article, we will focus in greater detail on

Key points

- Non-invasive imaging has become the mainstay of diagnosis and intervention planning in patients with vascular disease.
- Clinicians need to understand the basic principles of each imaging modality to choose and interpret the most appropriate imaging.
- MR angiography and CT angiography are predominantly anatomical modalities.
- Duplex ultrasound provides functional information about blood flow and detailing anatomical appearances.
- It is necessary to understand the limitations of each modality to ensure appropriate diagnosis and management.

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interpretation of the most frequently encountered abnormal imaging features of these pathologies.

**Basic principles**

**Duplex ultrasound**

Ultrasound (US) imaging relies on handheld probes, which can both emit sound waves of high frequencies (typically between 3 and 15 MHz) and also detect those waves as they are reflected back by tissues. Duplex ultrasound combines ‘B-mode’ imaging, whereby a real-time greyscale anatomical image is created, and Doppler imaging, which can measure the velocity of moving blood. 

Duplex ultrasound therefore allows both a structural assessment (e.g. ‘there is echogenic plaque occupying the majority of the vessel lumen’) and also a functional or haemodynamic assessment (e.g. ‘there is a four-fold increase in peak systolic velocity [PSV], indicating a severe stenosis’). Doppler waveform analysis, discussed in greater detail as follows, can also give useful information about the vascular tree upstream and downstream of the probe.

Aside from providing functional information about blood vessels, the major advantages of DUS are that it is relatively inexpensive, widely available, generally well tolerated by patients and does not involve ionising radiation or injection of i.v. contrast agent. In the critical care setting, the ability to perform DUS at the bedside can be a considerable advantage compared with cross-sectional modalities, notwithstanding the challenges of US in immobile patients with multiple lines, tubes, dressings, etc.

The major disadvantage of DUS is that the image acquisition is inherently more operator dependent than CT and MRI; the scan is interpreted in real time by the DUS practitioner, usually a sonographer or radiologist, and only a few representative images are selected and saved. Cross-sectional scans, on the other hand, can be reviewed in their entirety at any time. Larger patients tend to make poorer subjects because US signals are attenuated in subcutaneous fat, and there are other situations where US imaging may be degraded or non-diagnostic, as the US beam cannot pass through skin dressings, gas (e.g. in bowel), calcification and metalwork.

**CT angiography**

Modern CT scanners comprise an X-ray source and a ring of small detectors spinning around a patient to acquire a three-dimensional data set, which can be reconstructed to generate a stack of imaging slices in multiple different planes (e.g. axial, coronal and sagittal).

A bolus of iodinated contrast medium (ICM) injected into a peripheral vein transits through the pulmonary circulation before entering the systemic arteries. Computed tomography angiography aims to capture the imaging when the concentration of ICM is at its peak in the arteries in the imaged volume, in order that there is optimal contrast between the flowing arterial lumen and adjacent structures. There are various methods of timing the scan acquisition after the bolus of ICM, including using a small test bolus before the scan or directly tracking the bolus and triggering the scan when a threshold enhancement is achieved in a target artery.

Computed tomography angiography has the advantages of being quick, widely available and able to image every vascular territory. The disadvantages of CT are that it involves a considerable radiation dose (of particular concern in younger patients and when multiple scans are required), and the requirement for ICM has implications in patients with impaired renal function. Hypersensitivity reactions after ICM injection are relatively common (0.7% according to a recent large case series), with severe or life-threatening reactions in 0.01%. 

Computed tomography images are susceptible to artefact from very radio-dense material: the main implication in angiographic imaging is that heavy calcification associated with atherosclerotic disease can obscure contrast in the adjacent lumen, and therefore, the degree of stenosis can be exaggerated.

Computed tomography angiography is indispensable for intervention planning in aortic aneurysmal disease, as it allows for the most comprehensive assessment of aneurysm morphology and potential sealing zones for endovascular repair. Computed tomography is also the ‘workhorse’ for emergency vascular imaging, particularly if a postoperative complication, such as bleeding, pseudoaneurysm or vessel thrombosis, is suspected in a territory that is not amenable to a targeted US study.

**Magnetic resonance angiography**

Magnetic resonance imaging relies on a very strong magnetic field, which is generated by an electromagnet cooled to extremely low temperatures (in the order of minus 270°C). The magnetic field causes the hydrogen ions in the soft tissues of the body to align. Short radio-frequency pulses transiently alter their alignment, generating a detectable signal that can be reconstructed to generate imaging slices. A wide variety of different sequences can be acquired; on any specific sequence, it may not be possible to distinguish between different tissues (e.g. fat and haematoma and proteinaceous fluid may all have a similar signal), and therefore, multiple sequences are often necessary to optimise diagnostic yield.

Magnetic resonance angiography sequences are designed to optimise the contrast between moving blood in the target vessel lumen and the rest of the body; these often involve i.v. injection of a magnetic resonance-specific contrast agent (typically containing chelated gadolinium), but in recent years, a wide variety of non-contrast angiographic sequences have been developed.

Magnetic resonance angiography, like CTA, can image all of the major vascular territories. It can be used as an alternative for patients with contraindications to CT. However, non-contrast MRA may be preferred in patients with severe renal impairment, given the potential for gadolinium-based contrast agents to cause nephrogenic systemic fibrosis, a potentially life-threatening multisystem disorder, in those with estimated glomerular filtration rate <30 ml min⁻¹.⁶ Magnetic resonance angiography does not involve ionising radiation, and therefore, it is generally preferred for younger patients, especially those requiring serial imaging (e.g. aneurysm surveillance in a young patient with connective tissue disorder).

The main disadvantages of MRA are that it is generally not feasible in patients with implanted electronic devices, such as pacemakers, cardioverter defibrillators and nerve stimulators. For patients in the critical care setting, any anaesthetic and monitoring equipment must be MRI compatible, which may make MRA less desirable in this group. Whilst MRA is less susceptible than CTA to artefact from artery wall calcification, metallic stents usually generate more artefact on MRA, and
therefore, magnetic resonance is less favourable for assessment of previously stented vessels. Scanning times are longer than CT, meaning greater expense and lower patient throughput. Most magnetic resonance scanners are enclosed and loud, and are poorly tolerated by patients who are prone to claustrophobia. Those patients unable to lie still for several minutes will generate movement artefact, which can lead to non-diagnostic images.

**Digital subtraction angiography**

Digital subtraction angiography (DSA) involves direct intra-arterial injection of ICM (or less frequently CO2), with real-time X-ray imaging to track the movement of the contrast medium in the target arteries. The fluoroscopic imaging equipment can subtract the background structures, such as soft tissue and bone, leaving just the arterial lumen visible. Digital subtraction angiography has higher spatial resolution than the cross-sectional modalities and can provide a dynamic assessment of flow in a vascular bed. Direct manometry in the target vessel can also give information about the haemodynamic significance of a stenosis. In circumstances where non-invasive imaging is insufficient, DSA may be required for diagnosis. However, given that it is inherently invasive, carrying risks related to vascular puncture and catheter manipulation and injection of ICM, in modern practice it is generally reserved for circumstances where endovascular intervention is likely to be required. Digital subtraction angiography is therefore not considered in detail in this article.

A related form of imaging is cone-beam CT, in which the fluoroscopic equipment rotates around the patient and acquires an imaging volume, rather than a two-dimensional image. Cone-beam CT can be performed during an angiographic procedure, with a contrast injection via a catheter in a specific target vessel. This technique provides three-dimensional angiographic information of a specific vascular bed with greater spatial resolution than conventional CT. As with DSA, cone-beam CT is typically undertaken during an interventional procedure rather than as a primary diagnostic tool.

**Image interpretation: A systematic approach to each modality**

**Duplex ultrasound**

Shallow structures can be imaged with high-frequency US probes, which have a very high spatial resolution but cannot reliably image at more than 5–10 cm depth from the skin. Therefore, superficial vascular structures, such as carotid or femoral arteries, can be imaged in slimmer patients in great detail. Lower-frequency probes, with lower spatial resolution and less image clarity, are required for deeper vascular structures, such as the abdominal aorta. Therefore, imaging interpretation varies to some degree between each vascular territory and each patient.

A systematic approach to DUS involves assessment of vessel diameter, wall thickness and Doppler waveform. A normal vessel has a thin, smooth wall, with a characteristic waveform, as discussed as follows, and no focal changes in PSV along its course. It may be difficult to visualise the entire target artery, and certain manoeuvres may be required, such as patient repositioning, removal of dressings if appropriate or steady abdominal pressure to move gas-containing bowel.

In general, DUS can detect all of the major arterial pathologies: atherosclerosis, aneurysm, pseudoaneurysm, dissection, thrombus and abnormal arteriovenous connection (i.e. fistula or malformation). Many of these disease processes can cause luminal narrowing or occlusion. Absence of flow on Doppler analysis indicates complete occlusion, whilst assessment of PSV can grade the haemodynamic significance of a stenosis. Basic physical laws of conservation, as expressed in the continuity equation, dictate that the change in velocity of a non-compressible fluid through a narrowing in a tube is inversely proportional to the degree of reduction in the cross-sectional area of the tube. Allowing for some simplifications (particularly given that blood vessels are branching structures and blood demonstrates pulsatile rather than continuous flow), it follows that a doubling of PSV compared with the immediately upstream vessel is an indicator of 50% stenosis. In most vascular territories, 50% is taken as a threshold for haemodynamic significance.7

In this article, DUS is covered in detail. However, DSA and cone-beam CT are covered only briefly, as they are primarily interventional procedures rather than as a primary diagnostic tool.
Caution is required at arterial branch points, for example the carotid bifurcation, where some degree of velocity change is expected as flow dynamics change between the distal common carotid artery (CCA) and internal carotid artery (ICA) origin. Hence, there are a variety of more complex calculations to estimate stenosis severity based on absolute ICA PSVs and ICA:CCA PSV ratios.\(^5\)

In addition to PSV, other elements of the Doppler waveform can give useful information. The overall shape of the waveform is influenced by the upstream vasculature and the elasticity of the artery in question. A healthy artery in the peripheral circulation with no upstream disease is expected to demonstrate a triphasic waveform, the three phases being a systolic peak, reversed flow in early diastole and forward flow in late diastole. End-diastolic flow can provide information about the downstream vascular bed, but this must be interpreted appropriately according to the territory; for example, high-velocity end-diastolic flow in a renal artery is an expected feature, given the low resistance in a healthy kidney’s microvasculature, rapid end-diastolic flow in a normally high-resistance vascular bed (e.g. the peripheral circulation) may be a sign of a pathological downstream arteriovenous connection (Fig. 1).\(^9\)

**CT angiography**

In many ways, CTA interpretation is more straightforward than DUS, as there is a finite set of static, anatomical images, and the reader’s attention can focus solely on imaging analysis without having to acquire the images and maintain rapport with the patient at the same time.

Systematic interpretation requires not only a detailed assessment of the target arteries but also the rest of the imaged volume, which, for many scans, includes much of the abdomen, thorax and bony skeleton. Sometimes, assessment of non-vascular structures can give useful information about end-organ perfusion, which may be highly relevant to the underlying vascular disease. For example, renal and splenic infarcts in addition to acute lower-limb arterial occlusion imply an embolic source proximal to the abdominal aorta.

For optimal evaluation of vascular pathology, changing the orientation of the imaging may be required to show the full length of the vessel in question. It is also possible to generate three-dimensional reconstructions, which can display an entire vascular tree in one image, with the surrounding non-vascular tissues subtracted (Fig 2). These manipulations have become easier with steady improvements in picture archiving and communication systems software.
Whilst CTA has a lower spatial resolution than high-frequency US, and therefore may be less sensitive for subtle pathology in smaller arteries, the former is still an excellent tool for diagnosing the major arterial pathologies in large and medium-sized vessels. The site, severity, number and length of stenoses or aneurysms should be determined, and any significant anatomical variants can be documented, particularly if there are implications for intervention (e.g. duplication of renal arteries must be appreciated when planning AAA repair).

**Magnetic resonance angiography**

Whilst MRA interpretation is similar to CTA, there are certain specific considerations. Like CTA, MRA images can be viewed in relatively unprocessed form by scrolling through the data set in the plane in which the images were acquired. With certain MRA sequences, post-processing may allow the images to be reconstructed in any plane or presented in three-dimensional form, providing a snapshot of an entire vascular territory (Fig 3).

Whilst a CTA usually covers the entire imaged volume in one acquisition, the size of a single MRA acquisition is limited by the coverage of the radio-frequency-emitting coil. A typical MRA study of the peripheral vasculature, which covers the abdominal aorta down to the feet, may require three or four separate acquisitions, which need to be assessed separately.

Given that MRA sequences are optimised for vascular assessment, the non-vascular anatomical detail is generally worse than CTA. If additional information is required, additional sequences may be necessary. For example, if the differential diagnosis for leg claudication includes both vascular and neurogenic aetiologies, dedicated spinal magnetic resonance sequences may be needed in addition to the MRA, and this must be decided before the patient undergoes the scan.

**Imaging indications for the most common vascular pathologies**

**Carotid artery stenosis**

Carotid imaging is most commonly requested after carotid-territory ischaemic stroke. Other less common indications include preoperative planning before coronary artery bypass grafting. The question is usually whether CAS, which typically affects the origin of the ICA, is present; if CAS is confirmed, imaging is central to the accurate grading of severity, which in turn helps to determine whether carotid revascularisation is appropriate. Fifty per cent stenosis is the most widely accepted threshold for intervention in symptomatic patients (i.e. those with recent non-disabling stroke or transient ischaemic attack in the relevant territory), although different methods exist for estimating severity of stenosis.8,10

In most UK centres, DUS is the first-line imaging modality, given that it is widely available, comparatively inexpensive and generally of high diagnostic yield. However, UK stroke guidelines state that any of DUS, MRA and CTA are acceptable first-line investigations. It is increasingly common for patients presenting with acute stroke to undergo CTA at initial presentation to guide decisions related to i.v. thrombolysis or mechanical thrombectomy. It is recommended that if a significant stenosis (50%) is detected on the first imaging test, a second or repeat study should be considered for confirmation before intervention.10 Whilst not mandatory before carotid endarterectomy, CTA is usually required before carotid stenting to ensure that the latter treatment is technically possible.

**Abdominal aortic aneurysm**

The most widely accepted definition of AAA is dilatation of the abdominal aorta to a diameter >3 cm. A diagnosis of AAA may be made as an incidental finding on abdominal imaging, based
on clinical features (e.g. pulsatile mass, with or without symptoms), or as part of a dedicated screening programme (which is offered to men in the UK aged ≥65 years). Ultrasound is the main modality for screening or diagnosis in the elective setting, as it is quick to perform, does not involve ionising radiation and has a high sensitivity (approaching 100%).\(^{11,12}\) If AAA has been diagnosed but does not meet threshold for intervention (typically 5.5 cm), US is used for surveillance to monitor aneurysm growth.

Computed tomography angiography provides the most detailed assessment of AAA morphology and extent. It is therefore the primary tool for planning intervention, either electively when an aneurysm has reached threshold or in the acute setting of symptomatic or ruptured AAA (provided the patient is sufficiently stable for a scan). Important anatomical features can be determined, such as presence and length of infrarenal neck, number and position of renal arteries and involvement of the iliac arteries. For endovascular repair, sealing zones and access vessels can be evaluated, and the relevant stent grafts can be selected. For surgical repair, clamping strategy and choice of graft can be decided.

Imaging of the aortic wall and overall aneurysm morphology on MRA is less reliable than CTA, and therefore, the former is not typically used for preoperative planning or diagnosis.

**Peripheral arterial disease**

A diagnosis of lower-limb PAD is usually made in patients with symptoms of intermittent claudication or features of critical limb ischaemia (CLI). Clinical assessment involves examination of the legs for ischaemic features and tissue loss, palpation of pulses and measurement of the ankle brachial pressure index.\(^{13}\)

Many patients with intermittent claudication, but no features of CLI, are managed successfully with medical therapy and supervised exercise. These patients may never be considered for surgical or endovascular intervention, and therefore do not require imaging. Patients with CLI or lifestyle-limiting claudication despite optimum medical therapy may be considered for intervention. The National Institute for Health and Care Excellence guidance in the UK recommends DUS as first-line imaging in all patients, with MRA for those...
who need additional information before intervention, and CTA only when MRA is contraindicated or not tolerated.\(^{13}\)

In practice, DUS is usually sufficient to guide intervention for chronic femoropopliteal and tibial disease but is often inadequate if there is a suspicion of stenosis in the aorto-iliac segment, as these vessels are difficult to image comprehensively with DUS.

For patients presenting with acute limb-threatening ischaemia, it is appropriate to use the most rapidly available modality, which in many centres is CTA, especially out of hours. Computed tomography angiography may also be used in preference to MRA in patients with chronic symptoms, simply because of limited local MRI capacity.

In some centres, patients undergo regular DUS surveillance after surgical bypass or even stenting for PAD. The intention is that bypass graft or in-stent stenosis can be detected and treated early in the hope of improving long-term patency rates, but this practice is of uncertain benefit and not universally accepted.\(^{14}\)

**Normal imaging appearances**

In an accompanying article, we will demonstrate the commonly encountered pathological findings, but here, we include a brief account of the expected range of normal imaging appearances of the carotid arteries, abdominal aorta and lower-limb arteries.

**Carotid arteries**

A comprehensive DUS study of the carotid arteries involves the whole of the visible portion of the CCAs and ICAs bilaterally. Doppler waveforms are also typically acquired from the external carotid arteries and vertebral arteries to provide some information about the extracranial and posterior circulation. Particular attention is paid to the B-mode appearance and Doppler waveform in the proximal ICA, which is the most common site for significant stenosis. Absence of atherosclerotic plaque, wall-to-wall filling on colour Doppler imaging and a low-resistance waveform with PSV \(< 125 \text{ cm s}^{-1}\) are typical normal features.

Computed tomography angiography and MRA studies of the carotid arteries should cover from the aortic arch up to the major intracranial vessels. Therefore, these cross-sectional studies allow a more comprehensive assessment of the head and neck vasculature (Fig. 4).

**Abdominal aorta**

Ultrasound of the abdominal aorta aims to survey as much of the abdominal aorta as possible, taking as many diameter...
measurements as possible. Abdominal aortic aneurysm is excluded if the maximal diameter is less than 3 cm. It is generally accepted that US measurements in the anteroposterior plane are most accurate and reproducible, but there is some variability internationally about whether measurements are taken from the outer aortic wall or the inner. The UK screening programme advocates inner-to-inner measurement.12

On CTA, images can be reconstructed along the plane of the abdominal aorta to enable the most accurate diameter measurement. Computed tomography angiography also enables assessment of the position and condition of the major visceral branches and the iliac vessels, and appreciation of the normal anatomical variants (e.g. multiple renal arteries and horseshoe kidney) (Fig. 5).

**Peripheral vasculature**

Lower-limb PAD can be caused by stenotic or occlusive disease from the aorta all the way down to the small vessels in the foot.

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**Figure 6** Normal imaging of the peripheral vasculature. (A) DUS image showing the anterior tibial artery (ATA). There is wall-to-wall filling of the artery on the Doppler image and a normal triphasic waveform. (B) Axial image from a CTA showing the superficial and deep femoral arteries in cross section. (C–E) Three-dimensional MRA reconstructions. The scan has been acquired in three separate stations: (C) aorto-iliac, (D) femoropopliteal, and (E) tibial, and it shows normal vessels with no stenotic, occlusive or aneurysmal lesion.
Therefore, a comprehensive assessment includes the abdominal aorta, iliac vessels and all of the major infrainguinal arteries.

A focal lesion in the aortoiliac segment may not be detectable on DUS in many patients, given the depth of the vessels and overlying bowel gas. However, an indirect assessment of aortoiliac disease can be made from the nature of the femoral pulses and the Doppler waveform in the common femoral arteries (CFAs). The combination of a normal femoral pulse and a triphasic CFA waveform with a rapid systolic upstroke is usually sufficient to exclude a haemodynamically significant upstream stenosis. The infrainguinal vessels are usually more amenable to direct DUS assessment, albeit the tibial vessels are often not clearly visible throughout their entire length.

Magnetic resonance angiography and CTA generally give a more comprehensive view of the aorto-iliac segment. A significant stenosis is excluded if there is no lesion causing luminal narrowing of >50% compared with the immediately adjacent vessel (Fig. 6).

Summary
Non-invasive imaging has become the mainstay for diagnosis and intervention planning in vascular disease. The main imaging modalities—DUS, MRA and CTA—each has specific advantages and weaknesses, which influence when they are used and how they are interpreted. The range of normal appearances for each modality has been presented earlier. In Part 2 of this series, we will focus on interpretation of the most common pathological appearances in the setting of PAD, CAS and AAA.

Declaration of interest
The authors declare that they have no conflicts of interest.

MCQs
The associated MCQs (to support CME/CPD activity) will be accessible at www.bjaed.org/cme/home by subscribers to BJA Education.

References