CHAPTER 1

Methods of Arterial and Venous Assessment

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Diagnostic and therapeutic decisions in patients with vascular disease are guided primarily by the history and physical examination. However, the accuracy and accessibility of non-invasive investigations have greatly increased due to technological advances in computed tomography (CT) and magnetic resonance (MR) scanning. CT angiography (CTA) and MR angiography (MRA) continue to evolve rapidly, and are best described as ‘minimally invasive’ techniques when used with intravenous (i.v) contrast. This chapter describes the main investigative techniques used in arterial and venous disease.

OVERVIEW

- This chapter describes the main investigative techniques used in arterial and venous disease.
- The ankle–brachial pressure index (ABPI), calculated from the ratio of ankle systolic blood pressure (SBP) to brachial SBP, is a sensitive marker of arterial insufficiency in the lower limb, and correlates with survival.
- Blood velocity increases through an area of narrowing. Typically, a 2-fold increase in peak systolic velocity compared with the velocity in a proximal adjacent segment of the same artery usually signifies a stenosis of 50% or more.
- In detecting femoral and popliteal artery disease, duplex ultrasonography has a sensitivity of 80% and a specificity of 90–100%.
- The introduction of multidetector computed tomography (MDCT) has had a dramatic effect on vascular imaging. CT pulmonary angiography (CTPA) for suspected pulmonary embolism is a good example, but CT angiography and magnetic resonance angiography are widely used to investigate large artery pathology.
- Colour duplex scanning is both sensitive and specific (90–100% in most series) for detecting proximal deep-vein thrombosis (DVT).

Principles of vascular ultrasound

In its simplest form, ultrasound is transmitted as a continuous beam from a probe that contains two piezoelectric crystals. The transmitting crystal produces ultrasound at a fixed frequency (set by the operator according to the depth of the vessel being examined) whilst the receiving crystal vibrates in response to reflected waves and produces an output voltage. Conventional B-mode (brightness mode) ultrasonography records the ultrasound waves reflected from tissue interfaces and a two-dimensional picture is built up according to the reflective properties of the tissues.

Ultrasound signals reflected off stationary surfaces have the same frequency with which they were transmitted, but the principle underlying Doppler ultrasonography is that signals reflected from moving objects, e.g. red blood cells, undergo a frequency shift in proportion to the velocity of the target. The output from a continuous-wave Doppler ultrasound is most frequently presented as an audible signal (e.g. a hand-held pencil Doppler, Figure 1.1), so that a sound is heard whenever there is movement of blood in the vessel being examined. With continuous-wave ultrasonography there is little scope for restricting the area of tissue that is being examined because any sound waves that are intercepted by the receiving crystal will produce an output signal. The solution is to use pulsed ultrasound. This enables the investigator to focus on a specific tissue plane by transmitting a pulse of ultrasound and closing the receiver except when signals from a predetermined depth are returning. For example, the centre of an artery and the areas close to the vessel wall can be examined in turn.

Examination of an arterial stenosis shows an increase in blood velocity through the area of narrowing. The site(s) of any stenotic lesions can be identified by serial placement of the Doppler probe along the extremities. Criteria to define a stenosis vary between laboratories, but a 2-fold increase in peak systolic velocity compared with the velocity in a proximal adjacent segment of the artery usually signifies a stenosis of ≥50% (Table 1.1).

The normal (‘triphasic’) Doppler velocity waveform is made up of three components which correspond to different phases of arterial flow (Figure 1.2a):
- Rapid antegrade flow reaching a peak during systole
- Transient reversal of flow during early diastole
- Slow antegrade flow during late diastole.
Figure 1.1 A hand-held pencil Doppler being used to measure the ankle-brachial pressure index

Table 1.1 Relationship between increased blood velocity and degree of stenosis

<table>
<thead>
<tr>
<th>Diameter of stenosis (%)</th>
<th>Peak systolic velocity* (m/s)</th>
<th>Peak diastolic velocity* (m/s)</th>
<th>Internal common carotid artery velocity ratio†</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–39</td>
<td>&lt;1.1</td>
<td>&lt;0.45</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>4–59</td>
<td>1.1–1.49</td>
<td>&lt;0.45</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>60–79</td>
<td>1.5–2.49</td>
<td>0.45–1.4</td>
<td>1.8–3.7</td>
</tr>
<tr>
<td>80–99</td>
<td>2.5–6.1</td>
<td>&gt;1.4</td>
<td>&gt;3.7</td>
</tr>
<tr>
<td>&gt;99 (critical)</td>
<td>Extremely low</td>
<td>NA</td>
<td>NA</td>
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*Measured in lower part of internal carotid artery.
†Ratio of peak systolic velocity in internal carotid artery stenosis relative to proximal measurement in common carotid artery.

Figure 1.2 Left: Doppler velocity waveforms: (a) a triphasic waveform in a normal artery; (b) a biphasic waveform, with increased velocity, through a mild stenosis; (c) a monophasic waveform, with a marked increase in velocity, through a tight stenosis; and (d) a dampened monophasic waveform, with reduced velocity, recorded distal to a tight stenosis. Right: the results of a routine lower limb Doppler examination are typically recorded on an anatomical chart, as shown, where three stenoses are identified with velocity increases of 7×, 3× and 4× that in adjacent unaffected segments of the respective arteries.
Doppler examination of an artery distal to a stenosis shows characteristic changes in the velocity profile (Figure 1.2d):
- The rate of rise is delayed and the amplitude decreased
- The transient flow reversal in early diastole is lost
- In severe disease, the Doppler waveform flattens; in critical limb ischaemia, it may be undetectable.

**Investigations of arterial disease**

**Ankle–brachial pressure index**

Under normal conditions, systolic blood pressure (SBP) in the legs is equal to or slightly greater than the SBP in the upper limbs. In the presence of an arterial stenosis, a reduction in pressure occurs distal to the lesion. The ankle–brachial pressure index (ABPI), calculated from the ratio of ankle SBP to brachial SBP, is a sensitive marker of arterial insufficiency in the lower limb, and correlates with survival (Figure 1.3). The highest pressure measured in any ankle artery is used as the numerator in the calculation of the ABPI (Figure 1.3). An ABPI of ≥1.0 is normal and a value <0.9 is abnormal. Patients with claudication tend to have ABPIs in the range 0.5–0.9, whilst those with critical ischaemia usually have an index of <0.5. In patients with diabetes (in whom distal vessels are often calcified and incompressible), SBP measured in the lower limbs may be less reliable, which can result in falsely high ankle pressures and a falsely elevated ABPI.

Exercise testing will assess the functional limitations of arterial stenoses and differentiate occlusive arterial disease from other causes of exercise-induced lower limb symptoms, e.g. neurogenic claudication secondary to spinal stenosis. A limited inflow of blood in a limb with occlusive arterial disease results in a fall in ankle SBP during exercise-induced peripheral vasodilatation. Patients can be exercised for 5 min, ideally on a treadmill, but walking in the surgery or marking time on the spot are perfectly adequate. ABPI is measured before and after exercise. A pressure drop of ≥20% indicates significant arterial disease (Figure 1.4). If there is no drop in ankle SBP after a 5 min brisk walk, the patient does not have occlusive arterial disease proximal to the ankle in that limb.

**Duplex scanning**

By combining the pulsed Doppler system with real-time B-mode ultrasound imaging of vessels, it is possible to examine (or ‘sample’) Doppler flow patterns in a precisely defined area within the vessel lumen. This combination of real-time B-mode sound imaging with pulsed Doppler ultrasound is called duplex scanning. The addition of colour frequency mapping makes the identification of arterial stenoses even easier and reduces scanning time (Figure 1.5).

In detecting femoral and popliteal disease, duplex ultrasonography has a sensitivity of 80% and a specificity of 90–100% but ultrasound is less reliable for assessing the severity of stenoses in the tibial and peroneal arteries (Table 1.2). Duplex scanning is especially useful for assessing the carotid arteries and for routine surveillance of infrainguinal bypass grafts where sites of stenosis can be identified before complete graft occlusion occurs and before there is a significant fall in ABPI. The normal velocity within a graft conduit ranges between 50 and 120 cm/s. As with native arteries, a 2-fold increase in peak systolic velocity indicates a stenosis of ≥50%. A peak velocity <45 cm/s occurs in grafts at high risk of failure.

**Transcranial Doppler**

Lower frequency Doppler probes (1–2 MHz) can be used to obtain a dynamic measurement of relative blood flow and detection of microemboli in arteries comprising the Circle of Willis and its principal branches (Box 1.1). It enables blood flow assessment and
Table 1.2 Uses of colour duplex scanning

<table>
<thead>
<tr>
<th>Arterial</th>
<th>Venous</th>
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<tbody>
<tr>
<td>Identify obstructive</td>
<td>Diagnosis of deep-vein thrombosis above</td>
</tr>
<tr>
<td>atherosclerotic disease:</td>
<td>the knee</td>
</tr>
<tr>
<td>Carotid</td>
<td>Assessing competence of valves in deep</td>
</tr>
<tr>
<td>Renal</td>
<td>veins</td>
</tr>
<tr>
<td>Surveillance of infrainguinal bypass grafts</td>
<td>Superficial venous reflux:</td>
</tr>
<tr>
<td>Surveillance of lower limb arteries after angioplasty</td>
<td>Assessing patient with recurrent varicose veins</td>
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<td></td>
<td>Identify and locate reflux at saphenopopliteal junction</td>
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<td></td>
<td>Pre-operative mapping of saphenous vein</td>
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</table>

Box 1.1 Clinical uses of transcranial Doppler scanning in adults

Ischaemic cerebrovascular disease:
- stenosis and occlusion in intracranial and extracranial carotid and verteobasilar arteries
- collateral flow
- detection of microemboli, including from patent foramen ovale
- monitoring flow after cerebral thrombolysis

Peri-operative monitoring in carotid endarterectomy and angioplasty
Detection of vasospasm after subarachnoid haemorrhage
Evaluation of vasomotor reactivity

Computed tomography angiography

Helical or spiral CTA is a technique that allows rapid and continuous acquisition of a helical ‘ribbon’ of data during the first pass of a bolus of i.v. contrast through the arterial tree. The data can be reconstructed at any slice level, reformatted into different planes and processed into high-quality two- or three-dimensional images of vessels. The introduction of multidetector CT (MDCT) has had a dramatic effect on CT imaging, and in particular imaging of the cardiovascular system. There are two main differences between conventional spiral CT and MDCT. First, MDCT has a much higher speed of data acquisition (0.37 s rotation speed versus 1 s rotation speed for conventional CT), and secondly MDCT acquires volume data instead of individual slice data. Thus, MDCT (without increasing the radiation dose) has led to faster scanning, improved contrast resolution and better spatial resolution. The effect of movement artefacts is also minimized.

The time taken to complete the procedure is determined by practicalities such as moving the patient and gaining venous access, but the scan acquisition time for the entire arterial system (aortic arch to pedal vessels) is <45 s for CTA compared with ~4–5 min for MRA (Table 1.3).

Magnetic resonance angiography

MR scanning allows the use of a pulse sequence which images moving blood, thus showing arteries or veins without the use of an injected contrast agent or exposure to ionizing radiation. Non-contrast MRA therefore has substantial safety advantages but is characterized by flow dependence. Contrast-enhanced MRA using

Table 1.3 Advantages and limitations of CT and MR angiography

<table>
<thead>
<tr>
<th>CTA</th>
<th>MRA (non-contrast+/ i.v gadolinium)</th>
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<tbody>
<tr>
<td>Rapid data acquisition; less prone to movement artefact</td>
<td>Slower; more prone to movement artefact</td>
</tr>
<tr>
<td>High-resolution images</td>
<td>Lower resolution but dependent on technique and location</td>
</tr>
<tr>
<td>Anatomical image of contrast in vessel</td>
<td>Flow dependent (non-contrast MRA)</td>
</tr>
<tr>
<td>Loss of accuracy with circumferential calcification</td>
<td>May indicate flow direction</td>
</tr>
<tr>
<td>Ease of access, especially in emergency context</td>
<td>May overestimate degree and length of stenosis, due to signal dropout in areas of turbulence</td>
</tr>
<tr>
<td>Acutely ill patients can be supported during scan</td>
<td>Scanners less available</td>
</tr>
<tr>
<td></td>
<td>Contraindicated by need for intensive patient support</td>
</tr>
<tr>
<td></td>
<td>Contraindications include implants such as pacemakers, defibrillators, cochlear implants and spinal cord stimulators</td>
</tr>
<tr>
<td></td>
<td>Small scanner tunnel not tolerated by some patients due to claustrophobia or body habitus</td>
</tr>
<tr>
<td></td>
<td>More expensive</td>
</tr>
<tr>
<td></td>
<td>No radiation</td>
</tr>
<tr>
<td></td>
<td>Non-contrast MRA is non-invasive</td>
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<tr>
<td></td>
<td>Effective hydration helps prevent nephropathy, but the benefit of prophylaxis with iso-osmolar contrast agents remains controversial</td>
</tr>
<tr>
<td></td>
<td>In contrast-enhanced MRA, gadolinium contrast has been associated with nephrogenic systemic fibrosis</td>
</tr>
</tbody>
</table>

monitoring in a number of applications, particularly carotid endarterectomy.
Methods of Arterial and Venous Assessment

Figure 1.6 T2-weighted axial MR scan of the neck showing a left internal carotid artery dissection, with blood in the vessel wall producing a high signal (arrow)

Figure 1.7 In the same patient as in Fig. 1.6, this MRA reconstruction shows a stenosis just above the origin of the left internal carotid artery (arrow)

an i.v. bolus of gadolinium contrast can cover a larger area, allows more rapid data acquisition and higher resolution, and gives a more direct image of the vascular lumen. Therefore, contrast-enhanced MRA is more commonly used, but recent advances in MR technology, partially driven by complications associated with the gadolinium-based contrast, have led to major improvements in scan quality of non-contrast MRA vascular imaging, which is likely to result in greater use in the future.

A variety of imaging sequences are used depending upon the vessels being studied and the field strength of the machine. Information is obtained both from the axial images and from vessel reconstructions (Figures 1.6 and 1.7).

Applications of CTA and MRA

CTA and MRA are both widely used to investigate large artery pathology (Figures 1.8 and 1.9). Each technique has different advantages and disadvantages (Table 1.3). CTA has the major advantage of speed, but local preferences and availability often determine which technique is used. CT pulmonary angiography (CTPA) for suspected pulmonary embolism (PE) is probably the most commonly used computerized angiographic investigation (Figure 1.10). Whereas single-detector CT shows a sensitivity of 73% and a specificity of 87% in the diagnosis of PE (based on pooled data), corresponding figures for MDCT (mostly four-slice images) are 83 and 96%. The positive predictive values for MDCT are 97% for PE in a main pulmonary artery or lobar artery, 68% for a segmental vessel and 25% for a subsegmental branch.

In abdominal aortic aneurysm (AAA) and aortic dissection imaging, CTA is the preferred investigation because it images the vessel wall and can provide information about mural thrombus, inflammatory changes and rupture. Software reconstructs hundreds of images and displays them in two- or three-dimensional planes (Figures 1.11 and 1.12). This becomes a powerful tool for pre-operative planning and post-operative follow-up, especially in regard to use of endovascular stent grafts for AAA repair. CTA is more sensitive and specific than conventional angiography in detecting the presence of endoleaks.

MDCT angiography and MRA have equally high sensitivity and specificity for the detection of renal artery stenosis, but CTA is often preferred in order to avoid gadolinium administration, especially in patients with renal impairment (Figure 1.9). MDCT can also be used post-stenting to assess for recurrent renal artery stenosis.

Some centres prefer to use MRA to image lower limb vascular disease due to the adverse effect of heavy circumferential calcification which, when using CTA, can limit accuracy and make interpretation more difficult. However, CTA has several advantages in peripheral arterial disease, e.g. visualization of extraluminal pathology, including aneurysms, better assessment of eccentric lesions and visualization of more arterial segments, particularly in occlusive disease where there is little or no flow.
Figure 1.8 CT angiogram showing a tight stenosis of the right internal carotid artery (arrow)

Figure 1.9 CT angiogram showing bilateral renal artery stenoses (arrows)

Figure 1.10 CT pulmonary angiogram showing a clot displacing contrast in both main pulmonary arteries (arrows)

Figure 1.11 CT angiogram showing an abdominal aortic aneurysm (arrow)
Figure 1.12 Volume-rendered reconstruction of the CT angiogram in the same patient as Fig. 1.11 (abdominal aortic aneurysm) (arrow)

In acute cerebral ischaemia, in addition to artery level information from angiography, data on parenchymal perfusion can be provided by MR diffusion–perfusion mismatch or CT blood volume–perfusion mismatch. These methods are gaining importance for predicting core infarct size and risk of progressive ischaemia, and for informing decisions about thrombolysis.

Investigations in venous disease

Venous thrombosis

Colour Duplex scanning is both sensitive and specific (90–100% in most series) for detecting proximal deep-vein thrombosis (DVT). Deep veins and arteries lie together in the leg, and the normal vein appears as an echo-free channel and is usually larger than the accompanying artery. Venous ultrasound has proved to be a very accurate method of identifying DVTs from the level of the common femoral vein at the groin crease to the popliteal vein, but the technique is much less reliable for diagnosing calf vein thrombosis (Fig. 1.13). Approximately 40% of calf DVTs resolve spontaneously, 40% become organized and 20% propagate. Propagating DVT can be excluded by serial duplex scanning with an interval of 1 week.

I.v. contrast administered into the arm during CTPA can be used simultaneously to image for DVT. Such indirect CT venography (CTV) performs well in the detection of DVT, and is preferred to direct CTV where contrast is injected locally into a vein on the foot.

MR venography (MRV) is useful for examining the intracranial venous system, particularly in evaluating suspected dural venous sinus thrombosis, and for demonstrating venous thrombosis in the iliac vessels and abdomen. Non-contrast MRV requires a long acquisition time and provides only limited delineation of peripheral veins because of slow blood flow. Contrast-enhanced MRV uses i.v contrast administered into any vein, and newer contrast agents (e.g. gadofosveset trisodium) provide better spatial resolution.

MR direct thrombus imaging (MRDTI) uses the paramagnetic properties of methaemoglobin formed from oxidized haemoglobin within a thrombus to generate a signal. MRDTI provides images of the thrombus without relying on i.v contrast medium or blood flow to detect an intraluminal filling defect.

Venous reflux

Colour duplex has revolutionized the investigation of the lower limb venous system because it allows instantaneous visualization of blood flow and its direction (Figure 1.14). Thus, reflux at the saphenofemoral junction, saphenopopliteal junction and within the deep venous system, including the popliteal vein beneath the knee and the gastrocnemius veins, can be demonstrated non-invasively. Although a limited assessment of venous reflux can be undertaken using a pencil Doppler, compared with colour duplex the pencil Doppler misses ~12% of saphenofemoral and ~20% of saphenopopliteal junction reflux.

Figure 1.13 Ultrasound detection of a DVT. The probe is held lightly on the skin and advanced along the course of the vein (left). Pressure is applied every few centimetres by compressing the transducer head against the skin. The vein collapses during compression if no thrombus is present (middle) but not if a DVT is present (right)

Figure 1.14 Colour duplex scanning of the saphenopopliteal junction. The calf muscles are manually compressed producing upward flow in the vein (top), which appears as a blue colour for flow towards the heart. Sudden release of the distal compression causes reflux, seen as a red colour, indicating flow away from the heart
Further reading


