Ultrasound imaging of the carotid arteries

Introduction

Stroke remains a leading cause of death in developed countries. Most are the result of atherosclerotic disease, usually involving the carotid arteries. A significant number of all strokes (10–20%) are caused by internal carotid artery stenosis. Carotid Doppler ultrasound (CDUS) is a commonly requested investigation, principally performed to assess the carotid arteries for the presence and extent of atheromatous plaque. Atheroma in the carotid arteries is typically localized to the carotid bifurcation and may give rise to microemboli causing transient ischaemic attacks in the contralateral limbs or amaurosis fugax in the ipsilateral eye.

Major prospective randomized trials have established the value of carotid endarterectomy (CEA) in symptomatic patients with high-grade (70–99% diameter) stenosis (European Carotid Surgery Trialists Collaborative Group, 1991, 1998; North American Symptomatic Carotid Endarterectomy Trial Collaborators, 1991). The superficial location of the extracranial carotid arteries makes them particularly amenable to assessment with duplex ultrasound, the most common imaging study for the diagnosis of carotid disease. Studies of the effectiveness of CEA as a treatment for high-grade carotid stenosis used digital subtraction angiography (DSA) as their 'gold standard' diagnostic investigation. However, DSA carries a relatively high morbidity including a 1–2% risk of stroke and is expensive in terms of time and resources. CDUS has the advantages of being readily available, cheap and non-invasive. It is often the sole investigation on which treatment decisions are based.

Several trials have addressed the role of CEA in asymptomatic patients with carotid artery stenosis. The largest and most definitive, the Asymptomatic Carotid Atherosclerosis Study, evaluated the efficacy of CEA in patients with asymptomatic high-grade stenosis (>60%) detected by ultrasound (Executive Committee for the Asymptomatic Carotid Atherosclerosis Study, 1995). The study was terminated at 2.7-year median follow-up because surgery had a 53% relative risk reduction in stroke compared to medical therapy.

The role of carotid artery angioplasty and stenting in the treatment of atheromatous carotid disease also needs to be clarified. The Carotid and Vertebral Artery Transluminal Angioplasty Study has provided the most robust data thus far. The investigators suggested that the procedures could be performed with a similar perioperative mortality and morbidity to CEA (Brown et al, 1999). Ongoing clinical trials will assess long-term outcomes and its potential role in the management of carotid stenosis in more detail.

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Indications

The commonest indication for CDUS is the investigation of ischaemic neurological events (*Table 1*). Patients with a transient ischaemic attack or amaurosis fugax without evidence of a cardiac cause should have a duplex ultrasound of their carotid vessels, since this group of patients may benefit from CEA. The value of routine carotid screening before major vascular procedures, particularly cardiac surgery, is unclear although there is some evidence to support its use routinely in patients over 60 years of age (Ascher et al, 2001).

Table 1. Indications for carotid duplex ultrasound

Symptomatic	Ischaemic neurological event
	Carotid dissection*
	Post-carotid endarterectomy/carotid stent with neurological symptoms or for routine follow-up
Asymptomatic	Preoperative evaluation before major vascular surgery
	Cervical bruit or pulsatile neck mass

*Carotid Doppler ultrasound may confirm the clinical diagnosis of carotid dissection but cannot always exclude it. Magnetic resonance or computed tomography angiography is more useful in this context

Technical aspects

B-mode grey scale imaging, colour flow Doppler and spectral Doppler are used in ultrasound assessment of the carotid arteries.

B-mode imaging

This is conventional two-dimensional grey-scale imaging in which a high resolution transducer (7–15 MHz) is used. It is the optimal method for measuring intima-medial thickness (IMT) and demonstrating atherosclerotic plaque.

The common carotid artery (CCA), external carotid artery (ECA), internal carotid artery (ICA) and carotid bulb are delineated in transverse and longitudinal axis.

Distinguishing the ICA from the ECA is not always straightforward, but several ultrasound features, in combination, may help make the distinction (*Table 2*). The most reliable parameter is the presence of ECA branches in the neck. The temporal tap technique (tapping on the superficial temporal artery and looking for fluctuations in the ECA waveform) is not reliable, as the resulting waveform change may also be detected in the ICA and CCA.

Plaque in the ICA or bifurcation is assessed in terms of its location and size (and consequent haemodynamic alteration), surface and echogenicity. Classifications of atherosclerotic plaques according to these three features have been described but are not routinely used to guide clinical management decisions (Thiele et al, 1992). The most important of these is the estimation of plaque size in terms of the percentage luminal stenosis.

Table 2. Ultrasound differentiation of internal and external carotid artery

	Internal carotid artery	External carotid artery
Size	Larger diameter	Smaller diameter
Location	Postero-lateral	Antero-medial
Branches	None	Multiple
Waveform	Monophasic Low-resistance Prominent diastolic flow	Bi/triphasic High-resistance Little diastolic flow

Three types of plaque echotexture are referred to: homogeneously echogenic composed of dense fibrous connective tissue (*Figure 1*), calcified (*Figure 2*) and echo-poor (*Figures 3a, b*). The echo-poor lipid-rich plaque is called unstable, since it is associated with intraplaque haemorrhage and rupture and therefore an increased risk of neurological events, whereas calcified and fibrous plaques are stable. Surface characteristics range from smooth, stable plaque to ulcerated, unstable lesions with intra-plaque haemorrhage.

The IMT should be measured on a magnified image of the distal CCA and consists of the thin echogenic intima and the echo-poor media. The normal IMT is less than 0.8 mm in diameter. Increased IMT (*Figures 4a–c*) is a marker of early atherosclerosis and correlates with an increased incidence of coronary artery disease (O'Leary and Polak, 2002) but is not directly relevant in assessing the symptomatic patient with a view to performing carotid surgery.

Figure 1. Echogenic, homogeneous plaque (arrow) in the proximal internal carotid artery. Such plaque is typically stable.

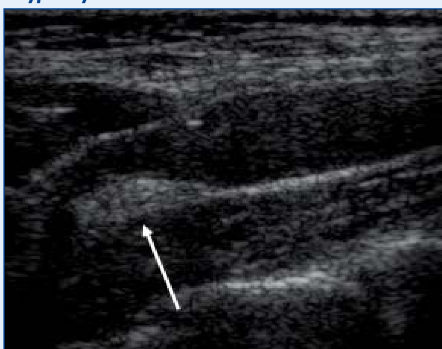


Figure 2. Calcified plaque (solid arrow) on the anterior wall of the internal carotid artery. This causes posterior acoustic shadowing (dashed arrows) obscuring the Doppler signal from the vessel lumen.

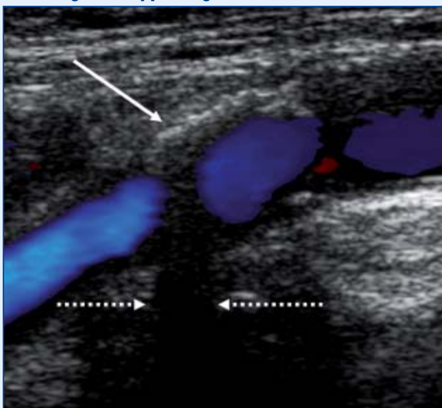


Figure 3. Echo-poor plaque. a. The grey-scale image of the carotid bulb shows a subtle echopoor plaque which is made conspicuous (b) after the addition of power Doppler (arrow). These plaques are lipid-rich and tend to be more unstable.

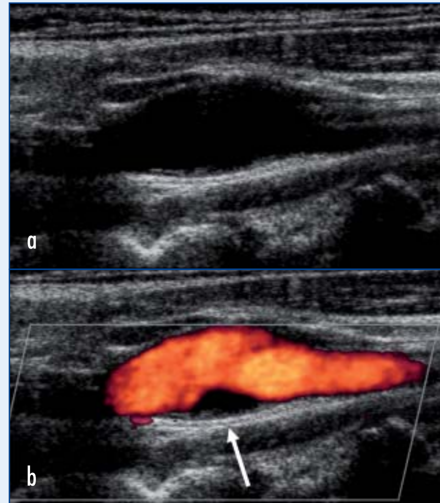
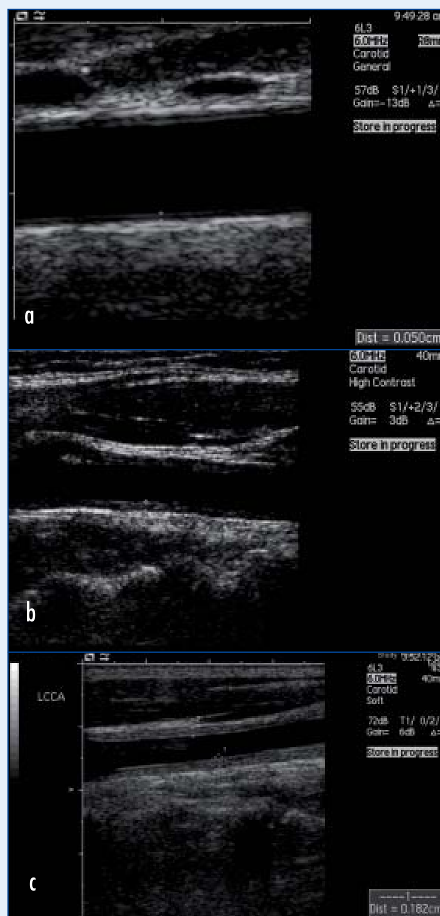


Figure 4. a. Normal intima-medial thickness (IMT) in the common carotid artery (<0.8 mm). b. Increased IMT in a patient with atheromatous disease. The normally hypoechoic media has become thickened and heterogenous. c. Concentric symmetrical increase of the IMT in a patient with Takayasu's arteritis (Macaroni sign).



Colour flow imaging and Doppler spectral analysis

Colour flow imaging provides an overlay of the red cell velocities (based on Doppler shift) in regions of blood flow in the carotid vessels. The colour assignment is arbitrary but is conventionally displayed with red representing flow towards the transducer and blue flow away from the transducer. Power Doppler depicts the amount of blood moving in a region and does not measure velocity and direction.

Spectral Doppler enables a flow velocity to be calculated from the Doppler shift frequency reflected from red blood cells within an operator-defined and positioned sample volume box placed in the mid-lumen parallel to the vessel wall. Narrowing of the vessel lumen increases the velocity across the stenosed segment. The resulting turbulent flow also causes spectral broadening in the Doppler waveform (*Figures 5, 6a, 6b*).

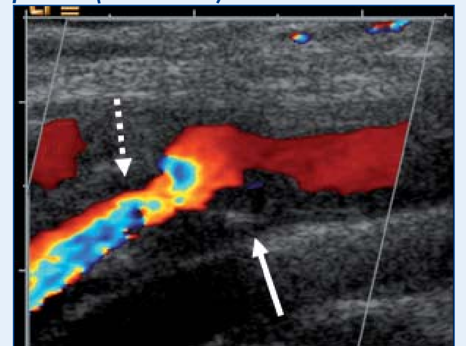
Widely-used criteria for the diagnosis of ICA stenosis were established at a consensus meeting of the Society of Radiologists in Ultrasound in 2003 and are summarized in *Table 3*. The key components are the peak ICA systolic velocity and the visual estimate of plaque percentage narrowing based on grey-scale and colour flow imaging findings (Grant et al, 2003).

Additional considerations

Near *vs* total ICA occlusion

No surgical options are available for a totally occluded vessel and therefore accurate differentiation between near and total occlusion is vital if appropriate treatment decisions are to be made. Velocity indices are

Figure 5. Plaque (solid arrow) in the proximal internal carotid artery causing stenosis. Colour Doppler shows high velocity turbulent flow in the post-stenotic segment seen as different colours because of the broad spectrum of red cell velocities produced (dashed arrow).



unhelpful in this context, as velocities may decrease before occlusion. At degrees of stenosis greater than 95%, flow velocity may drop to as little as 20 cm/s. Colour flow imaging, however, is a useful tool in distinguishing between a completely occluded vessel, and one with a small residual lumen. Power Doppler imaging can also be helpful to visualize a narrow residual lumen as it has higher sensitivity to the lower velocities which occur in these cases (*Figure 7*) (Koga et al, 2001). Indirect evidence of an occluded ICA may be provided by the presence of increased pulsatility ('externalization') of the CCA with decreased or absent diastolic flow (*Figure 8*). 'Internalization' of the ECA (with high diastolic flow) may occur as a result of the development of collaterals between the ECA and ICA across the orbits and meninges.

Table 3. Society of Radiologists in Ultrasound Consensus Conference criteria for diagnosis of internal carotid artery stenosis

	Primary parameters		Additional parameters	
Degree of stenosis (%)	ICA PSV (cm/s)	Plaque estimate (%)	ICA/CCA PSV ratio	ICA EDV (cm/s)
Normal	<125	None	<2.0	<40
<50	<125	<50	<2.0	<40
50–69	125–230	≥50	2.0–4.0	40–100
≥70	>230	≥50	>4.0	>100
Near occlusion	High, low or undetectable	Visible	Variable	Variable
Total occlusion	Undetectable	Visible, no detectable lumen	Not applicable	Not applicable

CCA = common carotid artery; EDV = end diastolic velocity; ICA = internal carotid artery; PSV = peak systolic velocity. From Grant et al (2003)

Vertebral arteries

Examination of the carotid vessels with CDUS will generally also include an assessment of the patency, direction of blood flow and relative size of the vertebral arteries. However, CDUS cannot reliably demonstrate focal stenoses in the vertebral artery. Complete reversal of flow in the vertebral artery is seen in subclavian steal syndrome and may be associated with ischaemic symptoms in the ipsilateral arm (*Figures 9a, b*). An occult steal may be revealed after exercise of the affected arm which causes a reactive hyperaemia.

Technical limitations

Several factors may render CDUS difficult to perform or reduce the reliability of the examination result. Heavily calcified plaques which cause posterior acoustic shadowing may obscure a vessel segment, although the absence of significant narrowing may be inferred if flow patterns immediately distal to the lesion are relatively undisturbed (*Figure 2*). Physiological factors such as a reduced cardiac output render internal carotid peak systolic velocity values less reli-

Figure 6. a. Normal spectral Doppler waveform in the internal carotid artery. b. Internal carotid artery (ICA) stenosis. There is elevated peak systolic velocity (5.9 m/s) and internal carotid/common carotid velocity ratios (6.8) measured just distal to a stenosed proximal ICA segment. There is also spectral broadening as a result of turbulent flow, seen as signal throughout systole and diastole.

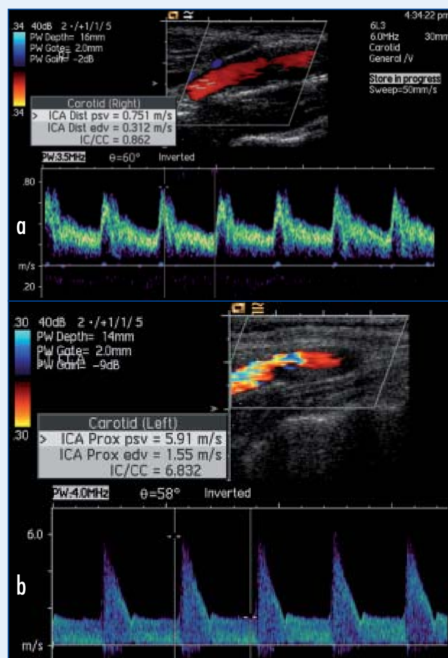


Figure 7. 'Trickle' flow through a tight internal carotid artery stenosis demonstrated with power Doppler.

Figure 8. Internal carotid artery occlusion with resultant 'externalization' of the ipsilateral common carotid artery spectral Doppler waveform. There is increased pulsatility with a triphasic waveform and little forward flow in diastole.

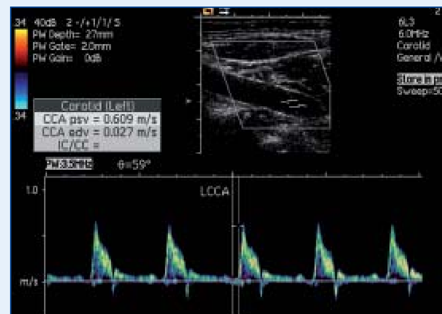
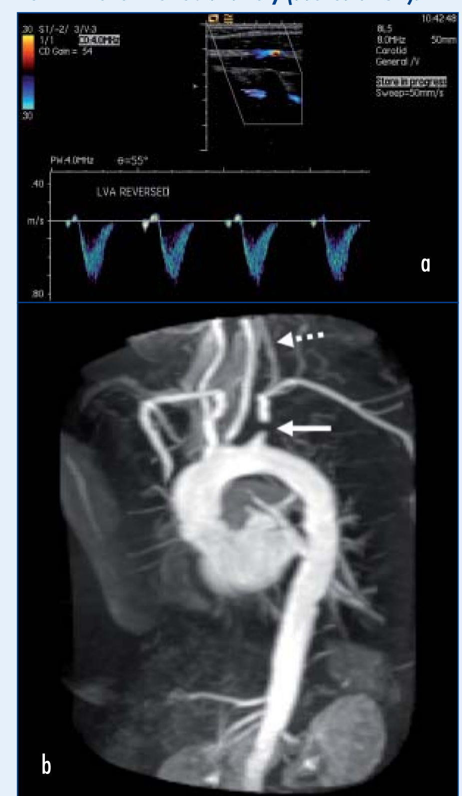


Figure 9. a. Subclavian steal showing complete reversal of flow direction in the left vertebral artery. b. Magnetic resonance angiography demonstrating a severe left subclavian artery stenosis (solid arrow) with compensatory retrograde flow in the left vertebral artery (dashed arrow).



able. In this setting, the ICA/CCA ratio becomes an important parameter. Occlusive disease in the contralateral vessel can also compromise the reliability of the examination (AbuRahma et al, 1995). Significant distal stenosis beyond the reach of the ultrasound probe may be suggested by indirect signs such as increased resistance within the ICA proximal to the lesion but smaller lesions may go undetected (*Figure 10*).

Comparison with other modalities

It is worth noting that, despite the acceptance of CDUS by many clinicians as the sole basis for management decisions, there is actually no direct validation data in the literature. The trials which established the benefit from CEA in patients with >70% symptomatic stenosis used the gold standard investigation of intra-arterial DSA.

A systematic review and meta-analysis of studies that compared CDUS with DSA found that a threshold peak systolic velocity of ≥230 cm/s has a sensitivity of 90% and a specificity of 85% for the diagnosis of ≥70% stenosis. At the threshold of ≥130 cm/s for the diagnosis of ≥50% stenosis, a sensitivity and specificity of 98% and 88% were identified (Jahromi et al, 2005). Importantly, substantial heterogeneity in measurement of stenosis by CDUS was reported. Variation in observer training and experience, equipment specification, scanning protocols and quality assurance standards were noted between centres. Such factors are the main drawback of using CDUS to identify patients likely to benefit from CEA. Ideally, each centre should audit and establish the accuracy of their local duplex criteria using intra-arterial angiography.

Figure 10. Spectral Doppler waveform in the proximal internal carotid artery in a patient with a distal internal carotid artery occlusion beyond the reach of the ultrasound probe. The blood flow shows alternating forward and reverse flow ('to-and-fro pattern'), with no forward flow up the vessel.

Computed tomography angiography and magnetic resonance angiography (MRA) have evolved as non-invasive imaging strategies for diagnosis of carotid disease. Contrast-enhanced MRA is generally superior to CDUS for occluded vessels and for evaluation of stenoses in the 70–99% range (Pan et al, 1995). These techniques may be used in addition to CDUS when results are unclear or do not agree with the clinical diagnosis. However, cost-effectiveness studies have confirmed CDUS as the least expensive and most effective modality. A combined strategy of CDUS and MRA yields a marginal benefit in outcome but at a significant cost (Buskens et al, 2004).

Conclusions

Owing to its non-invasiveness and cost-effectiveness, CDUS has become the first-line investigation for diagnosis of carotid stenosis. In most cases it is the sole investigation on which treatment decisions are based, with additional investigations such as MRA or computed tomography angiography used when there is a discrepancy between the ultrasound findings and clinical findings. As with any ultrasound technique, accurate carotid assessment with ultrasound depends upon the ability and experience of the operator. A standardized examination protocol and regular quality control are important to ensure the reliability and reproducibility of the examination. BJHM

Conflict of interest: none.

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KEY POINTS

- Carotid Doppler ultrasound (CDUS) is a cheap, non-invasive test which has become a first-line investigation in carotid disease.
- The primary indication for CDUS is in the investigation of ischaemic neurological events. Treatment decisions are now often based solely on the findings on CDUS.
- A combination of grey-scale imaging, colour Doppler imaging and spectral Doppler waveform analysis is used to accurately assess the carotid arteries.
- Consensus criteria established in 2003 are now widely used to diagnose a haemodynamically significant carotid artery stenosis on ultrasound.
- Rigorous quality assurance is needed to establish and maintain the accuracy of CDUS in individual imaging departments.
- Alternative modalities such as magnetic resonance angiography or computed tomography angiography may be used to confirm CDUS findings in equivocal cases.