MR angiography

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The primary use of angiography in the neck, either conventional catheter angiography or non-invasive techniques (MR angiography, CT angiography and ultrasound), is for the evaluation of the presence and severity of carotid stenosis. Other conditions such as vertebral artery stenosis, carotid and vertebral artery dissection and fibromuscular dysplasia are much less common but easily detectable with conventional angiography and are becoming increasingly reliably evaluated by non-invasive imaging. Intracranially, the value of MR angiography is less clear cut. It is certainly of use presurgery to look for vessel occlusion and encasement of vessels by tumour. It is also useful in excluding venous thrombosis as a cause of stroke. MR angiography for the detection and screening of intracranial aneurysms is less clear cut and, at present, it is the author’s belief that MR angiography cannot replace conventional catheter angiography. Straightforward spin echo imaging is the most accurate way of detecting arteriovenous malformations (AVMs) with magnetic resonance.

Extracranial MR angiography

Angiography, either conventional catheter angiography or non-invasive techniques (MR and CT angiography and ultrasound), is used for the investigation of arterial and venous pathology in the neck. Its primary use is for the evaluation of the presence and severity of carotid stenosis. Other conditions such as vertebral artery stenosis and occlusion, carotid and vertebral artery dissection, fibromuscular dysplasia are less common but easily detectable with conventional angiography and are becoming increasingly reliably evaluated by non-invasive imaging.

Conventional angiography

The ideal investigation is non-invasive, has no morbidity, has a high sensitivity and specificity, and is low cost. All non-invasive tests strive to achieve this ideal. Conventional angiography, the gold standard, is invasive and has morbidity, including locally at the puncture site, systemic...
complications and stroke. Conventional angiography is relatively safe in patients without atherosclerotic disease. Berenstein reports in the 4 years (1992–1995) in 1802 angiograms complications occurred in four procedures, three with temporary neurological deficit (0.17%) and one with permanent neurological deficit (0.05%)¹. However, a study looking at patients with cerebrovascular disease, the Asymptomatic Carotid Atherosclerosis Study (ACAS)² reports stroke rates from angiography of 1.2% and 1.6%. This is significant morbidity.

The majority of patients being investigated are those with carotid stenosis. Recent multicentre clinical trials, the European Carotid Surgery Trial (ECST) and the North American Symptomatic Endarterectomy Trial (NASCET), have shown that the risks of stroke are significantly reduced in medically fit patients with recent symptoms with severe carotid stenosis and consequently an increasing number of patients with TIA and stroke are being investigated, up to 10% of these having a source from the carotid artery³. Thus a non-invasive technique is ideal. It is our practice to use a combination of screening with ultrasound, followed by magnetic resonance angiography (MRA) if the ultrasound detects a significant stenosis. Doppler ultrasound has been fully discussed elsewhere in this issue, and will not be dealt with further here. In our practice, if a Doppler study is positive, i.e. showing stenosis greater than 70%, this then needs to be confirmed with an MRA study. The combination of both results has been shown to give sensitivities of 100% and specificities between 90–98%. This is based on data from 1995 and before⁴. Further technological improvements in ultrasound and MRI will improve these figures. If there is discordance between the two tests, conventional angiography is performed. We perform angiography in less than 5% of patients, although other authors report angiography rates of 16–21%⁵–⁷. The latter is higher than desirable and should be reduced because advances in technology since 1995 have made MRA more accurate.

Pitfalls and advantages of MRA

Artefacts and over-estimation of a stenosis

Turbulent flow can cause pseudostenosis in a normal bulbous bifurcation and a tight focal stenosis can cause distal turbulence and a large flow gap, mimicking a long 2–3 cm stenosis. Swallowing can cause marked artefact. Any metal, such as a stent or clips, can degrade the image. Review of the source images with the post processing images (maximum intensity projection, MIP) is always essential.
Differentiation of complete occlusion of the ICA from a very severe stenosis or string sign
This is important as a complete occlusion is treated medically, but a very severe, greater than 95% stenosis with a string sign may be treated surgically. MRA is 100% sensitive and specific in differentiating carotid occlusion from a string sign, but it is vital to analyse the cross sectional source images.

Tandem and intracranial lesions
Controversy exists in the vascular surgical community as to whether it is worth looking for tandem lesions. Many surgeons are happy to operate on carotid stenosis after ultrasound alone or ultrasound and MRA. Others still require full angiography, looking at the intracranial circulation. With conventional angiography, intracranial stenoses are easily and accurately detected. MRA is relatively sensitive, particularly with severe stenoses but MIPs should be interpreted with care. Stenoses can often be greatly overestimated and tortuous vessels coursing in and out of the scan plane can also suggest stenosis when it is not really there. It is our experience that significant tandem stenosis is rare and we do not routinely image the intracranial circulation with MRA. Similar arguments apply to the origin of the great vessels from the aortic arch with the incidence of stenoses in this region being quoted as high as 5%. Success in imaging the aortic arch with MRA has been poor to date but newer techniques involving Gadolinium-enhanced MRA, as discussed below, show great promise.

Techniques

I will now give a brief overview of techniques of MRA. These equally well apply to intracranial MRA, discussed later.

Until recently, the mainstay of MRA has been time of flight or phased contrast angiography. The objective in both techniques is to maximise the signal from rapidly flowing blood and to minimise signal from background stationary tissues. Keller and Rosovsky et al provide excellent reviews of the physics which will not be discussed in great detail here.

Time of flight
There are two forms of time of flight: two dimensional (2D ToF) and three dimensional (3D ToF). In time of flight or inflow imaging, the background protons are suppressed and the inflowing protons with full longitudinal magnetisation enter the excitation volume and generate a
strong signal. The difference in longitudinal magnetisation between the stationary saturated background tissue and unsaturated incoming blood generates high intensity within vessels, a phenomenon known as flow-related enhancement\(^{12,13}\). In 2D ToF, protons are excited slice by slice and with 3D ToF, a large volume is imaged. 2D ToF is most commonly used for carotid neck imaging due to its superior flow-related enhancement.

**Phased contrast (PC) angiography**

In phased contrast angiography, a magnetic field is applied to create a phase shift that is proportional to the velocity of flow. The magnitude of the phase shift is used to create an image with high signal representing flowing protons. The second step background suppression is accomplished mathematically using pixel by pixel subtraction of the flow-compensated mask. PC angiography requires the use and choice of a velocity encoding factor (VENC) which is usually selected to correspond to the maximum velocity through a region. Incorrect choice of VENC can lead to errors, particularly aliasing where areas of signal dropout can be mistaken for stenosis or occlusion (flow aliasing).

ToF imaging is acquired in a much shorter time than PC imaging, allowing more time for acquisitions and better resolution. PC imaging can have better background suppression, allowing better depiction of slower flow and smaller vessels\(^{14,15}\). We routinely use 2D ToF for carotid imaging. The final data are presented as a MIP which looks like a conventional angiogram. The brightest pixels are selected by computer and displayed. The data can be further manipulated to show both carotids and vertebrals or each individual vessel. It is, of course, essential, both in imaging vessels in the neck and in the head, to review the MIP imaging with source images otherwise errors can be made, particularly in distinguishing occlusion from near occlusion.

**Contrast-enhanced MRA**

Traditional ToF MRA cannot yet completely replace catheter angiography. Two non-invasive tests are needed, and conventional angiography is required in a number of cases. Gadolinium-enhanced MRA is a new technique available on the latest generation of MR scanners. This may be the leap forward in eliminating the use of conventional angiography. The technique is practical and straightforward to use, even in busy units\(^{16}\). Remonda et al have described the technique and compared it with conventional DSA in patients with carotid stenosis\(^{16}\). The images are acquired without a breath hold and with manual injection of contrast. The 3D images obtained during the arterial phase of the bolus passage are identified by means of visual inspection and the data set subtracted from the pre-contrast data set after the background signal of fat is eliminated. MIP images are then generated. Grading of stenoses in their study of
MR angiography

Fig. 1 (A) Maximum intensity projection MRA 2D time of flight, showing the aortic arch, carotid vessels in the neck and both vertebral arteries. On the left, a flow gap of about 1 cm is seen, perhaps indicating a long stenosis. On the right, there are 'steps' in the internal and external common carotid arteries due to swallowing artefact. Definition through the aortic arch is also poor with artefact. (B) Contrast enhanced (Gadolinium fast gradient echo) 3D time of flight imaging performed on the same patient at the same examination. This shows much better definition. The swallowing artefact on the right is eliminated, showing a normal bifurcation. On the left, the true extent of the stenosis is seen, with a very tight focal stenosis about 1 cm from the origin of the left internal carotid artery.

MRA agreed with DSA in 92% of 44 cases. All occlusions were accurately detected with MRA.

Timing from the start of the acquisition to the arrival of the contrast bolus is critical in contrast MRA. It can be acquired using a timing bolus or alternatively using an automated bolus detection and scan-triggering scheme such as SMARTPREP (GE Medical Systems, Milwaukee, WI, USA). Similar systems are available from other manufacturers.

Figure 1A,B is a comparison, in the same patient, of 2D ToF and contrast enhanced 3D ToF, showing much better demonstration of carotid stenosis and less artefact with contrast enhanced 3D ToF than 2D ToF.
Vertebral artery stenosis

One-tenth of all ischaemic strokes occur in the posterior circulation\textsuperscript{19} of which 20\% are thought to be cardio-embolic in origin, with a further 20\% due to intra-arterial embolism usually from the vertebral artery\textsuperscript{20}. Imaging of the arteries of the posterior circulation is often not considered because of the perception that it will not alter patient management. However, Crawley et al\textsuperscript{21} looked at 53 patients with conventional vertebral angiography and this was significantly abnormal in 60\% of patients, 16 of whom had vertebral artery stenoses, and 12 of whom were considered suitable for percutaneous transluminal angioplasty (PTA). The results indicated that using vertebral angiography to investigate posterior circulation ischaemia will identify a significant number of potentially treatable lesions. Vertebral angiography is not, however, without risk. It is invasive and is expensive. A good non-invasive technique is needed. MRA has been reported to be highly sensitive and specific (97\% and 98.9\%, respectively) compared with catheter angiography in identifying stenoses and occlusions in the posterior circulation. The sensitivity of ultrasound is less (76.4\%). My own view is that Gadolinium-enhanced MRA will be the imaging technique of choice, but this will initially have to be validated by comparison with conventional angiography. Our own experience is that neither MRA nor duplex ultrasound is sufficiently sensitive to stenosis at the origin of the vertebral artery (the commonest site to find lesions suitable for PTA) to be used for screening at the present.

Other non-atheromatous vascular diseases in the neck

Dissection
This is an increasingly recognised condition, particularly with the advent of MR. It causes approximately 2\% of all strokes but up to 20\% of strokes in younger patients\textsuperscript{22}. Dissection may be post traumatic, spontaneous or secondary to conditions such as fibromuscular dysplasia. Dissection is best detected with fat suppressed T1 and T2 axial images rather than MRA. MRA can elegantly show the length of the stenosis but does not necessarily aid the diagnosis of dissection. Duplex ultrasonography may be helpful. The primary investigation in a patient suspected of having distal carotid dissection is thus conventional spin echo MR. (Fig. 2A,B)

Fibromuscular dysplasia
MR can identify severe lesions but is much less sensitive than catheter angiography, which is the imaging method of choice. MR artefacts may also mimic lesions\textsuperscript{23}. 
Intracranial MRA

Screening for intracranial aneurysms

The gold standard for detection of intracranial aneurysms is intra-arterial digital subtraction angiography but, as discussed above, this is invasive and has morbidity. Recent papers, however, show a lower rate of rupture of coincidental aneurysms and question whether screening is indicated even in patients with two or three first degree relatives with subarachnoid haemorrhage\textsuperscript{24,25}.

Detection of aneurysms in patients with subarachnoid haemorrhage

Obviously, if a non-invasive test could detect an aneurysm with 100% sensitivity and specificity, this would be a major advance. However, as...
yet, MRA is only approximately 90% sensitive and specific\textsuperscript{24,26}, and thus cannot yet be recommended for first line imaging of ruptured aneurysms.

At present, formal angiography is required to accurately delineate the anatomy of the aneurysm neck and the surrounding vessels. Digital subtraction angiography with 3D acquisition and post processing is also being increasingly used, particularly when endovascular treatment is contemplated.

Figure 3A–C shows a large posterior communicating artery aneurysm demonstrated on spin echo MR, MRA and conventional angiography.
Arteriovenous malformations

Straightforward spin echo imaging in multiple planes is the most accurate method of detecting arteriovenous malformations (AVMs) with magnetic resonance; MRA does not really provide any more useful information. Catheter angiography is still necessary for accurate anatomical delineation of the AVM, its architecture and feeders prior to consideration for possible embolic, surgical or radiosurgical therapy. If a patient has had an intracranial haemorrhage, even if MR is negative, conventional angiography is mandatory if an AVM is suspected radiologically and clinically from the pattern of haemorrhage. Delayed angiography may also be indicated to allow for resolution of the mass effect. Small AVMs and fistulas can be invisible on MR.

New techniques such as MR digital subtraction angiography, however, do show promise in replacing catheter angiography, particularly in the work up for therapies such as radiosurgery.\footnote{27}

Dural sinus thrombosis

Dural sinus thrombosis accounts for approximately 1–2% of strokes in young adults. It may be idiopathic but is often associated with local and systemic diseases, being particularly common in pregnancy, the puerperium and in patients on the oral contraceptive pill.

On conventional MR, in dural sinus thrombosis, the normal flow void in the sinus is lost. Care must be taken in particular when looking at the transverse and sigmoid sinuses, as slow flow may mimic thrombosis. One or other transverse sinus may be small or atretic and lack of clear visualisation of a transverse sinus may not necessarily mean thrombosis. The right sinus is usually the largest. T2 spin echo imaging is the most useful and coronal images perpendicular to the dural sinus are particularly helpful.

MR venography provides an overall global view of the sinuses and helps non-neuroradiologists appreciate the extent of a thrombosis. However, as far as aiding the diagnosis, MR venography does not add very much to the standard spin echo sequences.

Routine MR also enables detection of any venous infarction or underlying causes of thrombosis such as infection or tumour.\footnote{28}

Key points for clinical practice

- Non-invasive techniques should replace invasive catheter angiography in the detection of carotid artery stenosis in the neck
Either ultrasound followed by MRA or MRA followed by ultrasound, if the first test is positive, should be performed. The combination of both studies shows sensitivities of 100% and specificities between 90–98%.

Conventional angiography should be performed if the results are discordant.

**Carotid dissection**: this is best detected with standard spin echo angiography, particularly using T2 and fat suppressed T2 images through the neck.

**Intracranial aneurysms**: MRA has as yet only 90% sensitivity and specificity. Catheter angiography is the gold standard and should be used in ruptured aneurysms. The role of screening for unruptured aneurysms is very debatable.

**Dural sinus thrombosis**: spin echo imaging, particularly perpendicular to the sinuses, is the most sensitive test. This can be supplemented by MR venography.

**References**

26 Wardlaw JM, White PM. The detection and management of unruptured intracranial aneurysm. [Review]. Brain 2000; 123: 205–21