Türk Beyin Damar Hastalıkları Dergisi 1998, 4: 63-69

CNS APPLICATIONS OF MAGNETIC RESONANCE ANGIOGRAPHY

Tim LEWIS

Consultant Neuroradiologist Frenchay Hospital, Bristol - United Kingdom

Introduction

Ever since the identification of magnetic resonance (MR) as a possible method of anatomical and physiological imaging it has been apparent that movement has a major effect on image quality. This is both in the form of artefact from unwanted motion and as the effects of physiological flow, both of blood and cerebrospinal fluid (CSF).

Initially this was treated as artefact and attempts made to reduce its effect. On occasions it was used diagnostically, as in the case of flow voids indicating patency of vessels and increased CSF flow demonstrating the changes of normal pressure hydrocephalus.

It was rapidly clear that several MR effects could be used to highlight flow, such as high velocity signal loss and inflow effects. These became the basis of MR angiography (MRA). Further enhancements allowed the demonstration of phase shifts in fluids moving through an altering magnetic field, resulting in the development of quantisation of flow and phase contrast angiography.

In the last five years the position of MRA has become established as a powerful tool to identify vascular pathology, both in the central nervous system and elsewhere in the body. The purpose of this paper is to give a brief overview of the physics and to provide a clinicians perspective of its current place within the spectrum of neuroradiological imaging procedures.

THE PHYSICS OF MRA

There are three well known techniques for MRA. These are referred to as "Black Blood" (BB) imaging, "Time of Flight" (TOF) and "Phase Contrast" (PC) methods. Each can be obtained as 2 dimensional (2D) or three dimensional (3D) data sets. The commonest method in clinical use is TOF and the majority of this overview will concentrate on this technique.

The acquisition of information as 2D or 3D sequences has profound implications on the time of the sequence and the available information. At its most basic a 2D sequence indicates that data has been collected in a way that allows its evaluation from one plane only, while 3D data can be viewed as a block of information which can be manipulated in many ways to allow interpretation. 3D data takes longer to acquire and needs rather different parameters. 2D data can also be acquired with multiple single slices, allowing later processing as a 3D data set. This is often referred to as Multiple 2D TOF (M2DTOF).

Time of Flight Angiography

The principle behind TOF angiography is simple 2. Protons entering an imaging slice with no residual magnetisation will be available to provide a full MR signal following radiofrequency (RF) excitation. This is referred to as the inflow effect. If the volume of tissue that the proton enters is subjected to multiple pulses the background signal will become depressed as the stationary protons become saturated with RF energy and no longer respond to the imaging pulses. In such a situation the entering protons (as in blood) will have a high signal and be clearly visible against the low signal background tissues. Pulses are provided at regular intervals (the TR - time of repetition of pulse) to acquire the data.

As the protons in blood move through the volume of tissue being examined they will absorb the repeated RF energy and gradually become saturated. The longer that the protons are subjected to RF energy the less signal they will return. This is avoided by ensuring that the volume of tissue examined is small enough that blood will pass through it without saturation and by ensuring that the RF energy used is low enough not to saturate protons too quickly.

The basic parameters of the TOF sequence are influenced by the following:

a) Blood velocity

The faster the flow of blood the less saturated it will get, resulting in higher signal

b) TR

The shorter the TR the more RF pulses can be delivered in a unit time, producing more saturation to static protons. Slow flowing protons may also be saturated.

c) Slice Thickness

A 3D TOF sequence can be viewed as a thick slice for the purpose of data collection. The thicker the slice the longer it will take blood to cross it and the greater will be the saturation of protons in blood at the distal edge of the slab. This can be overcome by using the technique of MOTSA3 (multiple overlapping thin slab acquisition) by which a volume of tissue is divided into smaller 3D chunks (the technique is also known as "Multichunk" by some companies) thus reducing the potential saturation.

d) Flip Angle

The energy imparted to a proton is often described by the extent of deflection of the axis of the spin from the long axis of the magnet. For conventional static spin echo imaging this will be 90 degrees. For Angiography such an energy deposition would rapidly induce saturation and much lower flip angles are used. For 2D TOF a flip angle of around 60 degrees is appropriate. For 3D TOF lower flip angles are needed, in the region of 20 - 25 degrees. The precise angle used should depend on the expected blood flow4 and will be lower in the elderly. As a general rule we use a 26 degree flip angle for young adult patients (although for children it may be possible to increase this to 30 degrees) reducing to an angle of 20 (or even 18) in the elderly. Although saturation is reduced with the lower flip angles there is both an associated signal loss and a reduction in background suppression, making the resulting images noisier. As with other imaging parameters there is a trade off between small vessel conspicuity and image noise.

Recently new techniques have allowed for the variation of flip angle through a slab 5. This variable flip angle allows for higher signal in the distal part of the slab. Protons entering the slab will have a low flip angle, which progressively increases through the volume, ensuring that saturation of spins is delayed and higher signal is obtained distally due to the increased flip angle.

e) TE

The time lapse between input of RF and sampling the returning signal is referred to as the TE (Time of Echo). The longer the TE used the greater the chance of dephasing from turbulence and motion. For this reason TE should be a short as possible. A short TE may require ultra fast gradients (not a standard feature on most scanners) and so a compromise is needed. By using a TE that ensures that protons in water and triglyceride are out of phase a lower background signal will result, producing a better signal to noise ration and consequently better image quality. At 0.5T and 1.5T field strength this will occur at a TE of 7msec while at 1.0T the same effect occurs at 11msec 6. It may well be preferable to lengthen the TE to these figures.

f) Background Suppression

In addition to choice of TE unwanted signal can be suppressed by other means.

i) A saturation slab distal to the imaging volume will saturate venous blood travelling in the opposite direction to arterial blood, thus reducing unwanted information.

ii) MTC: A Magnetisation Transfer Coherence prepulse will reduce signal from background tissue 4. While it may also have positive value in assessment of tissues with other sequences MTC is used in angiography to suppress unwanted background signal.

Further aspects which have to be considered in TOF angiography relate to resolution and acquisition time. These two factors are in opposition: the higher the resolution the longer it will take to acquire useful data. Resolution is usually identified by the matrix of the image in relation to its size. For TOF angiography at Frenchay we use a 110mm field of view with a 256 matrix, producing pixels of 0.42mm. Resolution will not exceed this. With such a sequence the acquisition time is 10 minutes 42 seconds, probably approaching the maximum time than patients can be relied on to keep quite still. Any patient movement will clearly profoundly reduce the resolution of the resulting images.

Multiple 2D TOF sequences are easier to manipulate and have less of a problem with signal to noise ration due to the much higher flip angle possible. In an M2D TOF sequence the duration of the scan depends on the extent of coverage required.

Phase Contrast Angiography

The principle of PC angiography 7. is fundamentally different to that from TOF. In PC angiography the signal detected depends on the phase shift induced in a proton while it traverses a magnetic field gradient. This will be dependent on the velocity of the proton and the strength of the magnetic gradient and can be used either to quantify the flow or to maximise signal from blood at a specific velocity. As blood flow is usually in 3

planes a 3D sequence is often the best to evaluate the complete course of an artery.

Phase contrast angiography is usually free of significant noise because of the subtraction effect induced by only imaging phase shift and the technique is quite suitable for 0.5T scanners as well as those of higher field strength. It is less sensitive to the whole range of flow than TOF but can be tailored to be better at low flow rates. This is achieved by incorporating a velocity encoding signal (Venc) into the sequence which maximises signal from protons moving at a specific spped.

Intravenous Contrast

IV contrast has been advocated to improve resolution in MRA 8. It works by increasing signal from moving protons in consequence of the reduction in T1 relaxation time. It is certainly helpful in evaluating smaller and slower flowing vessels but may not be of great help with aneurysm detection or vascular occlusion despite some strong proponents of such a technique 9. In addition the cost of Gadolinium based contrast media is high, representing a very significant increase in the cost of the overall procedure.

Black Blood Angiography

The principle of using signal loss from flowing blood to give vascular images is old.10 Its possible applications within the brain were investigated11 but the advances in TOF and PC imaging tended to eclipse it.

The technique has recently aroused interest again because of its relative sensitivity to the whole range of flow, thus allowing demonstration of the walls of arteries as well as the higher flowing central areas. It is technically quite difficult to set up and is not applicable where blood vessels pass through bone or adjacent to areas with high susceptibility. Because it is less sensitive to turbulence it may well be a useful addition to TOF for aneurysm detection.

The technique relies entirely on the principle of high velocity signal loss, where fast flowing spins have exited the imaging field before the signal is sampled. As such it requires a sequence with a relatively long TR and a long TE, tailored to reduce T1 and T2 weighting to give a neutral high signal background against which to contrast the signal voids from flow.

CLINICAL APPLICATIONS

MRA is now useful in a wide range of different clinical situations. These include:

Extracranial vascular disease
Intracranial disease:
  occlusive vascular disease
  Aneurysms
  Arteriovenous malformations
  Tumours
  Venous occlusive disease

The correct sequence options need to be taken for optimal results and some guidance will be given here as to the appropriate technique.

Extracranial Vascular Disease

Multiple 2D TOF angiography is good at evaluating the extracranial carotid and vertebral arteries. With the appropriate receiver coil the neck arteries can be imaged from the aortic arch to the Circle of Willis, giving excellent detail. For the carotid bifurcations a higher resolution sequence, usually a 3D TOF, is helpful.

Imaging of the bifurcation is of similar clinical accuracy as Ultrasound 12. In the absence of a good ultrasound service (which is often cheaper to obtain and subject to a shorter waiting time) then MRA is a sound diagnostic option. It is subject to artefact from turbulence in the carotid bulb (which may mimic atheroma) and, like ultrasound, requires careful attention to technique and sound experience to be reliable. It seems likely that MRA will completely replace conventional angiography in the diagnosis of carotid stenosis 13. In my practice we do not use MRA routinely as we have a high quality ultrasound service but we do employ the technique when a blocked internal carotid artery is seen on a head scan. In such situations atheroma or dissection 14. are usually easy to identify.

Intracranial Disease

1) Occlusive vascular disease

This is a common clinical problem. Most patients with a clinical diagnosis of stroke will not even have MRI in their investigations, reliance being placed on CT and clinical assessment. Where doubt exists then MRI has proved useful. MRA is an adjunct to conventional imaging, allowing the demonstration of stenoses and complete blocks within major vessels 15,16. It will only show abnormalities in the relatively acute stage of the disease as recanalisation can occur very early. In the chronic stage it may be helpful in evaluating the extracranial carotid arteries (see above). It

seems unlikely that MRA will have a place in the acute management of stroke. If there is the intention to treat large vessel occlusion with thrombolysis this has to be started within 4 hours of the onset of stroke. In such a case diagnostic angiography using DSA will be the investigation of choice, allowing immediate follow on to thrombolysis. For intracranial vascular disease I use the same 3D TOF sequence as is used for aneurysm detection (see above). Investigation of the extracranial circulation is as above.

In paediatric vascular disease MRA can be very helpful. Moya Moya may be shown with clarity and this is one situation where the MRA provides a much clearer image of the pathology than planar imaging.

2) Intracranial aneurysms

Aneurysm detection is an area of radiology where digital subtraction angiography has been the clear "Gold Standard" for some time. There is an unavoidable risk with the technique 17 which, although negligible in the face of proven subarachnoid haemorrhage, is of significance where the rate of aneurysm detection is low. We usually quote a figure of 1.5% for neurological complications of angiography, half of which will be permanent. Other studies have a higher incidence. The risk is higher with pre-existing vascular disease, inexperience of the angiographer and low through-put of the unit. These are not surprising findings.

MRA using 3D TOF has a good sensitivity and specificity 18 but in acute subarachnoid haemorrhage suffers from the restriction that the sequences are noisy and patients with acute haemorrhage do not like the experience. In an emergency it is viable and we have used it where DSA is unavailable.

In patients with the suspicion of an aneurysm or with a family history of subarachnoid haemorrhage MRA is the technique of choice. Patients tolerate the procedure well and images are usually of high quality. Results 18 suggest that all aneurysm of 6mm or more will be visible with 3D TOF along with the majority of smaller aneurysms. Given the clinical doubt as to the bleed rate of unruptured aneurysms the sensitivity and specificity of MRA seems to be a good compromise against the risks of DSA.

The technical aspects of the examination involve taking all the available time examining the areas where aneurysms are common. A high definition sequence to include the Circle of Willis is mandatory. The resulting source images should then be individually evaluated for the presence of vascular abnormalities and aneurysms. The source images should be combined into series of processed images, using either the maximum intensity projection (MIP) algorithm or a closest vessel projection (CVP) algorithm. Both of these techniques have strengths and weaknesses and it is my practice to vary the sequence used dependent on the anatomy. With multiple tortuous vessels the CVP technique can be very helpful, as it can with demonstrating the anatomy of an aneurysm neck. In general, however, the MIP approach is more widely used. I find that it is helpful to produce sequences for vessels from each part of the brain, resulting in series for the carotid territories and the basilar arteries. These are manipulated to provide different projections in the three orthogonal planes as a routine. Occasionally double oblique projections help.

There is as yet no evidence to indicate the frequency with which screening for asymptomatic aneurysms should take place in the at risk subject. Given the side effects of surgery for aneurysms it seems unlikely that surgery would be offered to patients in their later years and we do not recommend screening MRA for those over 60 years of age. The interval between examinations in younger patients is unclear. A repeat examination every five years may well be appropriate, with the option to reconsider this advice as more information concerning bleed rates comes out of the major study at present investigating this area. Remember that unruptured aneurysms in the presence of a clipped aneurysm cannot be safely followed up in this way. The presence of an intracranial aneurysm clip precludes any MR examination.

3) Arteriovenous malformations

AVM's are usually quite apparent on standard planar imaging, especially T2 sequences where the flow voids are clearly visible. Occasionally this can be difficult when the AVM is around the edge of a haematoma, where the flow voids may be indistinguishable from haemosiderin in the wall of the cavity. Phase contrast angiography is the best way to review large AVM's19 although the source images from 3D TOF may also be revealing. The velocity encoding with PC angiography allows considerable flexibility in the acquisition of data: for small AVM's I usually encode for a velocity of 30cm/sec, whereas for large AVM's with an apparent rapid shunt 60cm/sec may be preferable. 3D TOF may be helpful with AVM's less then 2cm in size19.

The definitive investigation for AVM's remains angiography as it is not usually possible to evaluate the different feeding vessels with MRA. Some rather crude saturation of one or other carotid artery will provide a little information but where there is an intent to treat an AVM by embolisation then detailed anatomy and flow rates are necessary. This can only be done with DSA.

4) Tumours

Most tumours will not need investigation with MRA (or angiography) and in particular it is very rare that intrinsic tumours will be better evaluated with angiography. Where MRA has a value is in the investigation of meningiomas and other tumours of the skull base. Meningioma blood supply is not usually of vital significance to a surgeon but the presence of sinus occlusion with a parasagittal lesion is vital information. 2D or 3D PC angiography will help here. Because it can be difficult to interpret 2D PC images it is my practice always to perform a whole head 3D PC MRA to evaluate the sinuses. This is encoded for a flow rate of 30cm/sec, allowing clear demonstration of veins and sinuses along with some residual signal from the main arteries. The 3D sequence allows similar processing of images to that given in detail for the assessment of aneurysms and thus a much clearer understanding of the pathological situation.

For skull base tumours there is benefit in knowing the position and involvement of both carotid arteries and jugular veins. 3D PC may also have a place here, along with multiple 2D TOF MRA. (3D TOF has a rather small coverage in an acceptable time and is not used greatly - for our aneurysm detection the combined slab is only 3cm thick).

5) Venous sinus obstruction

Sinus thrombosis is an important cause of morbidity and here 3D PC MRA is the investigation of choice. The technique has been mentioned for the evaluation of tumours and is not altered in any way. It is usually possible to see all the major sinuses clearly with a flow encoding (Venc) of 30cm/sec although some suggest a lower Venc of 20cm/s20. Care needs to be taken in the region of the transverse sinuses as flow effects from the veins of Labbe can produce dephasing simulating thrombosis.

Many people have observed that 2D TOF has a place in sinus thrombosis. In theory the T1 shortening from methaemoglobin in clotted blood should cause problems with the high signal returned by flowing blood but in practice the signal intensities seem to be quite different and are not a problem. That said - we use 3D PC MRA and not TOF!

Other Modalities

The position of MRA has to evaluated with respect to CT angiography as well as conventional DSA. CT angiography (CTA) has risen to prominence with the production of spiral CT scanners which allow rapid acquisition of data following a bolus injection of contrast. As with MRA a high degree of technical proficiency is necessary but in careful hands it appears at least as good as MRA. The need for contrast injection is a slight disadvantage but the quieter and shorter scans have appeal for patients with severe headaches.

Conclusion

In a brief essay it is not possible to go into exhaustive detail about the indications and findings in MRA. It has become apparent over the last year that MRA is coming of age and is now competing directly with DSA for the position as investigation of choice in all areas. Although the resolution of MRA is not as good as DSA the greater flexibility of image manipulation has the same effect on image quality as did the extra contrast from DSA have over conventional cut film angiography. I think that for most indications MRA is now the investigation of choice. With aneurysms the situation is less clear cut but MRA is rapidly overtaking DSA and will, in the next five years, become the chosen modality. Already many radiologists who coil aneurysms are arranging MRA as a pre-operative procedure on their patients. Only where the evaluation of AVM's is needed before embolisation will DSA remain the preferred option.

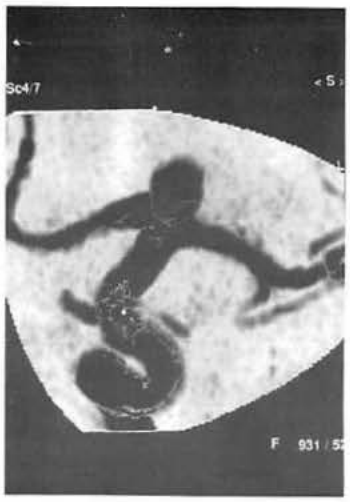

Fig 1) 3D TOF angiogram. The images have been reformatted using a Closest Vessel Projection algorithm and show a terminal carotid artery aneurysm (The reformation has been selective with exclusion of the contralateral carotid and the basilar arteries.

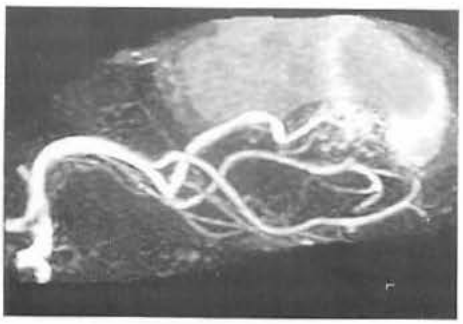

Fig 2) 3D TOF angiogram. This has also been reformatted using the CVP algorithm. It shows feeding vessels and an AVM nidus adjacent to a haematoma. The haematoma, containing methaemoglobin, has T1 shortening which allows it to be visible on the TOF images. If the haematoma is too bright the AVM may be shown less well. Phase Contrast angiography would then be helpful.

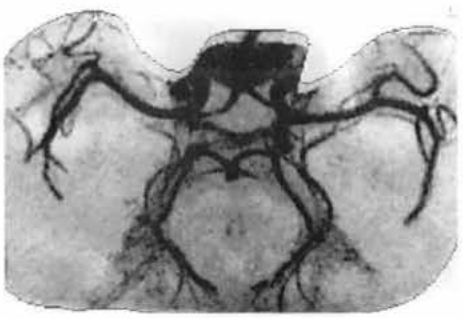

Fig 3) Black Blood angiogram utilising long TE and intermediate TR (TR = 1,000msec, TE = 120msec). This is very free of saturation effects but less sharp than TOF. It also suffers from the disadvantage of prominent low signal arising from bone, preventing visualisation of vascular structures within or adjacent to bone.

Fig 4) Phase Contrast venogram using Venc=30cm/sec. Note good imaging of the major venous sinuses. Note that some arterial signal is also present.

Fig 5) Source images from TOF angiogram. Note high signal from the internal carotid arteries and absence of signal from the basilar artery. This represents basilar thrombosis.

REFERENCES

1. Initial clinical evaluation of a whole body nuclear magnetic resonance (NMR) tomograph Young IR, Bailes DR, Bulr M et al (1982) J Comput Assist Tomogr 6: 1 - 18
2. First Principles of Magnetic Resonance Angiography Listerud J, (1991) Magnetic Resonance Quarterly 7: 136-170
3. Intracranial MRA: Single Volume vs. Multiple Thin Slab 3D Time-of-Flight Acquisition Davis WL, Warnock SH, Harnsberger HR et al (1993) J Comput Assist Tomogr 17(1) 15 - 21
4. Optimizing Blood Vessel Contrast in Fast Three-Dimensional MRI Haacke EM, Masaryk TJ, Wielopolski PA et al (1990) Magnetic Resonance in Medicine 14: 202 - 221
5.Time of Flight Method of MR Angiography Laub GA (1995) MRI Clin Nth America 3: 391 - 39
6. Time of Flight Angiography Anderson CM & Lee RE (1993) in: Clinical Magnetic Resonance Angiography ed Anderson CM, Edelmann RR & Turski PA, Raven Press, New York
7. Phase Contrast MR Angiography Techniques Dumoulin CL (1995) MRI Clin Nth America 3: 399 - 411
8. Efficacy Evaluation of Gadoteridol for MR Angiography of Intracranial Vascular Lesions McLachlan SJ, Francisco JC, Pernicone JR & Hasso AN (1994) JMRI 4: 405 - 411
9. Contrast enhanced MR Angiography Runge VM, Kirsch JE, Lee C (1993) JMRI 3: 233 - 239
10. Nuclear Magnetic Resonance Imaging of Atherosclerotic Disease Herfkens RJ, Higgins CB, Hricak H et al (1983) Radiology 148 161-166

11. Extracranial carotid arteries: evaluation with "black blood" MR angiography Edelman RR, Mattle HP, Wallner B et al (1990) Radiology 177 - 45 - 50
12. MR Angiography on Neurologic Disease Atlas SW (1994) Radiology 193: 1 - 16
13. MR Imaging and the Evaluation of Extracranial Carotid Stenosis Rubinstein D (1994) AJR 163: 1213 - 1214
14. Internal Carotid Artery Dissection: MR Imaging Features and Clinical-Radiological Correlation Ozdoba C, Sturzenegger M, Schroth G (1996) Radiology 199 191 - 198
15. Intracranial Vascular Stenosis and Occlusion: Diagnostic Accuracy of Three- dimensional, Fourier Transform, Time-of-Flight MR Angiography Korogi Y, Takahashi M, Mabuchi N et al (1994) Radiology 193: 187 - 193
16. MR Angiography in Acute Cerebral Ischaemia of the Anterior Circulation: A Preliminary Report Gillard JH, Oliviero PJ, Barker PB et al (1997) AJNR 18: 343 - 350
17. Complications of Diagnostic Cerebral Angiography and Tips on Avoidance Pryor JC, Setton A, Nelson PK & Berenstein A (1996) Neuroimaging Clins Nth Amer 6(3): 751 - 758
18. Blinded Prospective Evaluation of Sensitivity of MR Angiography to Known Intracranial Aneurysms: Importance of Aneurysm Size Huston III J, Nichols DA, Luetmer PH et al (1994) AJNR 15: 1607 - 1614
19. MR Angio evolves in key neurovascular areas Patay Z, Rodesch G & Baleriaux D (1996) Diagnostic Imaging Europe July/Aug 27 - 37
20. MR Venography and Cerebral Venous Thrombosis Turski P (1993) in Clinical Magnetic Resonance Angiography, Eds Anderson CM, Edelman RR & Turski P, Raven Press, New York