Chapter 23
Magnetic Resonance Angiography: Fundamental Techniques and Data Interpretation

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23.1 Introduction

Magnetic Resonance Angiography (MRA) techniques have become well established thanks to their increased use and broader application, made possible by several factors such as the use of high-field technology and stronger magnetic gradients. These advances, combined with faster processors and specific coils, have been employed to optimise the spatial resolution and resonance signal in MRA. Another important development has been the simplification of post-processing done at stand-alone workstations, which has enabled shorter examination times. Thus, MRA techniques are now a viable option for imaging of vascular structures throughout the body, as well as for characterisation of plaques and analysis of related complications.

23.2 MRA Techniques

Magnetic Resonance (MR) is a highly sensitive technique based on the movement of protons (hydrogen nuclei). This motion is harnessed to generate images in which voxels containing moving protons are distinguished from those containing stationary protons. In MRA, information is acquired by exploiting the differences between moving protons and stationary ones: either in terms of their respective absorption of radiofrequency (RF) pulses, or in terms of their respective dephasing when moving under weak magnetic gradients. The former is analysed using Time of Flight (TOF) sequences and the latter, using Phase Contrast (PC) sequences. (Table 23.1).

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Table 23.1 MRA techniques

2D PC
PC 3D
Cine PC
2D TOF
TOF 3D
MOTSA
CE-MRA
Black-blood techniques

23.2.1. Time of Flight sequences are based on the detection of unsaturated protons as they enter into a plane or volume in which the protons are saturated. When the plane or volume is subjected to repeated RF pulses using a short Repetition Time (TR), the saturated protons will exhibit a gradually decreasing longitudinal relaxation time and therefore, will give a much weaker resonance signal than will the unsaturated protons that have just entered.

23.2.2. Acquisition of PC images is based on the use of magnetic gradients to differentiate between stationary spins and moving ones. The dephasing between moving spins and stationary spins is proportional to the speed at which the former move. Thus, information on blood flow can be obtained by adjusting the acquisition speed to the blood flow speed in the desired area.

23.2.3. There are two options for studying a given anatomical region by MRA: either choosing a single volume of appropriate size (3D TOF or PC), or dividing the region into slices of an appropriate thickness for consecutive imaging of each one (2D TOF or POC) and subsequent reconstruction of the volume of interest.

23.2.4. Each one of the aforementioned approaches has its respective advantages and disadvantages. It is important to understand each approach well in order to choose the best one for each examination (Tables 23.2 and 23.3). In 2D TOF MRA sequences, the flow signal reaches its maximum intensity when the acquisition plane is perpendicular to the direction of the blood vessel, but it loses intensity in arterial branches and in arterial courses that are parallel to the plane. The signal also diminishes due to a phenomenon known as *intravoxel dephasing*, which is caused by turbulent flow related to ectasia or distal to stenosis. However, 2D TOF MRA can prove useful for studying slow venous flow in the intracranial venous sinuses or in the veins of the neck when contrast-enhanced MRA (CE-MRA) cannot be used. Three-dimensional TOF MRA is not as strongly influenced by vessel branching or directional changes and therefore, offers full potential for assessing the intracranial arteries. However, use of this sequence in patients with slow blood flow (such as those with low cardiac output or with other pathological conditions that affect flow) leads to a major increase in the saturation of moving spins, causing a gradual loss in visualisation of the fine distal blood vessels. To partially overcome this saturation effect, one can use a variant of 3D TOF known as Multiple Overlapping Thin-Slab Acquisition (MOTSA). In this technique, the volume of interest is divided

Table 23.2 Advantages and disadvantages of MRA techniques

2D PC:
Fast
Adjustable speed range for arterial or venous examination
Imaging of vascular topography for planning MRA studies
Rapid, motion-based evaluation of the circle of Willis
Detects flow in the large intracranial venous sinuses
Low spatial resolution
Random encoding of the speed range
3D PC:
Adjustable speed ranges
Good background suppression
Very slow
Very sensitive to signal loss caused by turbulent flow distal to severe stenosis
Very rarely used, except for studying the renal arteries
2D TOF:
Minimal saturation
Useful for slow flow
Used for MR Phlebography (MRP)
Short study time
Low spatial resolution
Difficult to distinguish material with short T1 times (hyperintense in T1-weighted sequences)
Very sensitive to signal loss in the direction parallel to the acquisition plane
3D TOF:
High spatial resolution
Intermediate study time
Not directionally dependent
Enables examination of stationary tissue
Flow saturation due to signal loss from slow flow
Difficult to distinguish material with short T1 times (hyperintense in T1-weighted sequences)
CE-MRA
High spatial resolution
3D acquisition
Short study time
Does not depend on the flow direction
Does not suffer from the flow artefacts of traditional MRA sequences
Does not allow examination of stationary tissue

into a series of smaller overlapping volumes that are independently imaged and subsequently reconstructed.

23.2.5. Two-dimensional PC sequences offer rapid acquisition, making them ideal for planning a more detailed MRA study. For example, they enable ready location of the carotid bifurcations and of the intracranial vessels for the initial assessment of any altered flow.

Phase-Contrast sequences can be synchronised with the cardiac cycle (this is known as *cine PC*) in order to provide information on vessel elastic-

Table 23.3 Applications of MRA sequences

2D PC:
Imaging of vascular topography for planning MRA studies
Rapid, motion-based evaluation of the circle of Willis
Detection of flow in the large intracranial venous sinuses
3D PC:
Rarely ever used, although it can be utile for studying the renal arteries
Cine PC:
Imaging of vascular topography for planning MRA studies
Superior-inferior flow direction encoding for studying subclavian steal syndrome
Anterior/Posterior and Right/Left flow-direction encoding to detect reversed flow in the branches of the circle of Willis or in the ophthalmic artery, due to carotid artery occlusion
2D TOF:
Useful for slow flow
Used for MR Phlebography (MRP)
3D TOF and variants (MOTSA):
Exploration of stationary tissue
Amenable to the study of carotid artery bifurcations
Enables study of:
Vessel walls, plaques, dissections and intramural haematomas
Circle of Willis and the basilar artery
Neurovascular contact between the trigeminal nerve and the basilar artery, or between the facial nerve and the anterior inferior cerebellar artery
Cerebral aneurysm, flow and mural thrombus
Cerebral AVM
CE-MRA:
Examination of patients with extracranial occlusive vascular disease
Couple to MOTSA or T1 sequence with fat suppression for carotid or vertebral artery dissection
Enables study of:
Congenital defects of the aortic arch
Obstructive, inflammatory or arteriosclerotic pathology of the aortic arch and its branches
Soft-tissue space-occupying lesions of vascular origin
The relationship between a soft tumour and adjacent blood vessels
Enables exploration of the intracranial venous sinuses, venous thrombus and surrounding tumour

ity and flow direction, which can be used to determine the normal flow direction or identify any flow reversal or collateral routes. Arterial or venous vessels can be studied by either adjusting the speed in a PC sequence or by using saturation pulses in a TOF sequence, each of which will suppress the flow from a given direction. Although the advent of contrast-enhanced MRA (CE-MRA) relegated some conventional (or "flow-based") MRA techniques to a minor role, the authors of this chapter believe that these techniques remain valuable for studying certain anatomical regions, especially the cerebral arteries.

23.2.6. Contrast-enhanced MRA

A diverse array of vascular structures can be studied by 3D (volume) imaging, by using very fast spin-echo gradient sequences, gadolinium (Gd)-based paramagnetic contrast agents to intensify the blood signal, and an infusion pump. These contrast agents enable study of blood vessels based on shortening of the T1 and T2 relaxation times of the blood, rather than according to blood flow. Gadolinium causes the protons surrounding each contrast agent molecule to relax more quickly (shortening of T1) while simultaneously influencing the local magnetic susceptibility (shortening of T2). In T1-weighted spin-echo gradient sequences, these agents give positive contrast (stronger blood signal), whereas in T2*-weighted sequences, they give negative contrast. Thus, for MRA, a T1-weighted, fast spin-echo gradient sequence is used with 3D (volume) acquisition. For the best results, the T1 values for blood should be lower than for other tissue (including fat).

Tables 23.4, 23.5 and 23.6 list the technical specifications for the sequences used at the two centres in which the authors work.

Table 23.4 Technical characteristics of MRA sequences

Scanner model and manufacturer	Symphony 1.5T, Siemens (Erlangen, Germany)	
Sequence	Multislab TOF 3D	MOTSA
TR (ms)	39	22.0
TE (ms)	7.12	Minimum
Angle	25°	20°
Field of view (FOV) (X)	200	200
Slice thickness (mm)	1.5	2.4
Acquisition plane	Axial	Axial
Matrix	192×512	256×192
Coils	Head array and neck array	Neurovascular
Saturation band (placement)	Craniocaudal (above)	Craniocaudal (above)
Acquisition time (min)	5.26	7.14

Table 23.5 Technical characteristics of MRA sequences

Symphony 1.5T/Siemens (Erlangen, Germany)	
Sequence	CARE bolus
TR (ms)	3.24
TE (ms)	1.08
Angle	20°
Field of view (FOV) (X)	350
Slice thickness (mm)	60
Acquisition plane	Coronal
Matrix	144×192
Coils	Head array, neck array
Scan rate	1 scan per second (60 scans per minute)

Table 23.6 Technical characteristics of CE-MRA sequences

Scanner model and manufacturer	Symphony 1.5T, Siemens (Erlangen, Germany)	SIGNA 1.5T, GE (Milwaukee, USA)
Field strength	1.5T	1.5T
Sequence	Fl 3D-CE	3D-fast SPGR (TOF)
Bolus tracking technique	CARE bolus	Real-time, smart-prep, test bolus
Bolus tracking region-of-interest	Aortic arch (contrast agent reaches supra-aortic vessels)	Aortic arch and supra-aortic vessels
Delay	Up to the supra-aortic vessels	Obtained from the test bolus
TR (X)	3.77	Minimum
TE (X)	1.54	Minimum
Angle	30°	30°
Matrix	168 × 384	384 × 256
Field of View (FOV) (mm)	300	340
Slice thickness (mm)	0.8	2
Acquisition plane	Subclavian-axillary vessels and supra-aortic vessels: coronal	Subclavian-axillary vessels and supra-aortic vessels: coronal
Coils	Head array & neck array	Supra-aortic vessels: neurovascular coil
Contrast medium	Gd: Gadovist® 1 M	Gd: MultiHance®
Concentration (M)	1.0	0.5
Delivery system	Infusion pump	Infusion pump
Injection speed (mL/s)	2	1.5
Acquisition time (s)	40	45
Stations	1: Supra-aortic vessels	1: Supra-aortic vessels
Mask	Supra-aortic vessels	Supra-aortic vessels
Repeated acquisitions	–	Vascular malformations
		Vascular tumours
		Carotid-cavernous fistula
Apnoea (breath-hold) required?	No	No
Elliptic-centric techniques	Yes	Yes

23.2.7. Contrast-enhanced MRA techniques are especially utile for patients that are contraindicated to iodinated contrast agents due to kidney failure or to allergy: the Gd-based contrast agents used in CE-MRA exhibit lower nephrotoxicity than do the iodinated contrast agents used in conventional angiography, DSA or CT. The reader is reminded that paramagnetic contrast agents very rarely cause allergic reactions, and these are less severe than those caused by iodinated contrast agents. In order to avoid the risk of the patient developing nephrogenic systemic fibrosis related to chronic kidney failure, the healthcare professional must take into consideration the patient's glomerular filtration rate (GFR). Patients with stage 4 or 5 chronic kidney disease (CKD) and a GFR lower than 30 mL/min are at high risk, whereas patients with stage 3 CKD and a GFR of 30–59 mL/min are at lower risk. The recommended type of contrast medium to be used is stable gadolinium macrocycles (gadobutrol, gadoterate meglumine, gadoteridol, etc.). Regardless, the healthcare professional must never deny any well-indicated patient a CE-MRA. Another advantage of MRA compared to certain other imaging methods is that it does not expose the patient to any ionising radiation.

23.2.8. The only limitations and contraindications of these techniques are those inherent to the use of magnetic fields: they are not adequate for patients with pacemakers, neural stimulators, inner ear prostheses or older models of cardiac prostheses, or with vascular clips made of materials that incompatible with MR. Furthermore, before proceeding to examine any patient that regularly works with metal, the healthcare professional must first confirm that the patient's eyes do contain any residual metal fragments. One common problem among patients is claustrophobia, which can be avoided by sedating the patient.

23.3 Clinical Applications and Indications

Whilst the previous section described the nomenclature of MRA, this section outlines its diagnostic utility and indications. For examination of patients with a suspected cerebrovascular pathology that have been screened by appropriate Doppler ultrasound techniques, MRA has replaced conventional angiography.

23.3.1 Supra-aortic Vessels

Among the most frequent applications of MRA is the examination of carotid bifurcations. According to numerous studies, MRA offers comparable results to those obtained with Doppler ultrasound or even DSA. To study the supra-aortic vessels by CE-MRA, elliptic-centric K-space filling is employed. In this approach, those central lines of the K-space that are responsible for the contrast are filled, thereby reducing signal interference from jugular vein overlap. The recommended screening method is

ultrasound; if a haemodynamically significant stenosis (>50 %) is identified, then the patient should be examined by Computed Tomography Angiography (CTA) or MRA. The authors of this chapter use DSA primarily for those cases in which the results from Doppler ultrasound are inconsistent with those of MRA, and in which re-examination of the results previously obtained with each technique does not enable any conclusive diagnoses, although to date such cases are only anecdotal (Fig. 23.1). Another important application of DSA is for definitively ruling out any pseudo-occlusion of the carotid artery caused by a critical stenosis that has blocked the flow of blood to the cervical portion of the internal carotid artery (ICA). However, for certain patients some healthcare teams prefer surgical exploration of the carotid sinus, in order to avoid the vascular intervention and contrast media required for DSA.

The reader is reminded that some types of MRA sequences can lead to overestimation of the grade of stenosis (from low to moderate), due to dephasing of the spins inside the vessel caused by turbulent flow; however, this rarely causes any alteration in treatment plans. Regardless, use of CE-MRA has minimised this problem. There are three methods for grading stenosis: the North American Symptomatic Carotid Endarterectomy Trial (NASCET), European Carotid Surgery Trial (ECST) and Common Carotid (CC) methods. The most common method is the NASCET method (see Step 23.4.2.8), but the CC method can also be useful (Fig. 23.2).

If a carotid or vertebral artery dissection is suspected, than a combination of CE-MRA and MOTSA or 3D TOF MRA sequences can prove highly valuable: it can reveal not only the compression of the arterial lumen, but also vessel wall haematoma; double lumen caused by detachment of the intima; vessel occlusion; or recanalisation of previously occluded vessels (Figs. 23.3 and 23.4). Another option is to image the suspected arterial region by acquiring T1-weighted slices with fat suppression.

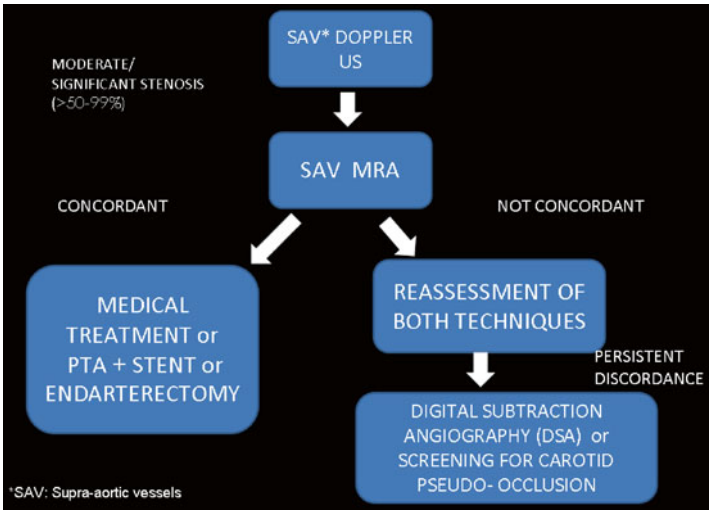

Fig. 23.1 Clinical algorithm for carotid artery stenosis

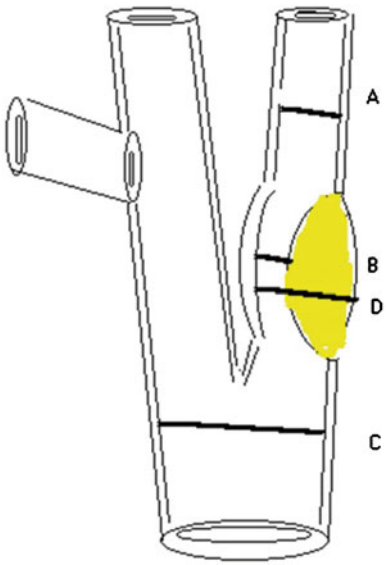

Fig. 23.2 Common methods for grading carotid artery stenosis. *A*: Normal diameter of the internal carotid artery distal to the stenosis. *B*: Diameter of the minimum residual lumen. *C*: Visually estimated diameter of the internal carotid artery. *D*: Diameter of the common carotid artery. Formulas for grading carotid artery stenosis: 1. NASCET: (A–B)/A × 100 % stenosis, 2. ECST (D–B)/D × 100 % stenosis, 3. Common Carotid: (C–B)/C × 100 % stenosis

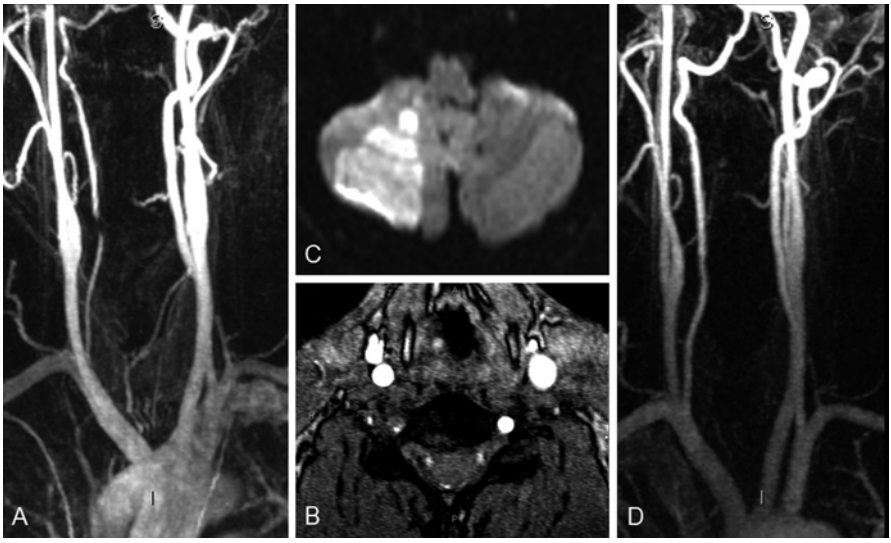

Fig. 23.3 (**a**) Coronal MIP reconstruction of CE-MRA of the supra-aortic vessels, revealing stenosis in the V2 segment of the right vertebral artery. (**b**) Partition of the MOTSA sequence: the intramural haematoma appears hyperintense, indicating a vertebral artery dissection, which has led to the reduction in the arterial lumen. (**c**) DWI B1000: restricted diffusion in the basal aspect of the right cerebellar hemisphere secondary to an acute infarct. (**d**) Coronal MIP reconstruction of CE-MRA of the supra-aortic vessels performed 3 months later, revealing near-complete resolution of the previously observed stenosis in the V2 segment of the right vertebral artery

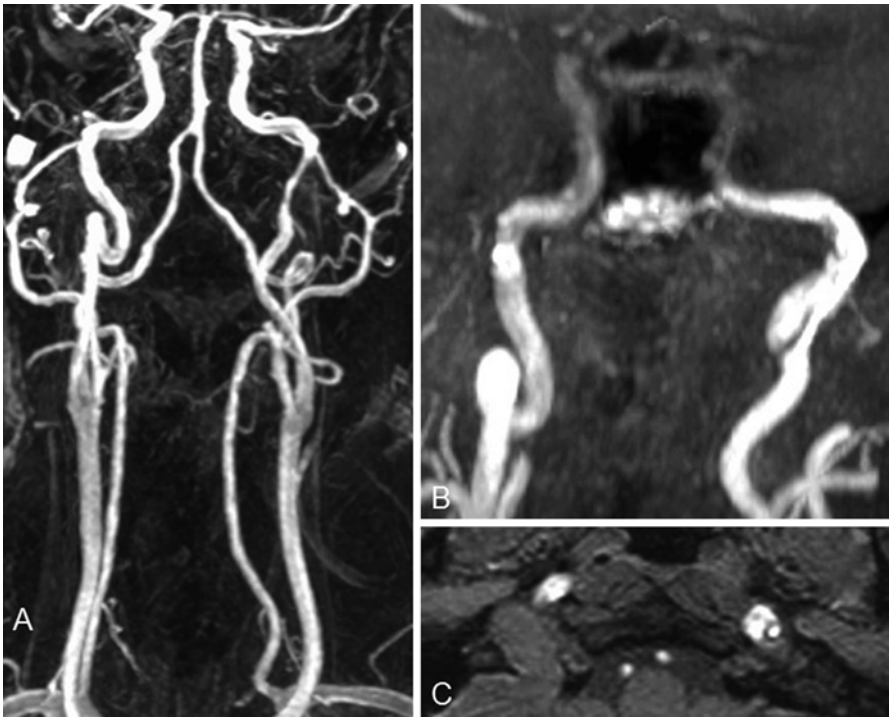

Fig. 23.4 (**a**) Coronal MIP reconstruction of CE-MRA of the supra-aortic trunk, revealing reduction in the diameter of the cervical portion of the left internal carotid artery. (**b**) Oblique-coronal MIP reconstruction of 3D TOF MRA of the intracranial and upper cervical segments of the carotid arteries, revealing an intramural haematoma and showing a double lumen. (**c**) Partition of a 3D TOF MRA sequence: the intramural haematoma appears hyperintense, indicating a carotid artery dissection, which has led to the reduction in the lumen of the internal carotid artery

Likewise, for carotid artery obstructions or critical stenoses, use of cine PC sequences enables evaluation of the flow direction in the arterial segments comprising the circle of Willis or in the ophthalmic artery, for use in determining their role in compensation in the distal vascular bed. Cine PC sequences are also valuable in cases of Subclavian Steal Syndrome, as they can reveal reversed flow in the vertebral artery ipsilateral to the subclavian stenosis.

Severe obstruction or stenosis of the prevertebral subclavian artery can be hidden behind other blood vessels. Therefore, detection of any occult stenoses requires MIP reconstruction of the MRA studies in different planes (Fig. 23.5).

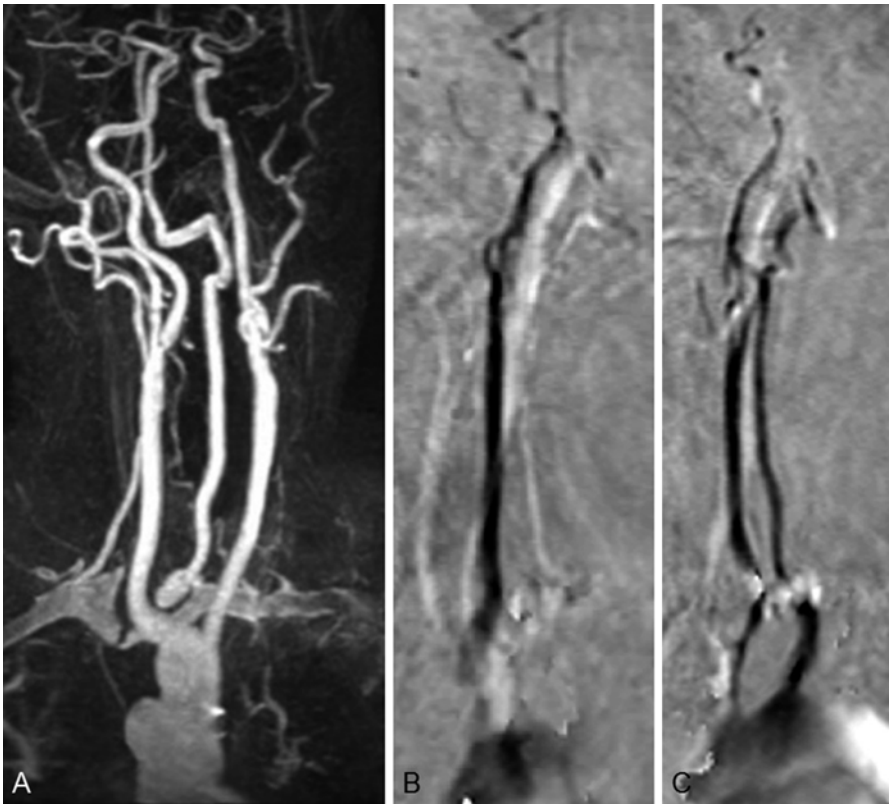

Fig. 23.5 (**a**) Oblique-coronal MIP reconstruction of 3D SPGR CE-MRA, evidencing obstruction of the prevertebral segment of the left subclavian artery. (**b**) Sagittal cine PC with superior-to-inferior flow encoding on the right axis: caudocranial venous flow appears hypointense (*dark*) and craniocaudal venous flow appears hyperintense (*light*). Cranial flow is observed in the right carotid axis and from the right verterbral artery, and craniocaudal venous flow is observed in the internal jugular vein. (**c**) Sagittal Cine PC with superior-to-inferior flow encoding on the left axis: cranial flow is observed in the left carotid axis; craniocaudal venous flow, in the internal jugular vein; and craniocaudal venous flow from the left vertebral artery indicates reverse flow in the vertebral artery

23.4 Basic Protocol for MRA of the Cranium and the Supra-aortic Vessels

23.4.1 Image Acquisition

23.4.1.1. Before entering the MR examination room, confirm that the patient does not have any contraindications to MR.

23.4.1.2. Describe the procedure to the patient. Remember that the patient's collaboration is fundamental: by ensuring that the patient does not move during the acquisition, the healthcare professional can minimise the

generation of artefacts in the image (these artefacts seriously degrade image quality).

23.4.1.3. Choose the appropriate head array coil and a neck array coil.

23.4.1.4. The contrast medium is administered via intravenous (IV) injection into the right arm, in order to prevent the brachiocephalic venous trunk causing any artefacts in the images of the aortic arch and the origin of the supra-aortic vessels.

23.4.1.5. Multiplanar localiser images

23.4.1.6. Sagittal cine PC or 2D PC MRA images of each carotid axis are acquired for use in planning the MRA examination.

23.4.1.7. To study the circle of Willis, choose the following axial 3D TOF volume (with saturation of craniocaudal venous flow) on the sagittal 2D PC localiser image: from the cavernous portion of the internal carotid arteries to beyond the anterior cerebral arteries.

23.4.1.8. To study the cervicocranial transition of the internal carotid artery (segments C2–C5), the V4 segment of the vertebral arteries, and the basilar artery, choose the following axial 3D TOF volume on the sagittal 2D PC localiser image: from below the V4 segment of the vertebral arteries to beyond the basilar artery.

23.4.1.9. Another option is to acquire a single MOTSA volume in the axial plane, from below segment V4 of the vertebral arteries to beyond the anterior cerebral arteries; however, in case of slow flow, there will be excessive phasing at the boundaries between slabs.

23.4.1.10. To study the carotid bifurcations in detail, choose the following axial MOTSA volume (with saturation of craniocaudal venous flow) on the sagittal 2D PC localiser image: from below the carotid bifurcations to the cervical portion of the internal carotid arteries.

23.4.1.11. Choose the CE-MRA volume (in the coronal plane) on the sagittal 2D PC localiser image, making sure to include the following area: from the aortic arch to above the C5 segment of the internal carotid arteries, in front of the C4 segments of the internal carotid artery and behind the vertebral arteries.

23.4.1.12. A 3D SPGR (CE-MRA) volume without contrast medium is acquired for use as a mask in subsequent subtraction studies. For the highest quality images, use the thinnest possible slice thickness.

23.4.1.13. The contrast medium bolus is injected by infusion pump (2 mL/s), followed by a saline flush (30 cc) to ensure that the contrast medium is pushed through the venous circulation. The standard gadolinium dose is 0.1 mmol/kg.

23.4.1.14. The authors of this chapter use the CARE (Combined Applications to Reduce Exposure) bolus technique to optimise arrival of the contrast medium bolus to the study area and synchronise it with the acquisition sequence. Another option is to run a test bolus in order in order to calculate the delay between the time of injection and the time of arrival. This is done by first injecting 1 mL of gadolinium, followed by a 20 mL

saline flush, while simultaneously performing a rapid acquisition (one low-resolution image per second) up to the area of interest. The delay is calculated using the following formula:

$$D = CT - Kt + (AT / 2)$$

Where D is the delay; CT is the circulation time; Kt is the time at the centre of K-space (specific value for each sequence); and AT is the acquisition time.

23.4.1.15. Acquisition of a 3D SPGR (CE-MRA) volume with contrast equal to the mask volume

23.4.1.16. Quality control of the acquired images: working directly from the acquisition console

Listed below are several basic parameters for different MRA sequences, the values of which must be adjusted according to the scanner used, as they depend on the magnetic field and gradient strength, the software used and the manufacturer (see Tables 23.4, 23.5 and 23.6).

23.4.2 Reconstruction and Manipulation of the Images

23.4.2.1. Once the images have been acquired, they must be processed.

23.4.2.2. The 3D volume must be manipulated at an independent workstation. This entails subtracting the masks from the images with contrast in order to obtain enhanced images. Subtractions are especially utile for studying highly peripheral vessels. Subtraction can also be performed directly at the acquisition console; the resulting images are then sent off for processing.

23.4.2.3. Reconstructions are performed using the technique of Maximum Intensity Projection (MIP), which provides images similar to those obtained with conventional angiography and enables visualisation of the vascular segments in different planes and orientations. If signal interference from vascular overlap complicates the arterial examination, then individual MIP reconstructions should be generated for each arterial segment.

23.4.2.4. In order to adequately assess the anatomical relationships among and between the different vascular structures, to characterise any plaque present or to identify a carotid aneurysm, an ulcerated plaque (see Fig. 23.6), intramural haematoma, intimal flap or mural thrombus, every partition of the acquired volume must be visualised. Plaque should not be confused with the typical artefacts caused by complex flow in the carotid sinus. These artefacts extend from the posterior wall of the artery to the central portion of the vessel lumina (Fig. 23.7).

23.4.2.5. Another post-processing option is to perform Multiplanar Volume Reconstruction (MPVR), which is especially useful for anatomical

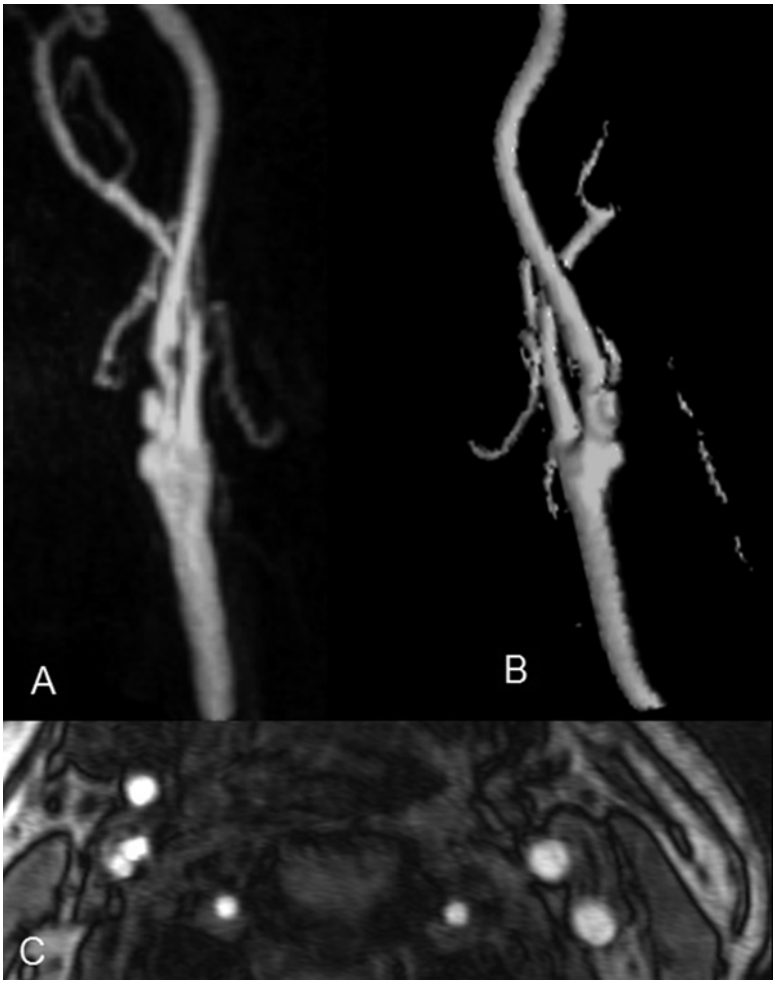

Fig. 23.6 (**a**) Oblique-coronal MIP reconstruction of CE-MRA, revealing an ulcerated plaque in the right internal carotid artery bulb. (**b**) Surface reconstruction, posterior view. This view provides better visualisation of the ulcer, thanks to the volume effect. (**c**) Partition of the MOTSA sequence, showing the double image produced by the arterial lumen and the ulcer crater in the posterior wall of the internal carotid artery

studies of complex vascular segments. This type of reconstruction also provides the measurements required for grading stenosis. To obtain the most accurate measurements possible with the software, the plane of study should be made perpendicular to the artery.

23.4.2.6. Surface reconstructions are another option for vascular imaging. Whilst they can exaggerate the grade of stenosis, they are invaluable for detecting ulcerated plaques or small aneurysms and for discovering concomitant occult stenosis in an arterial elongation.

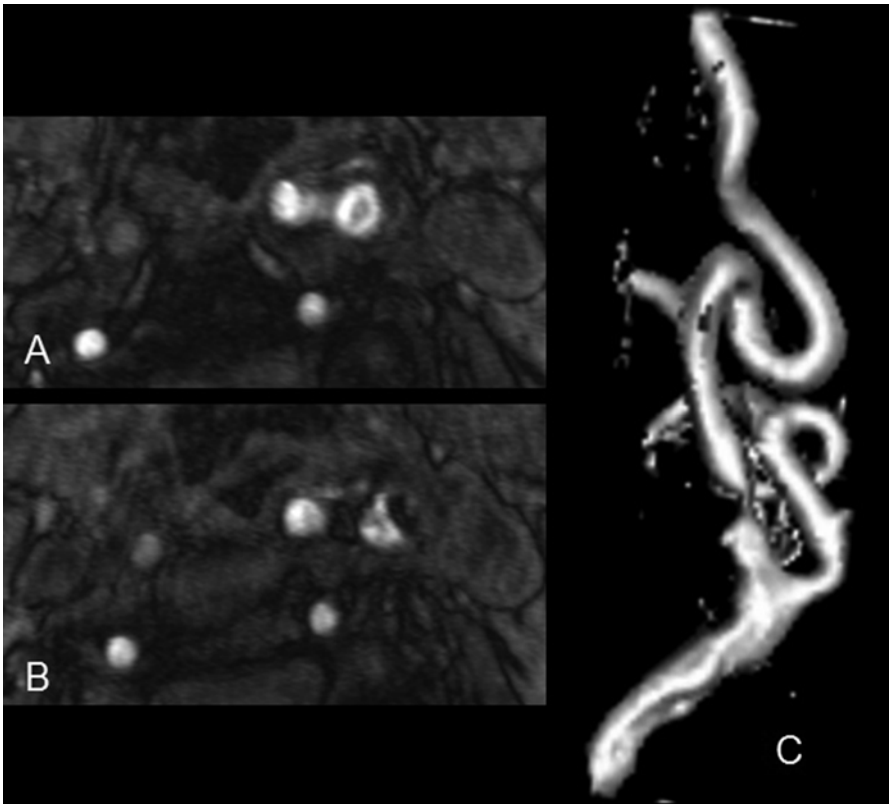

Fig. 23.7 (**a**) Partition of the MOTSA sequence, showing evidence of complex flow in the arterial lumen of the left carotid sinus. (**b**) Partition of the MOTSA sequence, showing a complex plaque formed by calcification (eccentric marginal hypointensity), a haemorrhagic plaque (central hyperintensity) and the residual lumen of the artery. (**c**) Surface reconstruction, lateral view: severe carotid artery stenosis

23.4.2.7. In order to avoid the errors inherent to collapse images, every partition must be closely examined. The partitions also provide information for characterising atherosclerotic plaques, as they can reveal signs of intraplaque haemorrhage, whether acute (hyperintensity) or chronic (hypointensity). One important factor to consider is that although MR is not sensitive to calcium (and therefore, cannot directly detect arterial calcifications), calcifications do appear hypointense in a characteristic signal on MR images (see Fig. 23.7).

23.4.2.8. The partitions also provide the arterial lumen diameter values for grading stenosis (based on percentage reduction in vessel diameter). Grading this way avoids the problem of overestimation of stenosis severity that occurs when grading based on MIP reconstructions (see Fig. 23.11). The most widely used grading method is the NASCET method, which is

based on measurement of the greatest reduction in vessel diameter (see Figs. 23.2 and 23.8).

23.4.2.9. Clinical symptoms in discordant anatomical regions might be caused by persistent carotid-vertebrobasilar anastomoses (persistent proatlantal, hypoglossal, trigeminal or otic arteries; see Fig. 23.9), which can be identified by following all the arterial courses and employing exclusively the criteria for locating stenoses. For example, this might correspond to

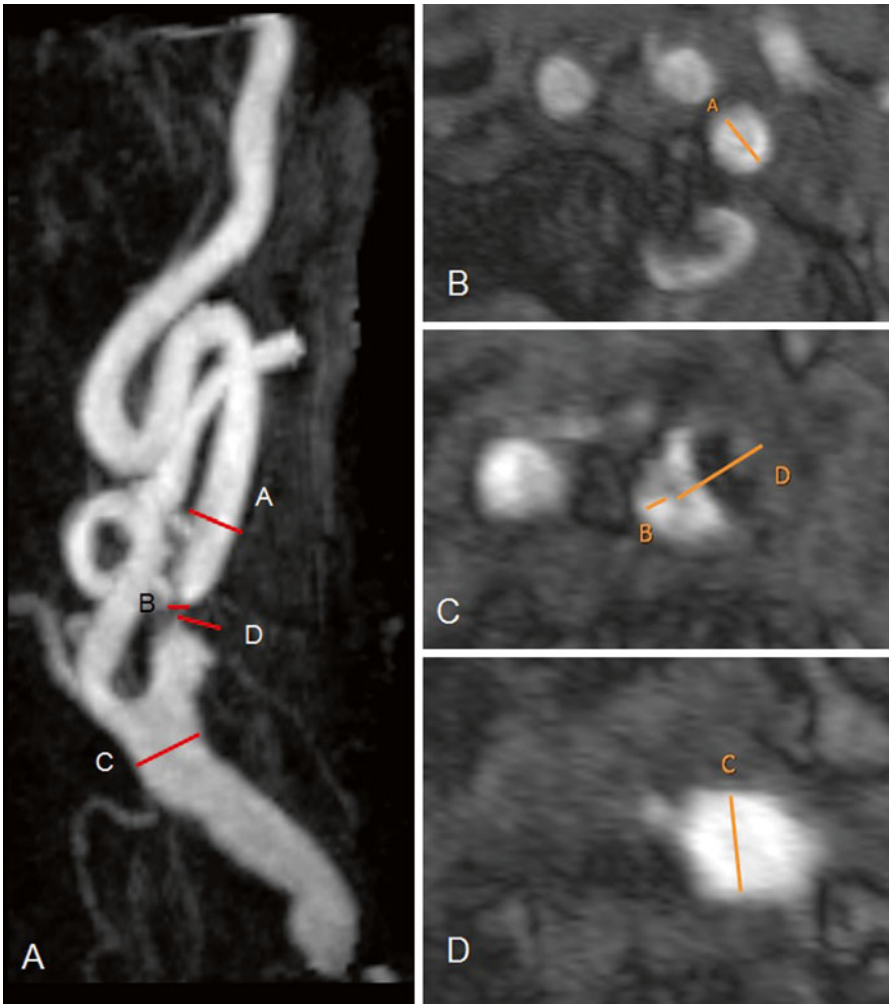

Fig. 23.8 Common methods for grading carotid artery stenosis. (**a**) Normal diameter of the internal carotid artery distal to the stenosis. (**b**) Diameter of the minimum residual lumen. (**c**) Visually estimated diameter of the internal carotid artery. (**d**) Diameter of the common carotid artery. Formulas for grading carotid artery stenosis: 1. NASCET: (A–B)/A × 100 % stenosis, 2. ECST (D–B)/D × 100 % stenosis, 3. Common Carotid: (C–B)/C × 100 % stenosis

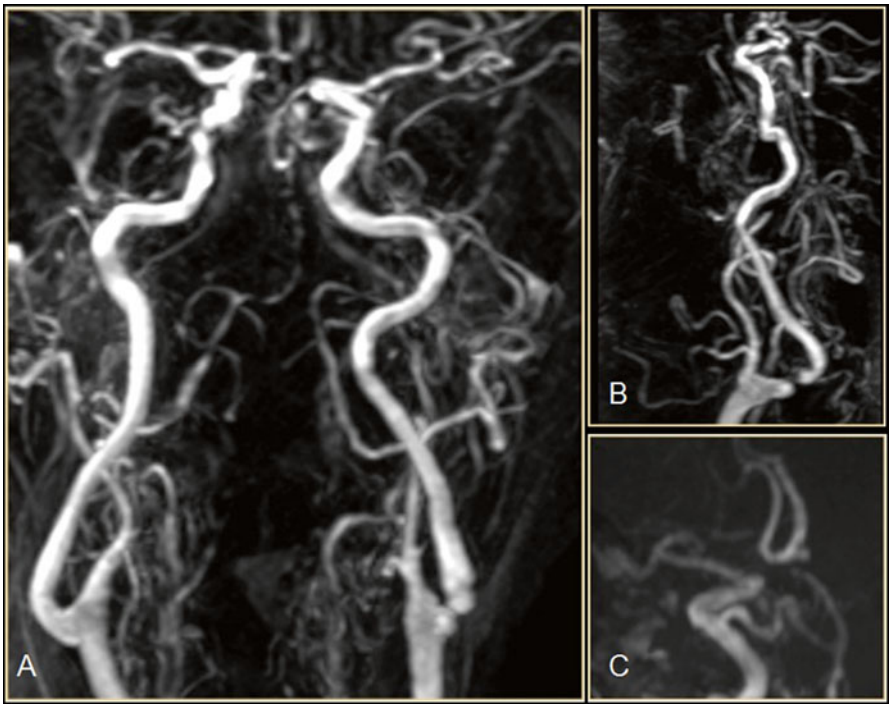

Fig. 23.9 (**a**) Coronal MIP reconstruction of CE-MRA, revealing marked hypoplasia of the V4 segment of the vertebral arteries, distal to the posterior internal cerebellar artery. (**b**) Sagittal MIP reconstruction on the left carotid axis, revealing a pre-obstructive stenosis of the left internal carotid artery. (**c**) Sagittal MIP reconstruction: identification of a persistent trigeminal artery that anastomises the intracavernous portion of the left internal carotid artery to the basilar artery

an infarct in the posterior region in patients with severe stenosis of the internal carotid artery and concomitant persistent trigeminal artery.

23.4.2.10. For patients with carotid or vertebral artery stenosis, differential diagnosis should take into account the presence of other vascular risk factors, history of clinical intervention or radiotherapy, imaging criteria (based on the lesion type and morphology), concomitant lesions, the arterial area affected, systemic illness, etc. Thus, for patients with atherosclerotic carotid artery stenosis, differential diagnosis should take into consideration other arterial diseases that can lead to stenosis or obstruction of the carotid or vertebral arteries, such as neurofibromatosis type 1 (NF1); Marfan syndrome; Ehlers-Danlos syndrome; collagen diseases (such as lupus erythematosus); antiphospholipid syndrome; actinic stenosis secondary to a locoregional procedure with previous radiotherapy or due to invasion of an adjacent tumour; dissection in the vertebrobasilar sector; or any of the various forms of fibromuscular dysplasia (Figs. 23.10 and 23.11).

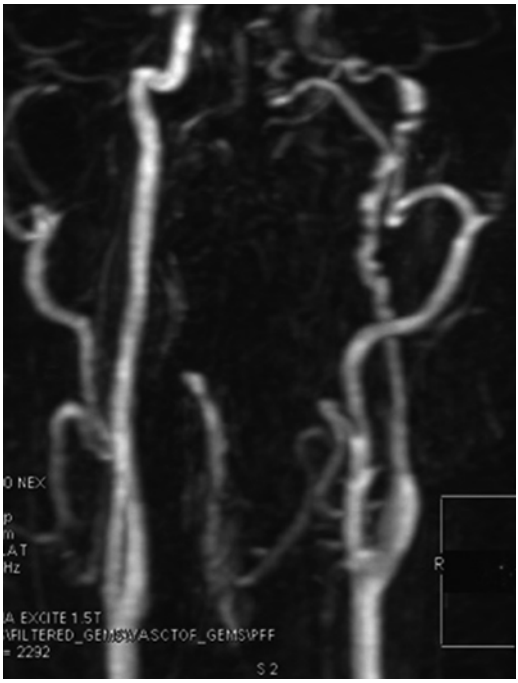

Fig. 23.10 Coronal MIP reconstruction of CE-MRA: the classic "string of beads" appearance indicates a fibromuscular dysplasia affecting the cervical portion of the left internal carotid artery

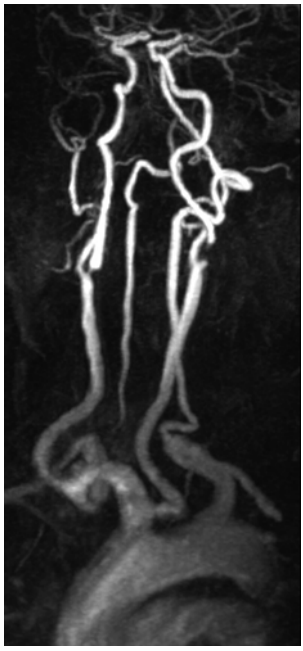

Fig. 23.11 Coronal MIP reconstruction of CE-MRA, showing bilateral stenosis of the internal carotid arteries. The grade of the left stenosis is overestimated (from severe stenosis to segmental obstruction) due to turbulent flow; however, this will not alter the course of treatment

23.5 Black-Blood Techniques

The vessel lumen appears hypointense, whereas the vessel wall appears hyperintense. These techniques are excellent for studying vessel walls. Used to study arterial dissections, to reveal intramural haematomas, ulcers or aortitis, and to analyse atheromatous plaques.

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