Time Resolved 3D MRA. Applications for Interventional Neuroradiology

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Summary

The decision for endovascular treatment of cranial dural AV fistulae and angiomas and their follow-up after treatment is usually based on conventional DSA. New techniques of magnetic resonance angiography (MRA) facilitate high temporal and spatial resolution images. The purpose of this study was to evaluate the applicability and clinical use of a newly developed 3D dynamic MRA protocol on a 3T scanner for neurointerventional planning and decision-making.

Using a 3T whole body scanner, a three-dimensional dynamic contrast enhanced MRA sequence with parallel imaging, and intelligent k-space readout (Keyhole and "CENTRA" k-space filling) was added to structural MRI and time-of-flight MRA in seven patients. DSA was performed in each patient following MR examination.

In all patients MRA allowed the identification and correct classification of the vascular lesion. Hemodynamic characteristics and venous architecture were clearly demonstrated. Larger feeding arteries could be identified in all cases. Smaller feeding vessels were overlooked in dynamic MRA and only depicted in conventional DSA

High temporal and spatial resolution 3D MRA may correctly identify and classify fistulae and angiomas and help to reduce the number of pre- or post-interventional invasive diagnostic angiograms.

Introduction

The choice of treatment for many cranial vascular malformations such as arteriovenous malformations (AVMs) and AV fistulae (AVFs) is often via an endovascular route. The indication for treatment and the decision for the best treatment strategy (surgical, radiation or interventional) is usually based on conventional DSA findings. Moreover, in the follow-up of treated vascular malformations, DSA is typically necessary to rule out a remaining arteriovenous shunt. Although magnetic resonance angiography (MRA) has significantly improved with contrast enhanced techniques and ultra-fast imaging strategies, conventional DSA still offers higher temporal and spatial resolution. However, due to patient safety, time and cost restraints, it is desirably to reduce the number conventional angiographies.

Recent developments in MR techniques facilitate high temporal and spatial resolution MRA. Two dimensional projection imaging techniques achieve a temporal resolution below one second¹. These techniques have the disadvantage that no multiplanar view of the lesion is possible, which is essential for the identification of feeding vessels.

With parallel imaging and special k-space filling strategies, three dimensional dynamic contrast enhanced MRA has become feasible^{2,3,4} with a temporal resolution around 1.5 - 2 seconds per frame. Though the in-plane resolution of these techniques was comparably high

(1.2-1.6 mm), the through-plane resolution was often limited. The reason for this limitation is a) the SNR decrease with increasing spatial resolution and parallel imaging acceleration factors, and b) the occurrence of specific artefacts and inhomogeneously distributed noise from parallel imaging.

We tested a new 3D MRA protocol on a 3 T scanner with sixfold accelerated parallel imaging (SENSE) in combination with dynamic keyhole-k-space-filling and CENTRA (contrast-enhanced timing-robust angiography)⁵. The purpose of this study was to evaluate its applicability with regard to neurovascular diseases, and specifically to compare the results of this technique to conventional DSA findings.

Methods

MRA protocol

All examinations were performed on a 3T whole body scanner (Philips Achieva 3.0T Quasar Dual, Philips Medical Systems, Best, The Netherlands) using an eight channel sense-head coil, which allows up to eight times accelerated parallel imaging.

3D MRA

A 3D fast field echo (FFE) sequence was applied with a 224 x 512 Matrix on a FOV of 290 mm with a rectangular field of view of 75%. TR and TE was 3.8 ms and 1.34 ms and the flip angle was 30°. 100 images were acquired with a slice thickness of 1.5 mm using overcontiguous slices to cover the whole head. The acquired spatial resolution was 1.29 x 1.29 x 3 mm and the reconstructed voxel size was 0.566 x 0.566 x 1.5 mm. A total of 16 dynamic scans were performed. Parallel imaging was performed with an acceleration factor of 4.0 in the in-plane phase encoding direction and 2.0 in the through plane phase encoding direction resulting in an overall sixfold acceleration.

With parallel imaging only a single dynamic scan time still requires more than five seconds. For further acceleration we used keyhole-k-space filling⁶ with a percentage of 25% and acquisition of the reference scan at the last dynamic. Keyhole imaging was further combined with CENTRA (contrast-enhanced timing-robust angiography)⁵ k-space sampling to provide high contrast with a minimum of artefacts. A single dynamic scan took 1.3 seconds and the overall scanning time was 25.2 seconds includ-

ing the dynamic reference scan which took 5.8 seconds. Contrast medium was immediately injected when starting the measurement.

We used a bolus of 0.1 mmol/kg body weight gadoben acid-dimeglumine (Multihance, Altana, Konstanz, Germany). Contrast bolus was administered manually at an injection rate of approximately 3 ml/s. A second bolus of 30 ml saline was administered immediately. The post processing includes automatic orthogonal maximum intensity projections of every dynamic phase, in addition multiplanar reconstructions in the desired plane (and desired dynamic) were performed using the scanner software.

Time of flight angiography and structural imaging

In addition to standard structural imaging including FLAIR, T2 TSE, T1 SE and T1 IR, flow sensitive standard MRA techniques employing a time of flight technique were applied.

The TOF sequence was optimized in daily clinical routine for imaging of aneurysms or fistulae. The 3D FFE sequence had a field of view of 200 mm x 200 mm. 148 slices were acquired with a thickness of 0.5 mm. The acquired voxel size was 0.25 x 0.49 x 1 mm and the reconstructed voxel size was 0.2 x 0.2 x 0.5 mm. Repetition time was 25ms, echo time 3.45 ms and flip angle 20°. Parallel imaging was performed with acceleration of 2.5 in the in-plane phase encoding direction and no acceleration in the through-plane direction. The scanning time was 7:15 minutes.

DSA

Conventional x-ray angiography was performed on a biplanar system (Siemens Neurorstar, Siemens Medical Systems, Erlangen, Germany) with a FOV of 22 cm and three or four frames per second depending on the clinical question.

Standard 5 F diagnostic catheters were used with manual contrast injection of 5-10 ml of a 300 mg I/ml contrast agent (Solutrast 300, Altana, Konstanz, Germany).

Subjects

Seven consecutive patients were included in this series, with aged ranging from ten to 64 years (mean 41.4 years). Four patients were suspected to have a cranial AV fistula from clinical complaints and external structural imaging. Two angioma patients who were pre-

treated with radiation therapy (gamma-knife) ten and two years prior to the control admission and one patient who was suspected to harbour an AVM were also imaged. Dynamic MRA was performed in each patient before conventional DSA.

Image analysis

Two experienced neuroradiologists analysed both the MR and DSA images qualitatively and made a consensus decision. MRA images were postprocessed at the scanner with simple rotating maximum intensity projections.

Fistula patients were analysed with regard to:

1. Location
2. Flow pattern
3. Grade of fistula
4. Visualization of feeders

Angioma patients were analysed for

1. Size and location
2. Feeders
3. Additional pathology (aneurysm, venous stenosis/ectasia)
4. Drainage pattern

Table 1 MRI, MRA and DSA findings. The fourth column lists the findings of dynamic MRA compared to structural MRI and TOF MRA. The right column shows the additional findings of DSA compared to dynamic MRA.

No Patient	Diagnosis	Findings: Structural MRI/TOF	Additional findings: Dynamic MRA	Additional findings: Conventional DSA
1	Type I-single hole dural avF	Dilated confluents	Type I-fistula, feeders from both occ. aa.	1 additional feeder from left occ. artery
2	Type I dural avF	Pathologic arterial vessels on TOF	Type I-fistula, feeders of both occ. aa.	Small feeders from proximal left occ. artery, small feeder from left middle meningeal artery
3	Type II a+b complex dural avF	Multiple dilated vessels in the brain and surface	Type II a+b-fistula with reverse intrasinusoidal flow, venous congestion, multiple large feeders from both ECA	Smaller feeders from: - both vertebral aa. (posterior meningeal) - both ICA (meningohypophyseal tr.)
4	Type II a+b complex dural avF	White matter edema	Type II a+b fistula, occlusion of both sigmoid sinus, feeders from left ECA	Small feeders from ECA, ICA, left vertebral, venous drainage through pterygoid sinus
5	Left central high flow angioma, pre treated with gamma-knife	Flow voids, glomerular portions of AVM	High-flow residual angioma, Feeders from left MCA and ACA	No additional information
6	Left hem. Angioma	Dilated veins	AVM with feeding from posterior choroidal artery. Venous stenosis and drainage into internal veins	No additional information
7	Right temporal pre-treated angioma	Slight contrast enhancement, no flow voids	No hint for residual angioma	No additional information

Figure 1 Ten-year-old patient with single-hole type I fistula. Upper row, left: T2 w image shows dilated confluents. Middle: TOF angiography shows single arterial feeders. Right: MIP of dynamic MRA shows large arterial feeders and orthograde flow in the right transverse sinus. Middle row: MIP images of dynamic MRA. Lower row: AP views of conventional DSA of right and left ECA.

Figure 2 Type I-Fistula in a 62-year-old woman. Left: Dynamic MRA: No retrograde flow could be identified. Lateral maximum intensity projection shows major (arrowheads) and minor (small arrows) feeders arising from the right occipital artery. Right: Conventional DSA of the ECA confirms orthograde flow in the sinus and shows additional smaller feeders, especially in the proximal portion of the occipital artery.

Results

In all patients, MR angiography with bolus contrast injection was feasible and adequate diagnostic images were obtained. Depending on individual circulation time, the first two to five dynamic scans showed no contrast before the arrival of the contrast bolus. Table 1 shows the findings of structural MR and TOF MRA, additional findings of dynamic MRA and additional findings of conventional DSA in each patient.

AV Fistulae

Patient 1 presented with chronic headache at the age of 10 years. The clinical history was otherwise empty. An external MRA showed a dilatation of the venous confluens (figure 1). Time-of-flight angiography shows feeding arteries of the fistula. Dynamic MRA showed multiple feeders of the fistula converging at one point of the confluens with orthograde flow in the right transverse sinus. Despite the aspect of a single hole AV fistula in a child, there were no further hints indicative of a genetic disease such as hereditary hemorrhagic telangiectasia (HHT). The fistula was com-

pletely occluded with transarterial glue embolization. Following occlusion of the fistula, the headaches initially worsened for one week followed by a near-complete remission. On follow-up four months after the embolisation, the child no longer complained of headaches.

Patient 2 presented with typical pulse-synchronous tinnitus and right occipital headache. Dynamic MRA showed different feeders of the fistula (figure 2), but small proximal feeders were only visible on the conventional DSA. Transarterial embolization employing particles was carried out leading to complete occlusion of the fistula on immediate post-angiographic controls. The patient has now been symptom-free for six months and a follow-up is scheduled.

Patient 3 suffered from intermittent diplopia and long-lasting headache. Initial structural MRA showed pathologic vessels surrounding especially the right hemisphere (figure 3). Dynamic MRA showed a complex type III fistula. Feeders from the ECA and vertebral arteries could be identified. Conventional DSA showed many additional small feeders from both ICA

Figure 3 Type II a+b-Fistula in a 59-year-old woman. Left upper: T2w image shows multiple dilated veins at the tentorium, cerebellum and right hemisphere. Middle and right upper: Conventional DSA of the right ECA (middle) and vertebral a. (right) shows multiple feeders and reverse flow pattern in the superior sagittal and straight sinus. Collateral veins and signs of venous congestion are visible. Lower row: Sagittal MIP of dynamic MRA shows feeders from the vertebral artery and reverse flow pattern as well as venous congestion.

and ACA, including the middle meningeal artery. The fistula was treated by two embolization sessions, and a residual fistula was treated by radiotherapy. Follow-up is scheduled.

Patient 4, a 63-year-old woman, presented with progressive headache for three years and recently developed ataxia. Structural MRI was suspicious of oedema (figure 4). Dynamic MRA depicted a fistula from the left occipital artery with reverse flow in the sigmoid sinus and the internal veins. Occlusion of right distal transverse sinus and left sigmoid sinus was clearly depicted. Conventional DSA showed additional smaller feeders from the left ECA. The fistula was successfully treated with particle embolization resulting in an immediate amelioration of the headaches. A follow-up visit is scheduled.

Angiomas

Patient 5 had a known and pre-treated angioma in the left central region (figure 5). After the last treatment ten years ago, paresis of the right hand had exacerbated within months. The patient is now undergoing staged embolization treatment employing glue.

Patient 6 underwent MRI because of headache. In structural images, pathologic vessels were seen in the right parahippocampal region and an AVM was suspected. Dynamic angiographic images showed early venous filling with a venous aneurysm and venous stenosis leading into the basal vein of Rosenthal. Dynamic MRA showed the supplying posterior cerebral artery and the early filling veins. DSA

Figure 4 59-year-old woman with type II a+b dural avF. Top left: FLAIR image shows white matter oedema. Coronal maximum intensity projection of dynamic MRA (lower row) shows a fistula in the left sigmoid sinus, which is distally occluded. Reverse flow in the right transverse sinus into superficial veins (double arrow) is clearly depicted and correlates exactly to the DSA image (upper row, middle image). Selective lateral DSA of the ECA shows multiple small feeders from the ECA (right upper image).

showed no additional findings. The patient underwent radiotherapy.

Patient 7 had a known temporal AVM which had been treated with gamma-knife two years prior to the control admission. Contrast-enhanced MRA was performed and showed no pathologic vessels, especially no early draining vein. DSA confirmed the complete occlusion of the AVM.

Discussion

The aim of magnetic resonance angiography in fistulas and angiomas must be the correct classification of a lesion, which is essential to evaluate the treatment indication. To spare an invasive diagnostic work-up (DSA), MRA

should give further information about the particular features of a lesion with regard to the treatment method of choice. At best, MRA should give enough information for concrete planning of an interventional procedure.

Recent developments of magnetic resonance technology have improved contrast-enhanced dynamic MR angiography. There are mainly three different technical aspects, which lead to enhanced spatial and temporal resolution as well as to increased SNR.

1. Parallel imaging. The classical, sensitivity encoding method theoretically allows acceleration factors of 32 and more, but inhomogeneous noise distribution and a general decrease of SNR leads to severe image deterioration. At present, acceleration factors of four to eight seem to be the upper reasonable limit.

Figure 5 34-year-old woman with left central angioma. Top left: FLAIR image with flow voids. Right: DSA after injection in the left ICA. Lower row: dynamic MRA MIP images (left: lateral, right posterolateral) illustrating feeding vessels and venous drainage.

2. K-space acquisition methods. For dynamic imaging, keyhole k-space filling provides further acceleration at an acceptable loss of SNR. There are many different strategies to fill the centre of k-space.

We used the CENTRA method in combination with keyhole to provide a more homogeneous representation of the contrast bolus in the dynamic images.

3. Field strength. 3Tesla offers higher signal to noise ratios.

In our study, the examined vascular lesions could all be correctly diagnosed and classified.

Especially the four fistulae could correctly be graded, which is essential for therapeutic decision and further invasive diagnostic procedures.

The major feeders of these lesions could be correctly identified by MRA. However, small feeders with low diameter and flow are usually overlooked in MRA. This may be due to two reasons. First, the spatial resolution of MRA is

insufficient compared to the small feeders of a dural AVM. Second, smaller feeders may be overlooked when only MIP reconstructions are used. The case with the type III fistula with simultaneous filling of multiple feeders of different arterial territories illustrates the difficulties to assign small feeders to their correct origin.

However, in all four fistula patients MRA was sufficient to classify the lesion and identify the major feeders of the fistulas. Conventional DSA showed further smaller feeders. Interventional procedures in these patients were targeted on the major feeders, which were all visible on MRA. One type II a+b fistula patient (no.3) had to be further treated with radiation therapy because safe distal catheterization of the small feeders could not be obtained.

This may indicate that our MRA protocol is sufficient to correctly diagnose high-flow fistulas and estimate the access for an interventional therapy.

Angiomas can be sufficiently visualized concerning location and size and major feeders. From this standpoint, MRA is sufficient to decide which treatment strategy (interventional vs surgical vs radiation) is appropriate. The exact angioarchitecture of an angioma especially in a high flow-situation (Case no.5), however, may not clearly be evaluated with a temporal resolution above one second.

For follow-up studies of angiomas after radiation therapy, dynamic MRA seems to be suitable to answer the question of complete occlu-

sion of the lesion. In our institution a minimum of three conventional angiograms is necessary for treatment planning and control of an angioma. With dynamic MRA, this number may be reduced.

This small series should be considered a preliminary description of a new technique potentially helpful for interventional neuroradiologists. Since only high flow fistulae were included, a word of caution concerning low flow fistulae must, however, be stated. It is not yet clear whether this technique also enables identification of these lesions, although we think that it should also be possible to use the hemodynamic information of this technique to identify those lesions.

Conclusions

With time-resolved 3D MRA high-flow dural AV fistulas and angiomas may be correctly diagnosed and classified. Major feeders can be identified which allows planning of interventional access. Small feeders, especially in dural AVFs are still overlooked at the present spatial resolution.

This technique enables the neurointerventionist to

- identify and classify a lesion
- identify major feeders
- develop a treatment strategy
- spare invasive diagnostic techniques (DSA) for follow up

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