Three-Dimensional Dynamic MR Digital Subtraction Angiography Using Sensitivity Encoding for the Evaluation of Intracranial Arteriovenous Malformations: A Preliminary Study

Jean-Yves Gauvrit, Xavier Leclerc, Catherine Oppenheim, Thierry Munier, Denis Trystam, Henda Rachdi, François Nataf, Jean-Pierre Pruvo and Jean-François Meder

*AJNR Am J Neuroradiol* 2005, 26 (6) 1525-1531

http://www.ajnr.org/content/26/6/1525
Three-Dimensional Dynamic MR Digital Subtraction Angiography Using Sensitivity Encoding for the Evaluation of Intracranial Arteriovenous Malformations: A Preliminary Study

Jean-Yves Gauvrit, Xavier Leclerc, Catherine Oppenheim, Thierry Munier, Denis Trystram, Henda Rachdi, François Nataf, Jean-Pierre Pruvo, and Jean-François Meder

BACKGROUND AND PURPOSE: Our aim was to develop 3D dynamic MR digital subtraction angiography with high temporal resolution without sacrificing spatial resolution by using sensitivity encoding for the evaluation of cerebral arteriovenous malformations.

METHODS: Nineteen patients with 19 angiographically proven arteriovenous malformations (16 supratentorial and 3 infratentorial) were assessed by conventional catheter angiography and 3D dynamic MR digital subtraction angiography. A 3D contrast-enhanced gradient-echo sequence with sensitivity encoding based on a parallel imaging technique was performed and acquired 20 dynamic images, repeated 18 times every 1.7 seconds. Three-dimensional dynamic MR digital subtraction angiograms were analyzed independently by two radiologists in a blinded fashion with regard to arteriovenous malformation nidus and venous drainage. Conventional catheter angiography was used as reference.

RESULTS: All MR imaging examinations were assessable. Interobserver agreement was excellent for the detection of nidus and for the evaluation of nidus size (κ = 1 and 0.875, respectively) but moderate for the visualization of the venous drainage (κ = 0.56). All nidi detected on conventional catheter angiography were clearly depicted on 3D dynamic MR digital subtraction angiography. The evaluation of the size of the nidus by both techniques was similar. On 3D dynamic MR angiograms, veins were correctly analyzed in 17 of 19 arteriovenous malformations.

CONCLUSION: Our preliminary study demonstrates that 3D dynamic MR digital subtraction angiography using sensitivity encoding with a high spatial resolution is appropriate for the assessment of arteriovenous malformations.

MR angiography with high spatial resolution is used as a noninvasive alternative to conventional angiography for the assessment of cerebral arteriovenous malformations. The 3D time-of-flight technique is considered the method of reference for the noninvasive assessment of intracranial vasculature. In cases of cerebral arteriovenous malformation, this technique is useful for the evaluation of feeding arteries and for the detection of extranidal aneurysms (1, 2). However, accurate delineation of the nidus and venous drainage remains poor on 3D time-of-flight MR angiography because of saturation effects that may be responsible for a decreased signal intensity in capillaries and veins.

Two-dimensional dynamic MR digital subtraction angiography has recently been developed to circumvent this drawback. It combines the T1 shortening effect of gadolinium, subsecond images, and the digital subtraction technique, allowing high temporal resolution MR angiograms (1–5). It provides hemodynamic information similar to that obtained by conventional catheter angiography with separation of arterial and venous phases of angiography. Previous reports showed the potential interest in 2D dynamic
MR digital subtraction angiography was performed for the diagnosis of arteriovenous malformations and for follow-up of stereotactic radiosurgery (1, 2, 4, 6–8). In particular, MR imaging plays an important role in the evaluation of the decrease of nidus size and/or disappearance of venous drainage.

Two-dimensional dynamic MR digital subtraction angiography has also been successfully used for the identification, classification, and follow-up of dural arteriovenous fistulas (2, 6, 9–11) and for the depiction of cervical and intracranial arteries (12). However, this method has several limitations, including poor visualization of small vessels or shunts because of partial volume effects, 2D acquisition with a large section thickness, and limited spatial resolution. Recent developments using multiple surface coils and parallel imaging methods such as sensitivity encoding allow a decrease in imaging time and the maintenance of spatial resolution (13–18). Current clinical applications, such as imaging of arteriovenous malformation nidus and venous drainage, that can benefit from these techniques mainly require sequential repeated images of the same plane with optimization of temporal resolution.

In this preliminary study, we investigate a 3D dynamic MR digital subtraction angiography sequence combining sensitivity and gradient encoding for arteriovenous malformation assessment.

### Methods

#### Subjects

From September 2003 to March 2004, 45 consecutive patients underwent conventional catheter angiography for a cerebral arteriovenous malformation. Only patients with a nidus size 1 cm and without residual arteriovenous fistulas were included. In fact, 19 patients (10 men and 9 women; age range, 19–62 years; mean age, 37 years) were studied and underwent conventional catheter angiography and 3D dynamic MR digital subtraction angiography with a time interval between examinations of <48 hours. Sixteen arteriovenous malformations were located on the supratentorial circulation (6 frontal, 2 parietal, 3 temporal, 3 occipital, 1 basal ganglia, and 1 corpus callosum) and 3 on the infratentorial circulation. The neurological initial presentation was intracranial hemorrhage (4 cases), seizure (3 cases), and headache (3 cases) (2). The remaining patients (10 cases) were asymptomatic.

Twelve patients had one patent arteriovenous malformation without previous treatment. The remaining 7 cases had arteriovenous malformations partially obliterated after an embolization treatment (3 cases), linear accelerator radiosurgery (3 cases), or both treatments (1 case). Posttreatment studies were performed from an average of 35 months (range, 12–61 months) after the radiosurgery (19).

#### MR Imaging

MR imaging was performed on a 1.5-T superconducting system (Signa Excite Echospeed, GE Healthcare, Waukesha, WI) with 33 mT/m gradient strength, used in conjunction with a multi-elements head coil with an 8-channel-receiver radiofrequency system. Patients were positioned with a 20-gauge intravenous catheter inserted into the antecubital vein. All patients were referred for MR imaging in line with accepted clinical practices at our institution. Routine MR imaging including pre- and postcontrast T1-weighted spin-echo and T2-weighted fast spin-echo imaging was performed.

Three-dimensional dynamic MR digital subtraction angiography with array spatial sensitivity encoding techniques was performed in the sagittal and coronal planes. Twenty dynamic images were obtained to track the contrast bolus. One frame of 20 dynamic images per 1.7 seconds was repeated 18 times. Imaging parameters for the dynamic images were the following: TR/TE/flip angle, 3.6/1.4/25°; 300 × 300 mm field of view; 320 × 192 acquisition matrix; section thickness of 10 mm with 20 overlapped sections resulting in a 1-cm-thick volume; and a 166.6-kHz bandwidth. Spatial resolution was 0.9375 × 1.562 × 10 mm² and 0.58 × 0.58 × 5 mm² after zero-filling interpolation. The coil was used for fourfold array spatial sensitivity encoding techniques reduction along the left–right phase-encoding direction for coronal scanning and along the anteroposterior phase encoding direction for sagittal scanning.

Three-dimensional dynamic MR digital subtraction angiography was initiated 5 seconds after the start of a 10-mL gadolinium (Dotarem, Guerbet, France) bolus administered intravenously at a rate of 3 mL/s using a Spectris power injector (Medrad, Indianola, PA) followed by a 10-mL saline flush. A separate contrast bolus was used for each anatomic plane. MR angiographic source images were transferred to a workstation (Advantage Windows 4.1, GE Healthcare, Buc, France). Image processing included subtraction of the first volume from the series and reconstruction of the maximum intensity projection obtained and consisted of lateral and anteroposterior projections. The time required for each examination was about 12 minutes, including 2 minutes for both acquisitions (sagittal and coronal) and 10 minutes to generate subtracted angiographic images.

#### Conventional Catheter Angiography

Conventional catheter angiography was performed within 2 days after 3D dynamic MR digital subtraction angiography (Integris BV3000, Philips Medical Systems, Best, the Netherlands), with a 4-French catheter via a femoral artery approach with a filming rate of 2 and 3 images per second. Follow-up angiography included a selective injection of internal and common carotid or vertebral arteries in the frontal and sagittal views completed by additional views when necessary. Images were printed with a 512 × 512 matrix and a field of view of 17 cm. For each projection, an 8- to 16-mL bolus of iodinated contrast material (iobitridol, Xenetix, Guerbet, France) was injected at a rate of between 3 and 6 mL/s using a power injector.

#### Image Evaluation

Two neuroradiologists (C.O., J.-Y.G.), both blinded to the results of either study but with knowledge of the medical history and the clinical score, independently reviewed the 3D dynamic MR digital subtraction angiography images. The observers were blinded to the conventional catheter angiography results. Conventional angiograms were reviewed by two other neuroradiologists (H.R., J.-F.M.), who were unaware of the 3D dynamic MR digital subtraction angiography findings.

Three-dimensional dynamic MR digital subtraction angiography image contrast was graded as low when the signal intensity in the enhanced arterial lumen was only slightly higher than the signal intensity in the background, moderate when the signal intensity was clearly higher, and high when the signal intensity was significantly higher.

Cerebral arteriovenous malformation size was analyzed in 3 projections (craniocaudal, anteroposterior, and lateral views), but only the largest dimension of the nidus was provided according to Spetzler and Martin’s classification (21) and then was classified into 1 of 3 groups: small (<3 cm, medium (3–6 cm), and large (>6 cm).

The venous drainage of arteriovenous malformations was recorded as deep, superficial, or superficial and deep.

We
defined the drainage as “superficial” when veins drained into the cortical venous system and as “deep” when veins drained into the vein of Galen or the straight sinus.

Statistical Analysis

All statistical studies were performed using MedCalc software (Mariakerke, Belgium). The first step of the analysis was an evaluation of the level of interobserver agreement for each set of 3D dynamic MR digital subtraction angiograms by means of the $\kappa$ statistic. The second step consisted of a comparison between 3D dynamic MR digital subtraction angiograms and conventional catheter angiograms for the detection of nidus and venous drainage and for the evaluation of the size of the nidus using the same statistical tests. Kappa values 0.6 suggested a substantial agreement, and values 0.8 indicated an excellent agreement. $P$ values $<.05$ were regarded as significant.

Results

On conventional catheter angiography, 19 arteriovenous malformations were seen in 19 patients. No patient had multiple arteriovenous malformations. Nineteen nidi were clearly demonstrated on conventional catheter angiography.

Image Quality

Successful 3D dynamic MR digital subtraction angiograms were obtained in all patients. The overall image quality of 3D dynamic MR digital subtraction angiograms was judged high in 18 patients and moderate in 1 patient; the moderate quality did not prevent interpretation.

Interobserver Agreement

Interobserver agreement was excellent for nidus detection and nidus size, ($\kappa = 1$ and $0.875$, $P = .22$, respectively) and moderate for the venous drainage ($\kappa = 0.56$, $P = .12$). Discrepancies between the 2 examiners were noted in 1 case for the evaluation of nidus size and in 5 cases for the visualization of venous drainage. In these cases, an additional reading by both examiners was performed to reach a consensus.

Intertechnique Agreement (Figs 1–2)

As indicated in Table 1, of the 19 arteriovenous malformations assessed in 19 patients, 19 nidi were clearly demonstrated on 3D dynamic MR digital subtraction angiography.
Nidus Size

There was complete agreement (κ = 1) between conventional catheter angiography and 3D dynamic MR digital subtraction angiography for classification of nidus size: 14 nidi were classified as small, 4 as medium, and 1 as large.

Venous Drainage

Of 19 arteriovenous malformations, conventional catheter angiography showed deep venous drainage in 11 cases and exclusively superficial drainage in 8. Three-dimensional dynamic MR digital subtraction angiography findings showed a good agreement with conventional catheter angiography in 17 cases (κ = 0.84, P = .1). In 1 case, 3D dynamic MR digital subtraction angiography misidentified superficial venous drainage as deep drainage, and in 1 case, 3D dynamic MR digital subtraction angiography incorrectly showed superficial venous drainage, whereas conventional catheter angiography demonstrated only deep venous drainage.

Fig. 2. Post-radiosurgery study of 48-year-old woman with a left frontal arteriovenous malformation.
A–B, Conventional angiograms in sagittal (A) and coronal (B) views show a medium-sized arteriovenous malformation fed by branches of the middle cerebral artery. It drains via 2 veins (anterior and posterior) into the superior sagittal sinus. Note stenosis of the anterior vein.
C–I, Several stages of 3D dynamic MR digital subtraction angiograms during the passage of a contrast bolus in sagittal (C, early arterial phase; D, late arterial phase; E, early venous phase; and F–G, late venous phase) and coronal (H, arterial phase; I, early venous phase) maximum-intensity-projection reconstructions show the nidus and 2 draining veins matching the conventional catheter angiography findings.
imaging techniques is appropriate for contrast MR
spatial and temporal resolution. The use of parallel
position of spatial harmonics (16, 17) can provide high
tivity encoding technique (30), or simultaneous acqui-
venous malformations (28, 29).
which are important for the diagnosis of arterio-
to distinguish nidus from draining veins, both of
reflect high-flow cerebral vascular malformations and
olution lack the temporal resolution to optimally re-
formations. These techniques with higher spatial res-
great value for the assessment of arteriovenous mal-
Other MR angiographic techniques with or without
small vessels or shunts due to partial-volume effects.
80 mm) that is responsible for a poor visualization of
tions (7, 9, 10, 26, 27). However limitations of this
process does not require an increase in contrast media because
array imaging might explain the higher inter-
observer agreement for the evaluation of feeding ar-
ties and draining veins (6).
Third, irrespective of the arteriovenous malforma-
tion size, coverage of 10 cm was always sufficient to
image the whole arteriovenous malformation without
view sharing or temporal interpolation.
Fourth, as with the 2D technique, 3D acquisition
did not require an increase in contrast media because
a small volume of contrast medium (10 mL) is suffi-
cient for each plane. Partial k-space updating for each
dynamic image is used to shorten the acquisition time.
The duration of the plateau concentration of contrast
agent is maintained at least over the duration of
multiple dynamic acquisitions used in view sharing
and interpolation (33). Hence, at a fixed injection rate
and a similar dynamic acquisition time, parallel im-

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CCA</th>
<th>3D dynamic MR-DSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection of nidus</td>
<td>19/19</td>
<td>19/19</td>
</tr>
<tr>
<td>Size of nidus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;3 cm</td>
<td>14/19</td>
<td>14/19</td>
</tr>
<tr>
<td>3–6 cm</td>
<td>4/19</td>
<td>4/19</td>
</tr>
<tr>
<td>&gt;6 cm</td>
<td>1/19</td>
<td>1/19</td>
</tr>
<tr>
<td>Venous drainage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>superficial</td>
<td>8/19</td>
<td>7/19</td>
</tr>
<tr>
<td>deep</td>
<td>3/19</td>
<td>3/19</td>
</tr>
<tr>
<td>deep and superficial</td>
<td>8/19</td>
<td>9/19</td>
</tr>
</tbody>
</table>

Discussion

Our study showed 3D dynamic contrast-enhanced
MR angiography to be highly sensitive for the detec-
tion of arteriovenous malformation nidus and for
determining nidus measurements according to Spet-
zler and Martin’s classification (21). Of 19 patients
with an angiographically proven nidus, 3D dynamic
MR digital subtraction angiography showed similar
findings in all cases.

The standard technique of contrast-enhanced 3D
MR angiography is based on a single acquisition of
the imaging volume during the peak of maximum
centration of gadolinium within the arteries. This
provides high contrast of images with minimized flow-
related artifacts. However, a major drawback of this
technique, because of the impossibility of repeating
sequences with a short time acquisition during the
passage of the contrast agent, is the absence of he-
modynamic information on the different phases of
the intracranial circulation; this point is crucial for the
evaluation of brain arteriovenous malformations (22,
23). To circumvent this issue, time-resolved 3D MR
angiography has been developed, and preliminary re-
ports suggest that this method constitutes a potential
tool for the follow-up of patients with cerebral arte-
riovenous malformations (2, 14, 24–26).

Two-dimensional dynamic time-resolved MR digi-
tal subtraction angiography has proven its effective-
ness for the evaluation of arteriovenous malforma-
tions (7, 9, 10, 26, 27). However limitations of this
technique include the low spatial resolution (1 × 2 ×
80 mm) that is responsible for a poor visualization of
small vessels or shunts due to partial-volume effects.
Other MR angiographic techniques with or without
contrast, namely time of flight or phase contrast, have
great value for the assessment of arteriovenous mal-
formations. These techniques with higher spatial res-
olution lack the temporal resolution to optimally re-
reflect high-flow cerebral vascular malformations and
to distinguish nidus from draining veins, both of
which are important for the diagnosis of arterio-
venous malformations (28, 29).

New technical developments using parallel imaging
such as sensitivity encoding (13), array spatial sensi-
tivity encoding technique (30), or simultaneous acqui-
sition of spatial harmonics (16, 17) can provide high
spatial and temporal resolution. The use of parallel
imaging techniques is appropriate for contrast MR
angiography because the relatively high signal intensi-
ity level can be exploited for improving spatial reso-

<table>
<thead>
<tr>
<th>Size of nidus</th>
<th>CCA</th>
<th>3D dynamic MR-DSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3 cm</td>
<td>14/19</td>
<td>14/19</td>
</tr>
<tr>
<td>3–6 cm</td>
<td>4/19</td>
<td>4/19</td>
</tr>
<tr>
<td>&gt;6 cm</td>
<td>1/19</td>
<td>1/19</td>
</tr>
<tr>
<td>Venous drainage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>superficial</td>
<td>8/19</td>
<td>7/19</td>
</tr>
<tr>
<td>deep</td>
<td>3/19</td>
<td>3/19</td>
</tr>
<tr>
<td>deep and superficial</td>
<td>8/19</td>
<td>9/19</td>
</tr>
</tbody>
</table>

Summary of CCA and 3D dynamic MR-DSA findings

Discussion

Our study showed 3D dynamic contrast-enhanced
MR angiography to be highly sensitive for the detec-
tion of arteriovenous malformation nidus and for
determining nidus measurements according to Spetz-
zler and Martin’s classification (21). Of 19 patients
with an angiographically proven nidus, 3D dynamic
MR digital subtraction angiography showed similar
findings in all cases.

The standard technique of contrast-enhanced 3D
MR angiography is based on a single acquisition of
the imaging volume during the peak of maximum
centration of gadolinium within the arteries. This
provides high contrast of images with minimized flow-
related artifacts. However, a major drawback of this
technique, because of the impossibility of repeating
sequences with a short time acquisition during the
passage of the contrast agent, is the absence of he-
modynamic information on the different phases of
the intracranial circulation; this point is crucial for the
evaluation of brain arteriovenous malformations (22,
23). To circumvent this issue, time-resolved 3D MR
angiography has been developed, and preliminary re-
ports suggest that this method constitutes a potential
tool for the follow-up of patients with cerebral arte-
riovenous malformations (2, 14, 24–26).

Two-dimensional dynamic time-resolved MR digi-
tal subtraction angiography has proven its effective-
ness for the evaluation of arteriovenous malforma-
tions (7, 9, 10, 26, 27). However limitations of this
technique include the low spatial resolution (1 × 2 ×
80 mm) that is responsible for a poor visualization of
small vessels or shunts due to partial-volume effects.
Other MR angiographic techniques with or without
contrast, namely time of flight or phase contrast, have
great value for the assessment of arteriovenous mal-
formations. These techniques with higher spatial res-
olution lack the temporal resolution to optimally re-
reflect high-flow cerebral vascular malformations and
to distinguish nidus from draining veins, both of
which are important for the diagnosis of arterio-
venous malformations (28, 29).

New technical developments using parallel imaging
such as sensitivity encoding (13), array spatial sensi-
tivity encoding technique (30), or simultaneous acqui-
sition of spatial harmonics (16, 17) can provide high
spatial and temporal resolution. The use of parallel
imaging techniques is appropriate for contrast MR
angiography because the relatively high signal intensi-
ity level can be exploited for improving spatial reso-

<table>
<thead>
<tr>
<th>Summary of CCA and 3D dynamic MR-DSA findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Detection of nidus</td>
</tr>
<tr>
<td>Size of nidus</td>
</tr>
<tr>
<td>&lt;3 cm</td>
</tr>
<tr>
<td>3–6 cm</td>
</tr>
<tr>
<td>&gt;6 cm</td>
</tr>
<tr>
<td>Venous drainage</td>
</tr>
<tr>
<td>superficial</td>
</tr>
<tr>
<td>deep</td>
</tr>
<tr>
<td>deep and superficial</td>
</tr>
</tbody>
</table>
aging techniques require less contrast agent to maintain appropriate vessel opacification (34).

A limiting factor of our technique is the use of a large field of view of 300 mm, thus decreasing the pixel size. However, increasing the field of view was necessary to obtain an acceleration factor of 4. With a smaller field of view, a factor of only 2 may be used, leading to a lower temporal resolution. The parallel imaging technique allows scan time to be reduced, although this is to the detriment of the signal-to-noise ratio (34). The loss in signal-to-noise ratio is equivalent to the square root of the reduction in acquisition time. Thus, a scan with an acceleration factor of 4 requires one quarter of the imaging time for a given resolution, but with √4 or 50% of the signal-to-noise ratio. To improve the signal-to-noise ratio, we reduced the readout bandwidth and slightly increased the field of view to 300 mm and the injection rate of the contrast agent to 3 mL/s (33).

Another limitation of the technique is an aliasing artifact affecting the periphery of the field of view and resulting in an overlap of the arteries and veins. This artifact is due to the geometry of the receiver coils. In our study, no artifact occurred with the use of a phased-array coil optimized for parallel imaging.

Finally, the temporal resolution on 3D dynamic MR digital subtraction angiography sequences remains limited with 1 frame per 1.7 seconds compared with 1 frame per 0.5 seconds with conventional catheter angiography. This may explain the low reproducibility of this technique for the assessment of venous drainage, especially in case of slow flow or residual small fistulas.

Recent studies have used 3D MR angiography acquisition and parallel imaging for the assessment of supraaortic extracranial or peripheral vessels or abdominal vasculature (14, 15, 33, 34). The results showed the ability of this technique to enhance spatial (1.0 × 2.0 × 4.0 mm³) and temporal resolution (4 seconds) in a clinical setting. One study (30) evaluated 2D dynamic MR digital subtraction angiography using sensitivity encoding techniques in the assessment of intracranial hemodynamics with an improved temporal resolution and showed that this technique could provide satisfactory examinations in patients with arteriovenous malformations. In that study, however, spatial resolution was poor because of the 2D acquisition, and maximum-intensity-projection reconstructions were not assessed.

Other techniques may be used to decide the therapeutic strategy. Recently, it has been shown that CT angiography including the newest scanners and subsecond cine function may be used to define the treatment planning and especially for the stereotactic location of the nidus before surgical resection or radiosurgical treatment (35).

Further optimization of the imaging sequence will be undertaken to improve the image quality. This will probably be achieved by combining an increased injection rate and a smaller imaging duration–bolus duration ratio (33, 36, 37). Three-dimensional dynamic MR digital subtraction angiography with parallel imaging techniques might replace conventional catheter angiography in certain circumstances and especially for treatment planning and follow-up of patients with cerebral arteriovenous malformations. Our study suggests that cerebral arteriovenous malformations may be controlled by 3D dynamic MR digital subtraction angiography after treatment by radiosurgery as long as an opacification of the nidus or an early venous drainage persists. When MR angiograms no longer show the nidus or a draining vein, conventional catheter angiography is performed to confirm the complete occlusion of the nidus or the presence of a residual fistula. Moreover, this technique may improve the etiological MR imaging work-up of hematomas in young patients (38).

Conclusion

Our preliminary study demonstrates that the 3D dynamic MR digital subtraction angiography using sensitivity encoding technique is suited for the evaluation of arteriovenous malformation and can provide essential information such as the size of the nidus and the presence of venous drainage. It allows an increased temporal resolution without sacrificing spatial resolution and provides adequate imaging coverage.

References

37. Maki JH, Prince MR, Chenevert TC. Optimizing three-dimensional gadolinium-enhanced magnetic resonance angiography: original investigation. *Invest Radiol* 1998;33:528–537