Use of Parallel Imaging in Peripheral Contrast-enhanced Magnetic Resonance Angiography: Retrospective Study

A Li, CC Chan, TW Ng, CF Lo, TKL Loke, SS Lo, JCS Chan
Department of Radiology and Organ Imaging, United Christian Hospital, Hong Kong

ABSTRACT
Objective: To evaluate the application of a parallel imaging technique — generalised autocalibrating partially parallel acquisition — in peripheral contrast-enhanced magnetic resonance angiography.

Patients and Methods: This was a retrospective review of 17 consecutive patients with peripheral vascular disease who underwent lower-extremity 3-dimensional contrast-enhanced magnetic resonance angiography from July 2003 to March 2005. Generalised autocalibrating partially parallel acquisition, with an acceleration factor of 2, was used in all 3 stations of a single-injection moving-table protocol. The image qualities, spatial, and temporal resolutions were evaluated.

Results: In all patients, the arterial segments under evaluation attained diagnostic quality. The degree of venous contamination was acceptable without obscuring the arterial pathology. There were significant improvements in spatial resolution (68.6% in the pelvic station, 40.0% in the thigh station, and 20.0% in the calf station), so that submillimetre near-isotropic resolution (1.0 x 0.8 x 1.0 mm) could be achieved in below-knee vessels, therapy providing excellent vascular detail. The overall acquisition time of magnetic resonance angiography data was reduced by 9.7% (22.0% reduction in data-acquisition time for the calf station). The overall examination time was less than 45 minutes (including patient transport and postprocessing image reconstruction). None of the patients had an adverse reaction to the contrast agent or contrast administration. There was no technical failure reported.

Conclusions: Parallel imaging with generalised autocalibrating partially parallel acquisition improves spatial and temporal resolution in peripheral contrast-enhanced magnetic resonance angiography. It is a reliable technique for optimising peripheral contrast-enhanced magnetic resonance angiography. Diagnostic high-quality images with an acceptable degree of venous contamination can also be achieved.

Key Words: Magnetic resonance angiography/methods; Parallel imaging; Peripheral vascular diseases/diagnosis

INTRODUCTION
Contrast-enhanced magnetic resonance angiography (MRA) has emerged as an accurate and non-invasive alternative to conventional angiography in the evaluation of peripheral arterial occlusive disease. In conventional MRA, the temporal and spatial resolutions are limited by the performance characteristics of the gradient hardware. With the recent introduction of parallel imaging techniques, it has become possible to shorten the MRA data acquisition time and/or increase the spatial resolution without increasing the gradient demands. Parallel imaging techniques use the spatial-encoding properties of multiple phase array coil elements to reduce the number of spatial-encoding steps required to generate an image, thereby partially overcoming the gradient hardware performance limits imposed on conventional MRA technique. In this way, only a fraction of phase-encoding steps have to be acquired directly, which results in accelerated image acquisition while maintaining full spatial resolution and image contrast. Besides increased temporal resolution at a given spatial resolution, the time savings due to parallel imaging can also be used to improve the spatial resolution in a given imaging time. The purpose of this study was to review the use of a parallel imaging technique — generalised autocalibrating partially parallel acquisition (GRAPPA) — in peripheral contrast-enhanced MRA.

Correspondence: Dr. A Li, Department of Radiology and Organ Imaging, United Christian Hospital, 130 Hip Wo Street, Kwun Tong, Hong Kong.
Tel: (852) 3515 4131; Fax: (852) 3513 5637; E-mail: liallen@yahoo.com

Submitted: 12 May 2005; Accepted: 2 August 2005.

© 2005 Hong Kong College of Radiologists
PATIENTS AND METHODS
Seventeen consecutive patients with peripheral vascular disease underwent lower-extremity 3-dimensional contrast-enhanced MRA from July 2003 to March 2005 at the United Christian Hospital. The patients’ ages ranged from 36 to 89 years (median, 75 years), and the ratio of males to females was 1:1. The mean ankle-brachial index was 0.63 (standard deviation, 0.21) among the 12 patients with relevant data. The prevalence rates of various medical conditions are shown in Table 1.

All examinations were performed by experienced radiographers with a 1.5-T magnetic resonance scanner (Magnetom Sonata; Siemens Medical Solutions, Erlangen, Germany). The entire arterial run-off from the pelvis to the infrapopliteal arteries was fully covered using a 3-station, automatic table-moving technique with floating-table MRA software (Siemens Medical Solutions). The signal was received with a combination of multiple receiver coil systems (Integrated Panoramic Concept; Siemens Medical Solution). Furthermore, there was a dedicated peripheral vascular coil (CP Peripheral Angio Array Coil; Siemens Medical Solution) with 8 separate elements (or channels) and a total length adequate to cover the entire lower extremities from the inguinal ligament to the foot, in conjugation with 2 phase-array body surface coils (2 channels) and a spine-array coil (6 channels) to cover the lower part of the abdomen and pelvis.

Data were collected by using a fast 3-dimensional T1-weighted gradient-echo sequence with linear k-space sampling. A field of view of 350 mm with 50-mm overlap between each station was required to cover the entire lower extremity. Timing of the start of data acquisition was determined by a test bolus strategy. Each patient received a weight-adjusted dose of 0.2 mmol per kilogramme of body weight of gadolinium-diethylenetriamine penta-acetic acid (with a maximum dose of 20 ml for patients of more than 25 kg). The contrast agent was diluted with isotonic saline to a volume of 60 ml and injected intravenously by a biphasic protocol: the first 25 ml was administered at a rate of 1 ml/s, and the remaining 35 ml was administered at a rate of 0.6 ml/s. A 25-ml saline flush was then administered at a rate of 1 ml/s.

The MRA acquisition settings were adapted for each station and are summarised in Table 2. The GRAPPA algorithm used an acceleration factor of 2 and was implemented in all 3 stations. Data acquisition times were 15 s (aortoiliac), 19 s (thigh), and 31 s (calf), with a 7-s scan time delay between each station. Contrast-enhanced source images were subtracted from the non-enhanced mask images at each level by using Syngo VA2002C software (Siemens Medical Solutions). Rotated maximum-intensity projected images were reconstructed over a 90° sector with anteroposterior, left anterior oblique, and right anterior oblique images.

All the studies were independently evaluated by 2 radiologists. To facilitate MRA evaluation, the entire vasculature was divided into the following arterial segments: pelvic station (infrainguinal aorta, common iliac, and external iliac), thigh station (common and superficial femoral), and calf station (popliteal artery, tibioperoneal, anterotibial, posterotibial, peroneal, and dorsalis pedis). Each segment in each lower extremity

### Table 1. Patients’ characteristics (n = 17).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patients (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diabetes mellitus</td>
<td>33*</td>
</tr>
<tr>
<td>Renal impairment</td>
<td>50*</td>
</tr>
<tr>
<td>Hypertension</td>
<td>50*</td>
</tr>
<tr>
<td>Ischaemic heart disease</td>
<td>22*</td>
</tr>
<tr>
<td>Smoking history</td>
<td>22†</td>
</tr>
</tbody>
</table>

* Missing data for 1 patient.
† Missing data for 2 patients.

### Table 2. Imaging settings for 3-station, single-injection, moving-table 3-dimensional contrast-enhanced magnetic resonance angiography protocols with or without generalised autocalibrating partially parallel acquisition (GRAPPA).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Aortoiliac</th>
<th>Thigh</th>
<th>Calf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-GRAPPA</td>
<td>GRAPPA</td>
<td>Non-GRAPPA</td>
</tr>
<tr>
<td>TR (ms)</td>
<td>2.8</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td>TE (ms)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>TA (ms)</td>
<td>15</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Flip angle (°)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>FOV (mm)</td>
<td>400 x 400</td>
<td>317 x 380</td>
<td>400 x 400</td>
</tr>
<tr>
<td>Matrix</td>
<td>256 x 256</td>
<td>320 x 384</td>
<td>256 x 256</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>GRAPPA factor</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

*Abbreviations: TR = repetition time; TE = echo time; TA = total acquisition time; FOV = field of view.*
Peripheral Contrast-enhanced Magnetic Resonance Angiography

was analysed separately, so that there was a total of 19 subsets per patient.

Analysis of arterial diagnostic quality was based on a 3-point scale: 1 (anatomical details were well shown), 2 (suboptimal but could exclude pathological conditions), and 3 (non-diagnostic in which pathological conditions could not be excluded). Analysis of venous contamination at each station was based on a 3-point scale: 1 (none), 2 (mild to moderate venous contamination that did not interfere with diagnostic assessment), and 3 (severe venous contamination in which arterial structures could not be adequately evaluated). The thigh and calf stations of each extremity were evaluated separately.

Any adverse reactions to MRA contrast agent, bolus contrast administrations, imaging artefacts, or technical problems related to GRAPPA were also recorded.

RESULTS

Without the use of GRAPPA, the spatial resolution was 1.6 x 1.6 x 1.5 mm for the aortoiliac station, 1.6 x 1.6 x 1.4 mm for the thigh station, and 1.4 x 1.6 x 1.0 mm for the calf station. With GRAPPA, the spatial resolution was 1.0 x 1.0 x 1.5 mm for the aortoiliac station, 1.0 x 0.7 x 1.4 mm for the thigh station, and 1.0 x 0.8 x 1.0 mm for the calf station (Figure 1). When compared with conventional MRA, GRAPPA had a significant improvement in the spatial resolutions (68.6% in the pelvic station, 40.0% in the thigh station, and 20.0% in the calf station) and achieved submillimetre near-isotropic resolution in the calf station.

For temporal resolution, there was a 22.0% reduction in MRA data acquisition time for the calf station (from 38 ms to 31 ms), and a 9.7% reduction in the overall MRA data acquisition time with GRAPPA. The overall examination time (including patient transport and postprocessing image reconstruction) was less than 45 minutes.

We did not encounter technical failure related to GRAPPA. In one of the studies, the optimal timing (peak of contrast enhancement) for image acquisition was missed. That was due to observer error in identifying the peak enhancement. The in-plane enhancement effect was misinterpreted as the peak of arterial enhancement during the initial test bolus run. The data acquisition of the aortoiliac station was repeated immediately after the calf station. The arterial signals were hence suboptimal and had considerable venous contamination. Nevertheless, the overall image quality after subtraction from the mask study was still diagnostic.

Results for 255 diagnostic arterial segments that were evaluated for diagnostic quality in terms of signal score (85 in aortoiliac, 68 in thigh, and 102 in calf stations)

![Figure 1. Oblique coronal maximum intensity projected images of the calf station from bolus-chase peripheral contrast-enhanced magnetic resonance angiography: (a) a conventional image by bolus-chase 4-station technique showing severe venous contamination that markedly degrades the image quality and interferes with interpretation of the arterial structures; and (b) image from generalised autocalibrating partially parallel acquisition with acceleration factor of 2, with excellent depiction of the arterial structures without significant venous contamination.](image-url)
Diagnostic quality images were obtained in all cases, with an arterial score of 1 (98% in aortoiliac, 93% in thigh, and 85% in calf stations) and overall score of 2 (2% in aortoiliac, 7% in thigh, and 15% in calf stations). None of the arterial segments was found to be of non-diagnostic quality.

Results for 85 stations that were evaluated for venous contamination (17 in aortoiliac, 34 in thigh, and 34 in calf stations) are shown in Table 4. None of the stations was found to have a severe degree of venous contamination (score 3). Mild to moderate venous contamination (score 2) was present in 18% of aortoiliac, 9% of thigh, and 24% of calf stations. No venous contamination (score 1) was found in 82% of aortoiliac, 91% of thigh, and 76% of calf stations. Venous contamination was not further analysed because this belonged to the superficial or deep venous system. Superficial veins do not hinder the interpretation of peripheral arteries, and if necessary, can be easily segmented out. The authors’ impression was that a substantial portion of the venous contamination in the thigh stations belonged to the superficial veins.

None of the patients was reported to have an adverse reaction related to MRA contrast agent or contrast administration.

DISCUSSION

GRAPPA is one member of a family of partially parallel imaging techniques that reconstruct images from each component coil before performing image combination. More precisely, the reconstruction algorithm calculates missing k-space lines before image generation by Fourier transformation of the data (Figure 2). The spatial information inherent in local coil arrays is used to replace time-consuming phase-encoding steps, so that the overall imaging time can be reduced.

In this study, an acceleration factor of 2 was used, thereby reducing the k-space line acquisition to once every second line. The imaging time could thus be reduced by nearly 50% depending on the number of autocalibration signal lines used. Autocalibration signal lines were referenced to determine the weighting of each coil element for the data reconstruction. With a reduction in overall examination time, there was an increase in examination efficacy, patient throughput, and, importantly, improved patient comfort and compliance with the examination. With the parallel imaging technique, there was flexibility in using the MRA signal, so that the gain in temporal resolution could be ‘traded’ to gain spatial resolution. By keeping the data acquisition time the same as that of a conventional examination, higher spatial resolution images could be acquired.\(^3,4\)

A significant consideration for bolus-chase multi-station MRA is the coordination of timing for imaging acquisition during the arterial phase of the bolus of contrast. The benefit of gaining temporal resolution with GRAPPA has to be taken with caution in bolus-chase MRA. There is a risk of data acquisition before peak enhancement, especially for patients who have slow blood flow. Technically, it is possible to shorten

<table>
<thead>
<tr>
<th>Diagnostic arterial segments (n = 255)</th>
<th>Arterial signal score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Aortoiliac station(^1) (n = 85)</td>
<td>83 (98%)</td>
</tr>
<tr>
<td>Thigh station(^2) (n = 68)</td>
<td>63 (93%)</td>
</tr>
<tr>
<td>Calf station(^3) (n = 102)</td>
<td>87 (85%)</td>
</tr>
</tbody>
</table>

\(^1\) The scoring system is based on a 3-point scale: 1 = anatomical details are well shown; 2 = suboptimal but can exclude pathological conditions; 3 = non-diagnostic but pathological conditions cannot be excluded.

\(^2\) Infrarenal aorta, common iliac, and external iliac arteries.

\(^3\) Common femoral and superficial femoral arteries.

\(^4\) Popliteal, tibial, peroneal, anteriotibial, posterotibial, peroneal, and dorsalis pedis arteries.

<table>
<thead>
<tr>
<th>Station</th>
<th>Venous contamination score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortoiliac (n = 17)</td>
<td>14 (82%)</td>
</tr>
<tr>
<td>Thigh (n = 34)</td>
<td>31 (91%)</td>
</tr>
<tr>
<td>Calf (n = 34)</td>
<td>26 (76%)</td>
</tr>
</tbody>
</table>

\(^*\) The scoring system is based on a 3-point scale: 1 = no contamination; 2 = mild to moderate venous contamination that does not interfere with diagnostic assessment; and 3 = severe venous contamination in which arterial structures cannot be evaluated adequately.

---

Table 3. Distribution of diagnostic arterial segments, according to arterial signal scores.*

Table 4. Distribution of stations according to venous contamination score.*

---

\* The scoring system is based on a 3-point scale: 1 = anatomical details are well shown; 2 = suboptimal but can exclude pathological conditions; 3 = non-diagnostic but pathological conditions cannot be excluded.
data acquisition of the first and second stations to less than 20 s before commencement of lower station data acquisition, so as to reduce venous contamination in the lower station. However, the narrow window of data acquisition has to be balanced against the risk of missing the contrast bolus at the peak of arterial enhancement. A mismatch between the peak of contrast enhancement and the filling of the central lines of the k-space would degrade the quality of acquired images. Theoretically, k-space modulation artefacts may result from premature acquisition of central k-space data during the rapid rising arterial signal. This artefact is recognised as alternating bright and dark lines that parallel the vessel lumen and may cause diagnostic confusion. Even though it is more often associated with centric phase-ordered acquisition, the artefact may occur during linear sequential k-space acquisition, which is used in all 3 stations.2

The test bolus technique of coordinating MRA data acquisition for peak arterial enhancement is not foolproof. One of the examinations in this study used incorrect timing during the test bolus run, which resulted in missed optimal MRA data acquisition during the peak of arterial enhancement. Obviously, this is not directly related to GRAPPA but to an in-flow enhancement effect during the test bolus run. In-flow enhancement is due to normal arterial in-flow and results in bright arterial signal even before contrast administration; it is a well known pitfall resulting in wrong timing of the arrival of contrast. This pitfall can be minimised by the application of superior and inferior saturation bands on both sides of the imaging slice, which will effectively eliminate in-flow on an axial timing bolus scan. The application of a saturation band will ensure that any signal increase is due to the arrival of contrast medium. An alternative method is to prescribe the test bolus imaging plan in the sagittal plane, so that it travels primarily within the imaging plane instead of through the plane.3 The routine protocol adopted at the United Christian Hospital uses a saline flush (25 ml at 1 ml/s by the same MRA-compatible injector) after both the test bolus and actual bolus injections, to minimise pooling of contrast within the extension tubing or peripheral venous system, and to lessen the variation of the timing between the test and actual contrast bolus. The image data for each station should be acquired during the arterial phase of the contrast bolus, which at least lasts the duration of the bolus itself.

Another challenge in contrast-enhanced MRA of the lower limbs is to acquire the data before substantial venous enhancement occurs, especially in the calf station; otherwise, this may substantially impair arterial visualisation. In this study, even though none of the patients was found to have severe venous contamination, only 76% of calf stations could achieve no venous contamination. Goldman has demonstrated an approach in which the GRAPPA acceleration factor is 2 during the 2 middle stations of a single pass, 4-station protocol.9 Although the commencement of data acquisition for the lower station started 31 seconds after aortic contrast arrival in Goldman’s study (compared with 48 seconds in the protocol in this study), venous contamination in the lower legs could not be completely prevented (60% had no venous contamination, 35% had mild superficial venous contamination, and 5% had moderate venous contamination). Higher parallel imaging factors that further reduce the imaging time may be helpful to further eliminate venous contamination. Thigh or calf compression has been tried with success to decrease venous contamination during bolus-chase peripheral MRA.10,11

By the use of GRAPPA, spatial resolution is improved when compared with a conventional scan of the same acquisition time. In this study’s protocol, this potential was used for the aortoiliac and thigh stations, resulting in improvements in spatial resolution by 68.6% and 40.0%, respectively. In the calf station, GRAPPA had the flexibility in the MRA signal, resulting in an improvement in both temporal and spatial resolutions when compared with the conventional non-GRAPPA technique. There was a 22.0% reduction in acquisition time and a 20.0% improvement in spatial resolution. This study thus demonstrates a technique that achieves a lower station resolution of up to 1.0 x 0.8 x 1.0 mm (0.8 mm³). Studies have shown that to accurately characterise a stenosis, resolution in all 3 planes must be less than approximately one-third of the vessel diameter.12 Arteries below the knee are approximately 2 to 3 mm wide, so to accurate depict disease, image resolution must be less than 1 mm isotropic.13 The calf station requires critical demand for spatial resolution, because accurate vessel depiction of the distal target vessel is required for pregraft planning.14

The use of GRAPPA does cause a loss in signal-to-noise ratio; however, the effect may not be statistically significant in contrast-enhanced MRA, which is a study of high intrinsic contrast-to-noise ratio. Signal loss may be reversed by faster gadolinium contrast injection.15 A study by Wilson et al that compared paired renal MRA
data with and without sensitivity encoding (SENSE) \([n = 20]\) demonstrated that there was no significant difference in signal-to-noise ratio between SENSE and conventional renal MRA.\(^{16}\) SENSE belongs to a different class of parallel imaging technique. The reconstruction algorithm combines the data sets obtained from individual coils after the raw data are Fourier-transformed into individual image sets. Further comparative studies would be required to determine the significance of reducing signal-to-noise ratio in terms of image quality after the use of GRAPPA.

Venous compression and higher GRAPPA acceleration factors are among recent advances to further optimise the technique.\(^{10,11}\) Further development may allow peripheral MRA to be a promising technique that could be used as the sole preoperative imaging modality for definitive vascular interventions.

**CONCLUSION**

Parallel imaging with GRAPPA implementation in peripheral contrast-enhanced MRA is a reliable technique with improve temporal and spatial resolutions. Diagnostic high-quality images with an acceptable degree of venous contamination can be achieved.

**REFERENCES**