Peripheral Vasculature: High-Temporal- and High-Spatial-Resolution Three-dimensional Contrast-enhanced MR Angiography¹

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Purpose:

To prospectively evaluate the feasibility of performing high-spatial-resolution (1-mm isotropic) time-resolved three-dimensional (3D) contrast material-enhanced magnetic resonance (MR) angiography of the peripheral vasculature with Cartesian acquisition with projection-reconstruction-like sampling (CAPR) and eightfold accelerated two-dimensional (2D) sensitivity encoding (SENSE).

Materials and Methods:

All studies were approved by the institutional review board and were HIPAA compliant; written informed consent was obtained from all participants. There were 13 volunteers (mean age, 41.9; range, 27–53 years). The CAPR sequence was adapted to provide 1-mm isotropic spatial resolution and a 5-second frame time. Use of different receiver coil element sizes for those placed on the anterior-to-posterior versus left-to-right sides of the field of view reduced signal-to-noise ratio loss due to acceleration. Results from eight volunteers were rated independently by two radiologists according to prominence of artifact, arterial to venous separation, vessel sharpness, continuity of arterial signal intensity in major arteries (anterior and posterior tibial, peroneal), demarcation of origin of major arteries, and overall diagnostic image quality. MR angiographic results in two patients with peripheral vascular disease were compared with their results at computed tomographic angiography.

Results:

The sequence exhibited no image artifact adversely affecting diagnostic image quality. Temporal resolution was evaluated to be sufficient in all cases, even with known rapid arterial to venous transit. The vessels were graded to have excellent sharpness, continuity, and demarcation of the origins of the major arteries. Distal muscular branches and the communicating and perforating arteries were routinely seen. Excellent diagnostic quality rating was given for 15 (94%) of 16 evaluations.

Conclusion:

The feasibility of performing high-diagnostic-quality time-resolved 3D contrast-enhanced MR angiography of the peripheral vasculature by using CAPR and eightfold accelerated 2D SENSE has been demonstrated.

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Three-dimensional (3D) contrast material-enhanced magnetic resonance (MR) angiography has become a commonly accepted method for imaging many vascular territories (1–3). More than a decade ago, basic advances were made with the intent of providing a high-quality arterial phase image. These included understanding the effect of missed timing of the acquisition to the contrast material bolus (4), development of methods to provide accurate timing (5–7), and development of centric phase encoding as a means for allowing high spatial resolution with good venous suppression (8,9). Methods were developed for time-resolved 3D acquisition (10), which in general involved a trade-off of temporal for spatial resolution (11). For MR angiography of the peripheral vasculature, a variety of methods have specifically been developed (12–17), including some that allow imaging over an extended field of view (FOV) (18–27).

The introduction of parallel acquisition (28–30) has permitted further reduction of acquisition time for a given reso-

Figure 1

Figure 1: MIPs demonstrate improvement in image quality attained by using time-resolved CAPR acquisition with acceleration factor of 7.3 and 2D SENSE with two different coil arrays. **(a)** Arterial phase MIP image in volunteer obtained by using array 1. Superior-to-inferior signal intensity falloff (arrows) was a result of limited 21.5-cm coil length. **(b)** Arterial phase MIP image in a different volunteer obtained by using array 2 with 27.1-cm coil length shows improved superior-to-inferior coverage and higher signal-to-noise ratio.

Advances in Knowledge

- The use of two-dimensional (2D) acceleration techniques of sensitivity encoding and homodyne reconstruction allows greater than 10-fold reduction in acquisition time for three-dimensional contrast-enhanced MR angiography, which allows time-resolved imaging with high spatial resolution and high overall image quality.
- Matching the sizes of the individual coil elements of the receiver array to the asymmetric left-to-right versus anterior-to-posterior field of view of the lower legs can be effective in reducing the g factor and the resultant signal-to-noise ratio loss of 2D acceleration.
- The spatial resolution attainable by using Cartesian acquisition with projection-reconstruction-like sampling (CAPR) imaging of the lower legs routinely allows the small branching vessels, such as muscular feeders and communicating and perforating vessels, to be clearly seen.

lution. Such methods have been applied to contrast-enhanced MR angiography of various vascular regions, initially with parallel acquisition along one direction (31,32). However, because of the typical 3D nature of contrast-enhanced MR angiography, parallel acquisition can be applied along two encoding directions (phase- and section-encoding directions) by using, for example, two-dimensional (2D) sensitivity encoding (SENSE) (33). Such methods have been applied to the

Implication for Patient Care

- Three-dimensional time-resolved contrast-enhanced MR angiography by using CAPR simultaneously allows high spatial (1-mm isotropic) visualization and clear distinction of arterial and venous phases as contrast material passes through the vasculature of the lower legs, even in subjects with rapid arterial to venous transit.

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Abbreviations:

CAPR = Cartesian acquisition with projection-reconstruction-like sampling
FOV = field of view
MIP = maximum intensity projection
SENSE = sensitivity encoding
3D = three-dimensional
2D = two-dimensional

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Guarantors of integrity of entire study, C.R.H., S.J.R.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; literature research, C.R.H., A.W.S., S.J.R.; clinical studies, C.R.H., J.F.G., S.J.R.; experimental studies, C.R.H., S.J.R.; statistical analysis, S.J.R.; and manuscript editing, all authors

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Figure 2

Figure 2: Evaluation of g factors for examples in Figure 1. (a) A g-factor map for array 1 through an axial section midcalf with acceleration factor of 7.3. (b) A g-factor map for array 2 for a similar section with acceleration factor of 7.3 shows improvement (reduction) in g factor. (c) Histograms of the g factors for array 1 (blue) with equal-sized elements and for array 2 (yellow) with different-sized anterior-to-posterior (A/P) and left-to-right (L/R) elements for each of the four 2D SENSE acceleration factors ranging from four to eight. For all acceleration factors, the g factors were reduced (improved) with array 2. (Reprinted, with permission, from reference 37.)

brain (34–36) and the lower legs (15), with acceleration factors of four or higher. In the latter study (15), 3D images of both lower legs were obtained with spatial resolution of $1.5 \times 1.2 \times 1.3$ mm in an acquisition time of 19 seconds.

The purpose of this study was to prospectively evaluate the feasibility of performing high-spatial-resolution (1-mm isotropic) time-resolved 3D contrast-enhanced MR angiography of the peripheral vasculature with Cartesian acquisition with projection-reconstruction-like sampling (CAPR) and eightfold accelerated 2D SENSE. We hypothesized that 1-mm isotropic resolution, high-quality MR angiographic imaging of both legs could be accomplished by using a 5-second frame time and an acquisition time per image, or “temporal footprint,” no longer than 20 seconds. This study was based on the CAPR technique (36) developed initially for neurovascular imaging. In this current study, we showed that the acceleration factors due to 2D SENSE and 2D homodyne acquisition can be as high as eight and 1.8, respectively, for a net acceleration factor due to

k-space undersampling of about 15. As part of the development of this method, we showed the importance of matching the geometric characteristics of the receiver coil array to the anatomic region of interest and the MR imaging acquisition.

Materials and Methods

All volunteer studies were approved by our institutional review board and were Health Insurance Portability and Accountability Act compliant; written informed consent was obtained from all participants.

MR Data Acquisition

The acquisition was obtained by using a 3D Fourier transform sequence called CAPR, which has previously been described (36). Briefly, by starting with a standard fully sampled Cartesian k_Y - k_Z phase-encoding plane, the following are done: (a) the corners of k-space are not sampled, (b) a central circular region is defined and is fully sampled, and (c) the remaining annu-

lar region is divided into groups of evenly spaced “vaness,” or asymmetric wedges, composed of the underlying k_Y - k_Z points. This vane pattern gives a visual appearance similar to projection reconstruction. Alternate vanes are sampled or not sampled, allowing for 2D homodyne detection to be performed across the k_Y - k_Z plane. Because homodyne detection is performed in this plane, full echoes are sampled along the readout (k_X) direction. For this study, the annular region was divided into a total of 64 vanes; of which, 32 vanes were sampled as decomposed into four groups with eight vanes per group. The central region consisted of 400 views. The CAPR k-space sampling pattern is shown in Figure E1 (Fig E1 [online]).

The performance goals of this study were to provide time-resolved 3D data sets with 1-mm isotropic spatial resolution in a volume encompassing both lower legs with a frame time of 5 seconds and temporal footprint of 20 seconds. To obtain this performance, and given the typ-

ical anterior-to-posterior and left-to-right FOVs of 13.2 and 32 cm, respectively, it was necessary to obtain an approximate order of magnitude acceleration due to a combination of 2D SENSE and 2D homodyne acquisition. Two-dimensional SENSE was implemented by using typical twofold acceleration along the section-encoding anterior-to-posterior direction ($R_z = 2$) and acceleration up to fourfold along the phase-encoding left-to-right direction ($R_y = 4$). Two-dimensional homodyne acquisition provides an additional acceleration factor of 1.7–1.9.

In Vivo and Phantom Experiments

Examinations were performed by using a 3.0-T MR imager (Signa, version 14.0; GE Healthcare, Milwaukee, Wis). Thir-

teen volunteers (mean age, 41.9 years; age range, 27–53 years), which included one man (44 years old) and 12 women (mean age, 41.8 years; age range, 27–53 years) with no known cardiovascular disease, were divided as follows into three groups: (a) Four volunteers were studied for initial coil design, (b) one volunteer was studied for comparison of the improved coil array versus the initial coil at a fixed acceleration, and (c) eight volunteers, designated as volunteers 1–8 throughout the article, were studied with the new coil array and the results were subjected to radiologic evaluation.

Three-dimensional time-resolved contrast-enhanced MR angiography was performed with a 7.3- to eightfold 2D SENSE accelerated CAPR acquisition by

using a fast gradient-echo pulse sequence with the following parameters: repetition time, 5.85 msec; echo time, 2.7 msec; flip angle, 30°; bandwidth, ± 62.5 kHz; and full echo with a central region size of 400 readout points. The acquisition format was coronal with FOV of 40 (superior-to-inferior) $\times$ 32 (left-to-right) $\times$ 13.2 (anterior-to-posterior) cm and reconstructed sampling matrix of 400 $\times$ 320 $\times$ 132, yielding 1 mm³ acquired voxels. These parameters provided a frame time of 4.93 seconds and a total acquisition time per view-shared reconstruction (ie, temporal footprint) of 19.6 seconds. A frame time this small was targeted to distinguish arterial and venous enhancement patterns. A temporal footprint only four times longer than the frame time was targeted to minimize artifactual signal enhancement (36).

SENSE calibration was performed by using a fast gradient acquisition with similar parameters except a flip angle of 10°, bandwidth of ± 31.25 kHz, and a fourfold reduction in the Y $\times$ Z spatial resolution, resulting in a sampling matrix of 400 $\times$ 160 $\times$ 66. Because of the time-resolved nature of the acquisition, no timing bolus was required. However, for proper subtraction of contrast-free background, a full reference frame was acquired prior to injection of contrast material. By using a commercially available power injector (Spectris; Medrad, Indianola, Pa), 20 mL of gadolinium-based contrast agent (gadobenate dimeglumine, Bracco Diagnostics, Princeton, NJ) was injected into the antecubital vein of each subject at 3 mL/sec followed by 20 mL of saline administered at the same rate. The above accelerated sequence was used to image a static phantom to assess spatial resolution. The phantom consisted of tubes with inner diameters of 10, 5, and 3 mm that mimicked vessels into which indentations of 10%, 20%, 40%, 60%, and 80% were made to simulate stenoses. The phantoms were filled with dilute gadolinium-based contrast material. The same acquisition technique was used to image the phantom as was used for in vivo studies, including FOV, spatial resolution along three directions, and the 2D SENSE acceleration factor of eight.

Automated reconstructions from all

Table 1

Evaluation Categories for Assessment of CAPR Contrast-enhanced MR Angiographic Reconstructions in Volunteers

Score	Assessment
Category 1: Presence of Artifact as a Result of Noise, Motion, Undersampling, or Aliasing	
1	Severe, nondiagnostic
2	Moderate, may interfere with diagnosis
3	Minor, will not interfere with diagnosis
4	None
Category 2: Arterial to Venous Separation	
1	Severe, extensive mixing of venous with arterial signal intensity or vice versa
2	Moderate, probably will interfere with diagnosis
3	Mild, venous contamination will not confound diagnosis
4	Excellent, many clear arterial frames prior to venous filling with crisp, clear progression from arterial to venous phase
Category 3: Vessel Sharpness	
1	Poor, vessels have poor spatial resolution with little or no structure
2	Mild, slight blurring of vessels that probably will not affect diagnosis
3	Good, any blur will not interfere with diagnosis
4	Excellent, crisp detail with adequate spatial resolution to visualize vessels of interest
Category 4: Continuity of Arterial Signal Intensity of Major Vessels	
1	Poor, lack of uniform signal intensity
2	Mild, variation in signal intensity
3	Good, minor variations that will not interfere with diagnosis
4	Excellent, vessels have uniform signal intensity along the vessel
Category 5: Demarcation of Origin of Major Arteries	
1	Poor, vessel origins are poorly seen because of poor signal or spatial resolution
2	Mild, variation in signal intensity or spatial resolution that can potentially confound diagnosis
3	Good, minor variations that will not interfere with diagnosis
4	Excellent, vessels origins are well seen
Category 6: Overall Diagnostic Quality of Images	
1	Nondiagnostic
2	Marginal
3	Good
4	Excellent

Table 2

Summary of Scores Assigned by Two Readers for Evaluation Categories

Parameter	Category 1, Artifact		Category 2, Arterial to Venous Separation		Category 3, Vessel Sharpness		Category 4, Continuity of Major Vessels		Category 5, Demarcation of Origin of Major Vessels*		Category 6, Overall Diagnostic Quality	
	Reader 1	Reader 2	Reader 1	Reader 2	Reader 1	Reader 2	Reader 1	Reader 2	Reader 1	Reader 2	Reader 1	Reader 2
Volunteer 1	3	4	4	3	4	4	4	4	4	4	4	4
Volunteer 2	3	4	4	4	4	4	3	4	4	4	3	4
Volunteer 3	3	4	4	4	4	4	4	4	4	4	4	4
Volunteer 4	3	4	4	3	4	4	4	4	4	4	4	4
Volunteer 5	3	4	4	3	4	4	4	4	NA	NA	4	4
Volunteer 6	3	4	4	4	4	4	4	4	4	4	4	4
Volunteer 7	3	4	4	3	3	4	4	4	4	4	4	4
Volunteer 8	3	4	4	4	4	4	4	4	4	4	4	4
Reader 1 [†]	3.0 ± 0		4.0 ± 0		3.88 ± 0.13		3.88 ± 0.13		4.0 ± 0		3.88 ± 0.13	
Reader 2 [†]	4.0 ± 0		3.5 ± 0.19		4.0 ± 0		4.0 ± 0		4.0 ± 0		4.0 ± 0	
Aggregate [†]	3.5 ± 0.13		3.75 ± 0.11		3.94 ± 0.06		3.94 ± 0.06		4.0 ± 0		3.94 ± 0.06	

Note.—Unless otherwise indicated, data are scores. See Table 1 for definition of scores in each category.

* NA = not available.

[†] Data are means ± standard errors of the mean.

studies were performed on a custom system interfaced to the MR imager. The reconstruction time per frame was less than 1.5 seconds, including Digital Imaging and Communications in Medicine generation and writing of data to the local disk. The total time for loading of data, generation of sensitivity profiles, calculation of the unfolding matrices, and all reconstructions including Digital Imaging and Communications in Medicine generation and saving to the local disk was approximately 70 seconds. Immediately after reconstruction, the images were transmitted back to the operator console of the imager for viewing. The time delay from end of acquisition to image display was no more than 2 minutes.

Design of Receiver Coil Array

Development of a custom-built multielement receiver coil was done as follows: In the four initial volunteer studies, an eight-element coil array was used, called array 1, which had equally sized elements, each 14.5 cm in width and 21.5 cm in length (superior-to-inferior) with two coil elements at each side of the FOV: anterior, posterior, left, and right. This was placed circumferentially around the calves. A sample maximum intensity projection (MIP) result obtained with a 2D SENSE acceleration factor of 7.3 is shown in

Figure 1. An axial image of the g-factor map (29) showing the noise amplification due to SENSE is shown in Figure 2.

Interpretation of these initial results suggested three possible changes in coil element size that could provide improved performance. First, the initial coil was limited in the superior-to-inferior coverage, with FOVs greater than 35 cm having undesirable signal intensity falloff (Fig 1). This suggested the need for longer coil elements. Second, the large 96-cm circumference of the coil array caused many of the elements to be 5 cm or more away from the legs, suggesting that a smaller circumference would provide closer proximity and improved signal-to-noise ratio. Third, analysis of the g maps (Fig 2) suggested a higher level of sensitivity to the anterior-to-posterior coil elements than the left-to-right elements. For imaging of the calves, the ratio of left-to-right FOV to anterior-to-posterior FOV coverage is typically greater than two (eg, 32 cm versus 13.2 cm as indicated previously). This means that equally sized coils placed anterior to posterior have proportionally twofold higher penetration of response than pairs placed left to right. This causes the sensitivity profiles of the anterior and posterior elements to be less distinct from each other, and therefore the SENSE inversion is more poorly conditioned in the

anterior-to-posterior direction, resulting in noise amplification.

The basis of the new coil design attempted to account for the above by reducing the depth of response of the anterior and posterior coil elements while preserving that of the left and right elements. A modified coil array, called array 2, was designed for circumferential placement around both calves and had two different sizes of coil elements: 10.5 × 27.1 cm for the four elements placed anterior to posterior and 14.3 × 27.1 cm for the four placed left to right. The overall circumference was decreased from 96 to 78 cm, bringing the coils closer to the legs. Finally, the length of all elements was increased from 21.5 to 27.1 cm for improved superior-to-inferior coverage, as shown in Figure E2 (Fig E2 [online]). An image obtained by using array 2 is shown in Figure 1b, and g factors are shown in Figure 2. When used, arrays 1 and 2 were each placed essentially in contact with the patient on both the anterior and posterior sides and were separated by only a thin cloth. In spite of this similar geometry, array 2 had improved g-factor response along the anterior-to-posterior direction. Even for acceleration factors as large as eight, the g factor for 75% of the voxels within the 3D image volume was no larger than 1.4. The improved coil array 2 was used with 2D

Figure 3

Figure 3: MIPs demonstrate temporal crispness of the CAPR sequence in three volunteers who exhibit common flow patterns. **(a)** Volunteer 8 shows symmetric blood flow in the left-to-right calves. There is clear progressive arterial enhancement over the four frames (1–4). The 3D rotational view through time is shown in Movie E1 (Movie E1 [online]). **(b)** Volunteer 7 exhibits asymmetric flow, with the right leg reaching venous phase (arrows) prior to the peak arterial phase in the left leg (**b**, MIP 4). **(c)** Volunteer 1 demonstrates rapid arterial to venous transit with presence of superficial varicose veins as verified at physical examination. For each of the three sequences, consecutive frames are shown at a frame time of 5 seconds.

SENSE and an acceleration factor of eight for eight volunteers. Results from this group were subjected to detailed radiologic evaluation.

Radiologic Evaluation

Eight of the 13 volunteers, referred to as volunteers 1–8, were studied by using array 2 with the CAPR sequence with 2D SENSE with an acceleration factor of eight and 2D homodyne acquisition with an acceleration factor of 1.8, for a net acceleration factor of 14.4. Results were evaluated by using radiologic criteria as indicated in detail in Table 1. Criteria were defined to evaluate the level of artifact, ability to distinguish temporal phases, vessel sharpness, continuity of vascular signal intensity for the major vessels of the calf (ie, anterior and posterior tibial and peroneal arteries), demarcation of origin of the major arteries, and overall diagnostic quality. For each category, a four-point scale was defined, with a score of 1 generally being nondiagnostic and a score of 4 being excellent. The visualization of the communicating and perforating arteries of the ankle near the terminal end of the receiver array was also noted. In evaluating these latter two groups, we found it valuable to perform threefold magnification by using zero padding of the k-space data (38).

Initial Comparison with Computed Tomographic Angiographic Patient Studies

Two patients (men, aged 70 and 61 years) clinically referred for peripheral runoff computed tomographic (CT) angiography were recruited for this study. CT angiography was performed by using the protocol routinely used in our vascular CT clinical practice with a 64-detector row CT scanner (Sensation 64; Siemens Medical Solutions, Forchheim, Germany). Patients were imaged in the supine position with arms above their head. An initial survey topogram was obtained for positioning purposes (120 kVp, 35 mA). Iodinated contrast material (Omnipaque 350; GE Healthcare, distributed by Amersham Health, Princeton, NJ) was injected with an 18–20-gauge catheter placed in the antecubital fossa or forearm. A total volume of 145 mL of contrast

material was injected into an antecubital vein by using a power injector with a consecutive biphasic flow rate of 25 mL at 5 mL/sec and 120 mL at 4 mL/sec followed by 30 mL of saline at 4 mL/sec. Spiral acquisitions in a single examination began 4 cm above the iliac crest and ended at the bottom of the feet. Imaging parameters were as follows: rotation time of 0.5 second, pitch of 0.8, 15 mm per rotation, 120 kVp, 250 mAs with automated triggering (CARE Bolus; Siemens) and exposure control (CARE Dose 4D; Siemens), 64×0.6 -mm collimation, and 0.6-mm in-plane resolution with 2-mm sections and 1.2-mm increment. This resulted in one data set of approximately 1200 axial images.

Automated reconstruction images were obtained at the operator console by CT technologists, which included coronal images of the lower abdominal aorta and iliac arteries, coronal images of the femoropopliteal arteries, and coronal images of the tibial arteries. In addition, directed volume-rendered and MIP images were processed at a freestanding 3D workstation. The same institution review board-approved protocol as was used for volunteer studies at MR angiography was applicable, and written consent was obtained. The same MR angiographic technique as described previously for the eight volunteers imaged with coil array 2 was used. Findings in the lower legs at MR angiography were compared superficially with those seen at CT angiography.

Statistical Analysis

Scores from the radiologic evaluation were tabulated, and the means $\pm$ standard errors of the mean were determined for each category.

Results

Figure E3 (Fig E3 [online]) shows an unsubtracted coronal MIP of the vessel phantoms used for the assessment of spatial resolution. All lesions were well seen in all tubes.

The results of the radiologic evaluation are shown in Table 2: The level of artifact was evaluated in all cases to be minor or none. Venous contamination was rated mild or none in all cases. The

Figure 4

Figure 4: Anteroposterior MIP after threefold interpolation shows origins of major vessels in volunteer 4. AT = anterior tibial artery, P = peroneal artery, PT = posterior tibial artery.

spatial resolution was rated as excellent in seven volunteers, with one case with minor degradation. The continuity of signal intensity of the major arteries of the calves was rated as excellent except in one case where stationary (standing) arterial waves—corrugated ringlike artifact that is sometimes seen in angiographic studies of the lower extremity arteries along the length of the vessel (39,40)—were observed in the lower leg. Demarcation of the origins of the major arteries was rated excellent in all volunteers except in volunteer 5 in whom placement of the coil caused proximal signal falloff to interfere with the evaluation. Overall diagnostic quality was rated as excellent in all cases except in the case of the stationary arterial waves, which was rated as good by one reviewer.

Figure 3 shows four temporally successive MIPs for three volunteers included in the clinical evaluation and chosen to illustrate common enhancement patterns. Clear progressive arterial enhancement was well seen in volunteers with symmetric flow, asymmetric flow, and rapid arterial to venous transit. Movie E1 (Movie E1 [online]) is composed of rotational MIPs through time in the volunteer with symmetric flow.

Figure 4 shows a targeted MIP of the origins of the major vessels in volunteer 4. Figure 5 shows enhancement of the small

Figure 5

Figure 5: Targeted MIPs demonstrate high fidelity with which the small muscular branches of the calves are seen. **(a)** Three temporally successive MIPs (1–3) in volunteer 2 obtained at different oblique orientations. The clarity with which the small muscular branches distal to the major arteries are seen demonstrates the isotropic nature of the 3D CAPR acquisition. **(b)** Three temporally successive MIPs (1–3) in volunteer 8 all obtained at the same oblique orientation. The temporal enhancement of the small muscular arterial branches is pronounced over the three successive frames and shows marked improvement in small vessel detail and overall image quality as the peak arterial phase is reached. The 3D rotational view through time of this is shown in Movie E2 (Movie E2 [online]).

muscular branches of the calves well seen with CAPR acquisition, and this is also shown in Movie E2 (Movie E2 [online]).

In volunteers 1–6, bilateral communicating branches were well seen, while in volunteer 7 only the left communicator was well seen and in volunteer 8 only the right communicator was well seen. Figure 6 shows targeted MIPs of the communicators of both ankles in volunteer 3. The perforating branches were seen bilaterally in volunteer 1. In volunteer 3, only the left perforating branches were seen. In the remaining volunteers, these branches were not well seen.

Figures 7 and 8 show results from the two patient studies. Targeted MIPs in the patient in Figure 7 are shown at the acquired frame rate in Movie E3 (Movie E3 [online]).

Discussion

Our study demonstrates that CAPR permits time-resolved 3D contrast-enhanced MR angiography of both calves over a 40-cm longitudinal FOV with 1-mm isotropic spatial resolution, a frame time less than 5 seconds, and an acquisition time per image of less than 20 seconds. The motivation for high temporal and spatial resolution MR angiography in the calves is the depiction of small vessel size, rapid venous return in many patients with ischemic extremities, and differential contrast material arrival in some patients. The CAPR sequence allowed depiction of the vasculature of the calves with high spatial resolution in a group of subjects who had a range of enhancement patterns, including those with symmetric filling, asymmetric filling, and rapid arterial to venous flow. Findings in two patients were corroborated with findings at CT angiographic studies.

We believe that CAPR has certain technical advantages over other methods for contrast-enhanced MR angiography of the calves having similar spatial resolution. For the same approximate 20-second acquisition time per image, CAPR provides images at a three to four times higher frame rate versus those previously reported (15,41,42). For the same approximate 5-second frame time, the 20-

second acquisition time per image for CAPR is about four times smaller than those of other time-resolved methods (43,44). CAPR avoids k-space interpolation of time-resolved imaging of contrast kinetics (or TRICKS) (10) and extensive sampling of peripheral k-space after central k-space of time-resolved angiography with interleaved stochastic trajectories (or TWIST) (45), characteristics that can degrade the sharpness in portraying the leading edge of the contrast material bolus (46). The radial-like k-space pattern of the CAPR sampling provides some intrinsic resistance to artifact, similar to that demonstrated in conventional projection reconstruction acquisition (47).

The overall high level of diagnostic image quality reported by the readers shows that CAPR consistently provides adequate image quality to visualize small muscular arteries and the communicating and perforating arteries of the ankle even with greater than an order of magnitude acceleration ($R_{\text{net}} > 10$). This is attributable to the following three specific elements of the imaging technique: (a) the improved performance of 2D versus one-dimensional parallel imaging, (b) the use of a peripheral vascular coil array that accounts for the disproportionate anterior-to-posterior to left-to-right FOV, and (c) the intrinsic signal amplification that can be attained with accelerated imaging of transient MR signals (48).

The improved robustness of 2D versus one-dimensional acceleration for a given acceleration factor has been rigorously demonstrated (33). This stems from focusing a given level of aliasing not in a single direction, as in one-dimensional acceleration, but instead onto a gridlike pattern for which case the sensitivities of the individual coil elements are more distinct, resulting in less noise amplification than for the one-dimensional case. In addition to the acceleration factor of eight provided by 2D SENSE, CAPR also uses 2D homodyne acquisition for an additional 1.8 acceleration factor, providing a net acceleration factor of 14.4.

Figure 6

Figure 6: (a) Targeted antero-posterior MIP of both legs with communicating arterial branches identified within the white boxes in volunteer 3. (b, c) Zoomed view of the communicating arterial branch (arrow) for (b) right (RT) and (c) left (LT) legs. P = peroneal artery, PT = posterior tibial artery.

Figure 7

Figure 7: Comparison of MR angiographic and CT angiographic results in patient with peripheral vascular disease and previous femoropopliteal bypass graft. **(a–d)** Coronal MIPs of four consecutive 5-second time frames from MR angiographic examination. **(a)** Fast arrival of contrast material into right anterior tibial artery (AT) (long arrow) through genicular branch (short arrow). The prior time frame portrayed no arterial enhancement in these vessels. **(b)** Subsequent arterial filling of right leg, including midcalf reconstitution of right posterior tibial artery (PT) from collateral flow (arrow). **(c)** Filling of left anterior tibial artery (AT) and filling from collateral flow from circuitous feeding artery (arrowheads) of left peroneal artery (P). Left anterior tibial artery has extensive atherosclerotic disease (arrow). **(d)** Subsequent arterial filling in left leg and early phase of venous return of right leg (arrows). **(e)** Coronal reformation of CT angiographic image shows flow into right lower leg through genicular branch (arrow), confirming the filling pattern seen on MR angiographic result in **a**. Femoropopliteal graft (arrowheads) is seen, but the lack of any proximal luminal signal intensity confirms the lack of graft patency, which is consistent with MR findings in **a**. **(f)** Oblique coronal reformation of CT angiographic images of lower left leg shows extensive atherosclerotic disease in left anterior tibial artery, confirming MR angiographic findings in **c**. **(g)** Oblique reformation of CT angiographic images of lower left leg shows collateral feeding artery identified in **c**. **(h)** Zoomed oblique subvolume image of MR angiographic frame of **d** shows collateral feeding artery and anastomosis with the native left peroneal artery (P) (long arrow) and extensive disease in anterior tibial artery (short arrows). At this angulation, the proximal portion of the posterior tibial artery is shown to be heavily diseased (arrowheads), confirming that distal flow in the peroneal artery is fed by the collateral artery. This is also seen on the 3D rotational view through time in Movie E3 (Movie E3 [online]).

Figure 8

Figure 8: Comparison of MR angiographic with CT angiographic results in patient suspected of having peripheral vascular disease. Only subvolumes of full FOV CT and MR angiographic results are shown. **(a)** Slightly oblique coronal reformation of right leg from CT angiography. A stenosis is identified at the origin of the right anterior tibial artery (AT) (arrow). **(b, c)** MIPs from two consecutive time frames of MR angiography of the same region as seen on CT angiographic result in **a** also show stenosis (arrow). **(d)** Slightly oblique coronal reformation of left leg from CT angiography. A stenosis is identified at the origin of the left anterior tibial artery (arrow). **(e)** MIP from one time frame of MR angiography of the same region as seen on CT angiographic result in **d** also shows stenosis (arrow), as well as another stenosis distally (arrowhead).

High-net SENSE acceleration also benefits from coils designed to provide sensitivities that minimize or reduce noise amplification intrinsic to the reconstruction. Our study showed that because of the high asymmetry in the anterior-to-posterior versus left-to-right FOVs, coil elements placed primarily in the anterior-to-posterior direction should have a different depth of response than those placed primarily in the left-to-right direction. This provided g factors over the volume of both calves, which were generally no larger than 1.4 for acceleration factors as large as eight. The high image quality observed suggests the potential for devel-

opment of arrays with a larger number of elements to allow higher net acceleration factors. However, in this case, the coil element designs may need to be further adapted.

The 3D contrast-enhanced MR angiographic examinations we performed also benefited from the signal enhancement effect associated with accelerated imaging of the passage of the contrast material bolus (48). Briefly stated, the SENSE acceleration focuses the peak contrast signal over a greater extent of the k-space than nonaccelerated imaging. This signal focusing effect compensates in part for the loss of signal-to-noise ratio due to the

undersampling and the SENSE reconstruction.

This study had several limitations. First, although receiver coil array 2 provided improved superior-to-inferior coverage compared with that of array 1, it is desirable to design coils with even larger superior-to-inferior coverage and allow imaging with superior-to-inferior FOVs of 45 cm or more. Second, it remains to be seen how the overall robustness of performance of this method is degraded by patient motion. Third, it is desirable to consider reduction of the contrast material dose below the 20 mL used in this study. This is particularly important if

multiple injections are necessary as in a full peripheral runoff study, although multistation (18) or continuously moving table acquisition (49) may temper this. Finally, although the initial comparisons of the CAPR MR angiographic results with CT angiographic results were promising, a more detailed clinical comparison is warranted.

In summary, we have demonstrated the feasibility of CAPR for time-resolved 3D contrast-enhanced MR angiography to provide diagnostic images of the peripheral vasculature with high temporal and spatial resolution.

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