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Time-Resolved Bolus-Chase MR Angiography with Real-Time Triggering of Table Motion

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Abstract

Time-resolved bolus-chase contrast-enhanced MR angiography (CE-MRA) with real-time station switching is demonstrated. The Cartesian acquisition with projection reconstruction-like sampling (CAPR) technique and high 2D sensitivity encoding (SENSE) (6x or 8x) and 2D homodyne (1.8x) accelerations were used to acquire 3D volumes with 1.0 mm isotropic spatial resolution and frame times as low as 2.5 seconds in two imaging stations covering the thighs and calves. A custom real-time system was developed to reconstruct and display CAPR frames for visually-guided triggering of table motion upon passage of contrast through the proximal station. The method was evaluated in seven volunteers. High spatial resolution arteriograms with minimal venous contamination were consistently acquired in both stations. Real-time stepping table CE-MRA is a method for providing time-resolved images with high spatial resolution over an extended field-of-view.

Keywords

contrast-enhanced MRA; extended FOV; time-resolved; real-time triggering

INTRODUCTION

Since the introduction of stepping-table bolus-chase CE-MRA over a decade ago (1-3), a host of technical developments have improved both image quality and acquisition timing. Tailoring parameters for each imaging station improved scan efficiency (4). Application of parallel imaging and development of phased arrays for imaging an extended field-of-view (FOV) led to significant improvements in spatial resolution for a given scan time (5-9). Calf and thigh compression and imaging parameter adjustments based on a priori measurements of individual hemodynamics helped guard against venous contamination (10-13). However, despite these advancements, the quality of bolus-chase arteriograms continues to lag that of single-station imaging due to the necessarily limited acquisition time at proximal stations, unpredictable contrast dynamics, and the challenge to retain image quality over a larger FOV.

Recently, 3D CE-MRA of the calves has been demonstrated with both high spatial and temporal resolution using the CAPR (Cartesian Acquisition with Projection Reconstruction-like sampling) technique (14). In combination with net 14.4x 2D sensitivity encoding (SENSE) and 2D homodyne acceleration, CAPR produces diagnostic quality time frames in the calves every 5.0 seconds with acquired 1.0 mm isotropic spatial resolution and sharp depiction of the bolus leading edge. Extension of the CAPR method to multiple stations

would have a number of potential benefits for bolus-chase MRA. First, high acceleration at each station would allow improved spatial resolution and reduced acquisition time. Second, time-resolved acquisition could possibly provide diagnostic arterial frames free of venous contamination, even for cases of rapid arterial-to-venous transit. Lastly, if the images were reconstructed in real-time, the ability to clearly depict the bolus leading edge could be used to trigger table motion, thereby eliminating need for a timing bolus or other means of a priori estimation of bolus progression.

The purpose of this work was to demonstrate in volunteers the feasibility of 3D time-resolved two-station bolus-chase MRA using CAPR with 2D SENSE and 2D homodyne acceleration. Additionally, we introduce CAPR-based real-time 3D MR fluoroscopy to monitor progression of the contrast bolus, trigger table motion, and dynamically switch imaging stations.

METHODS

CAPR Acquisition

When imaging multiple stations as in this project, it can be desirable to have different CAPR parameters for each station to accommodate different demands for spatial and temporal resolution. In imaging the calves with 1.0 mm isotropic resolution, it was found previously that the use of a four vane set “N4” CAPR acquisition worked well, with a 5.0 second image update time and 17.7 second temporal footprint (14). However, due to faster bolus progression in the thighs versus the calves (15), a shorter image update time may be desirable in the thigh station. Furthermore, because the time series of CAPR images at the thigh station is to be used in this project for real-time triggering of table motion, it is desirable to have a short image update time to prevent the contrast bolus transit from outstripping the table position.

The variants of CAPR generally used in this work for the calf and thigh stations are shown in Figures 1a-b, respectively. The CAPR pattern used for the calves (a) has been described previously (14) but the features relevant to this project are briefly reviewed here. CAPR apportioned the Cartesian phase-encoded k_Y - k_Z plane into a low-spatial-frequency center region, shown in orange in (a), and a high-spatial-frequency outer annulus. The annulus is further divided into sets of projection-like vanes, where each vane set is identified in (a) by a specific color. The corners of the k_Y - k_Z plane are not sampled and are zero-filled, and data for the unsampled gaps between vanes are estimated by 2D homodyne processing (16). An individual image update consists of elliptical-centric sampling of the center region and one annular vane set, with view sharing applied from previous samples of the other vane sets. With four sets, the CAPR version in (a) is referred to as “N4.” For the thigh station (b), in order to preserve spatial resolution but provide the aforementioned reduced frame time, the number of vane sets was increased to eight, referred to as “N8.” This provided a 2.5 second update time but an increase in temporal footprint to 19.0 seconds.

Fig. 1c shows the temporal play-out of CAPR image updates in the thigh and calf stations as used in this project. In the proximal station, the N8 CAPR acquisition of (b) is applied with a typical image update time of 2.5 seconds. The figure shows data selection for reconstruction of four fully-sampled view-shared images identified as I1-I4. Table motion to the calf station is assumed to occur after the fourth image. Once table motion ends, the N4 CAPR acquisition of (a) begins in the distal station with a 5.0 second update time. Due to the lack of prior image updates, the three initial reconstructed time frames (I5-I7) at the distal station have incomplete sampling of the k_Y - k_Z plane. However, it has been observed that even without view sharing the image updates can still have good quality (17,18). Sampling of all four vane sets is done for image I8 and all subsequent frames.

CAPR-Based Real-Time 3D MR Fluoroscopy

A system was developed to reconstruct CAPR image updates in real time for visually-guided station switching. This is schematically shown in Fig. 2a. A custom-built reconstruction cluster was interfaced to a 3.0T MRI system (Signa® v14.0, GE Healthcare, Waukesha, WI). Acquired raw data was fed from a data storage buffer on the native scanner to the reconstruction cluster immediately after digitization via a high-speed InfiniBand connection (10 Gbit/s). The cluster, running MPI/C++ code, processed the input feed on eight nodes, each with two 3.4 GHz processors and 16 GB RAM. The cluster is about 2x faster than the reconstruction system provided with the scanner (eight 2.6 GHz processors and 32 GB RAM). Reconstructed coronal maximum intensity projections (MIPs) of the image update volumes were then sent to a graphical user interface (GUI) using TCP/IP. The GUI was visible to the operator at the scanner console and had a button to trigger table motion. Upon receipt by the cluster of the operator command to trigger table motion, instructions were passed between the cluster and the MRI system's pulse sequence run-time process using TCP/IP. When table motion was triggered, the image update then being sampled was completed, and the table was moved a predetermined distance to the next station.

Fig. 2b shows a timing diagram and Fig. 2c a breakdown of the individual elements and times of 2D SENSE-homodyne reconstruction (16). These are for the specific case of the reconstruction of a CAPR image acquired at a 2.5 second image update time with 16 receiver channels and R=8 2D SENSE. In this example, the reconstruction time required to generate a MIP after sampling of an image update is 0.9 seconds (910 ms in Fig. 2c). The time for MIP transfer to and display on the GUI is negligible (<30 ms), leaving 1.6 seconds of the 2.5 second update interval for triggering of table motion before completion of the next image update. Much of the 0.9 second reconstruction time is spent performing Fourier transforms and SENSE unfolding. As a result, the real-time system latency, defined as the time delay from the completion of the acquisition of an image update to presentation of the reconstructed MIP of that update on the GUI, is dependent on the size of the sampling matrix, the SENSE acceleration, and the number of receiver channels used. In this work, 16 channels were simultaneously acquired and reconstructed for all studies and the latency ranged from 0.9 to 2.2 seconds depending on the sampling matrix and SENSE acceleration used. For a given sampling matrix, larger SENSE accelerations led to shorter latencies because the size of the Fourier transform of the aliased data decreased.

In Vivo CE-MRA Studies

Human studies were performed under a protocol approved by the IRB of our institution, and written consent was provided by all subjects. Seven healthy volunteers (aged 44-65; three males) were recruited consecutively for in vivo studies. The thighs and calves of each volunteer were imaged using two multi-element receive arrays, one placed circumferentially around the thighs and the other similarly around the calves. Initially, two identical arrays designed for the calves (14) were used for both stations (Volunteers #1-4). However, to better account for variation in volunteer size, a modular array having larger elements and the ability to easily add or remove elements was available for the thigh station of later studies (Volunteers #5-7). No comparable commercial coils were available. Due to MRI scanner hardware limitations, no more than 16 receive elements total could be used for both stations combined. In three of the seven volunteers the somewhat larger thighs necessitated use of ten elements in the receive array to allow full circumferential placement, thereby allowing only six elements for the distal array at the calves. This in turn limited 2D SENSE acceleration in the distal station to R=6 rather than the typical R=8. In order to maintain spatial resolution, the reduced allowable acceleration forced prolongation of the acquisition time in these volunteers. The arrays at both stations were simultaneously used for imaging to improve longitudinal coverage.

Due to pulse sequence and reconstruction software limitations, it was necessary to use the same FOV, spatial resolution, and SENSE acceleration for both stations. The longitudinal FOV for each station was 40 cm. The table was moved 30 cm between stations, yielding an extended FOV of 70 cm. Following a two-station scout, SENSE calibration images were acquired at each station with identical imaging parameters. The calibration images were acquired with $1.0 \times 2.0 \times 2.0 \text{ mm}^3$ resolution and were then interpolated to 1.0 mm isotropic resolution to match the CE-MRA images. SENSE inversion matrices for each station were then calculated prior to the diagnostic bolus-chase MRA acquisition to set up the real-time reconstruction, a process that took about 60 seconds using the cluster. Imaging parameters for the seven in vivo CE-MRA studies are summarized in Table 1. For all cases, a spoiled GRE sequence with a 30° flip angle, $\pm 62.5 \text{ kHz}$ readout bandwidth, and acquired 1.0 mm isotropic resolution was used. Either R=8 (4×2) or R=6 (3×2) 2D SENSE (R/L $\times$ A/P) was applied across the axial phase encoding plane of both stations, as dictated by that station having the lesser number of receiver coil elements. Additionally, 2D homodyne was applied, yielding an additional 1.8x acceleration. An N8 CAPR acquisition with an image update time as low as 2.5 seconds was used in the thigh station, and either N8 or N4 CAPR was used in the calf station. Temporal parameters are included in Table 1.

After the SENSE inversion matrices were determined, the actual contrast-enhanced scan was ready to start. Prior to intravenous contrast injection, CAPR images were acquired for use as subtraction masks, first at the calf and then at the thigh station. Next, 20 mL of contrast material (Multihance®, Bracco Diagnostics, Princeton, NJ) followed by 20 mL of saline flush were administered at 3.0 mL/s using a power injector (Spectris Solaris®, MEDRAD, Indianola, PA). CAPR acquisition commenced at the thigh station with real-time reconstruction. Table motion from the thigh to the calf station was manually triggered upon passage of contrast material along the full extent of the thigh station as observed in the real-time display. The time for table motion and stabilization was separately measured to be just over five seconds. Consequently, we allowed six seconds for table motion to ensure mask registration. CAPR acquisition in the distal station was then performed for approximately 150 seconds.

Evaluation

The in vivo studies were evaluated from the standpoints of: (i) the image quality at each of the two stations; (ii) the image quality of the overall extended-FOV exam; and (iii) the technical ability of the real-time system. For the first of these, three criteria were used at each of the two stations: depiction of the major vessels, level of artifact, and venous contamination. Each of these was evaluated on a four-point scale. Depiction of major vessels was evaluated as (1=non-diagnostic; 2=marginally diagnostic; 3=good quality; 4=excellent quality). Level of artifact was evaluated as (1=severe, rendering an exam non-diagnostic; 2=moderate, possibly interfering with diagnosis; 3=minor, not interfering with diagnosis; 4=negligible apparent artifact). Venous contamination was evaluated as (1=severe, interfering with diagnosis; 2=moderate, possibly interfering with diagnosis or having limited spatial resolution in the arterial frame; 3=good quality arterial frame with minor, non-interfering venous signal; 4=good quality arterial frame with no venous signal). The major vessels assessed in the proximal station were the femoral and proximal popliteal arteries, while those in the distal station were the distal popliteal and anterior tibial, posterior tibial, and peroneal arteries. These were all assessed bilaterally. The extended FOV exam was evaluated using the criterion of continuity of the vascular and background signal across the entire FOV using a four-point scale (1=severe signal discontinuity which could confound diagnosis; 2=disruption of continuity but diagnosis still possible; 3=minor discontinuity; 4=no apparent discontinuity). The technical performance of the real-time station switching was assessed by answering three questions: (Q1) did the real-time images allow

visualization of the contrast bolus in the thigh station?; (Q2) did the table move to the new station after operator instruction to do so?; (Q3) was the motion adequately fast to provide a venous-free image in the distal station? Q1 and Q2 were both answered Yes or No. Q3 was answered using the criterion of venous contamination for the distal station. The first, senior, and radiologist co-authors reviewed all studies together. The radiologist co-author assessed diagnostic quality and the first and senior co-authors rated technical performance.

RESULTS

Evaluation results for the seven in vivo CE-MRA studies are shown in Table 2. The arteries of both the thighs and calves were visualized in all seven volunteers. In all but one volunteer (#7), arterial phases free of venous enhancement were acquired in both stations. The progression of the bolus leading edge was clearly visualized in multiple frames in the thighs and led to successful triggering in all studies. The images of both stations were of good diagnostic quality in all studies with the exception of the thigh station for one volunteer (#3), which was marginally diagnostic. Minor artifacts were present in some studies but did not interfere with radiological interpretation.

Results from Volunteer #4 are shown in Figures 3-4. Fig. 3 shows a sequence of eight consecutive MIP images as presented to the operator in real time during the contrast-enhanced run, with (a-d) of the thigh station and (e-h) of the calf station. In this case, the operator triggered table motion after observing the image in (c), at which point acquisition of the current update was completed (d) and table advance occurred. For this volunteer, the frame interval for the thigh station was 2.5 seconds. Fig. 4a shows a composite extended-FOV MR angiogram, as formed from the proximal image at 38.1 seconds and the distal image at 56.7 seconds post-injection. Figs. 4b-e are magnified coronal views of the right calf (dotted box of 3a) acquired at 46.6, 51.7, 56.7, and 61.8 seconds. Note the high spatial resolution, lack of any venous enhancement, and clear progression of contrast enhancement. Also, note the subtle improvement of vessel sharpness laterally in the progression from (b) to (e) as more phase sets are sampled. These images correspond to reconstructed updates I5-I8 in Fig. 1c. (See also Supplemental Videos #1 and #2.)

Results from Volunteer #6 are shown in Figures 5-6. The presentation order is similar to that in Figures 3-4. However, as described earlier, for this volunteer the relatively larger thighs necessitated use of a ten-element thigh coil that ultimately limited the 2D SENSE acceleration to R=6 in both stations, causing extended update times proximally (4.6 s) and distally (9.5 s). In spite of this, table motion as triggered upon observing the image in 5b still allowed two venous-free distal frames (5d-e) with only minor early venous enhancement in (5f) (arrow). (See also Supplemental Videos #3 and #4.)

DISCUSSION

We have demonstrated the feasibility of high-spatial-resolution 3D time-resolved contrast-enhanced MR angiography of two stations (calves and thighs) using the CAPR acquisition technique. We have further demonstrated high speed reconstruction of 2D SENSE-homodyne-accelerated CAPR acquisitions and shown how the resultant images can be reliably used for real-time triggering of table motion.

In 6/7 of the thigh station results and in all 7/7 calf station results the depiction of major vessels was considered to have either good or excellent quality. Generally, the quality was higher in the calves than the thighs. In the thigh station, most studies received a slightly degraded score of 3 vs. 4 for the depiction of major vessels due to signal dropout at the superior and inferior edges of the FOV. The effect was most pronounced proximally and is

attributed to limited receive array coverage. On the other hand, in the calves only one study was scored less than a 4 in this category. For presence of artifact, 5/7 of the thigh station results received a score of 3 primarily due to vessel blurring, particularly distally, as a number of the vane sets might have been sampled prior to peak contrast enhancement. One study was scored a 2 due to subtraction errors caused by patient motion. In the calf station, inconsistent vessel signal caused by view sharing prior updates with higher vessel contrast caused minor signal dropout in the center of the popliteal artery in 3/7 studies, which led to a score of 3 for artifact. Venous contamination was not observed in the thighs and was only seen superficially in the calves in one study (Volunteer #7). This was likely caused by the extensive image update times in both stations due to a large sampling matrix and limited 2D SENSE acceleration, leading to poor temporal resolution for triggering table motion and a prolonged calf station acquisition extending into the venous phase.

From a technical standpoint, the real-time table triggering worked effectively in these initial studies. In all seven volunteers the bolus transit in the thighs was well seen, and table motion was performed as triggered by the operator. In 6/7 volunteers the table advance was fast enough to provide calf MRA images with no venous contamination, while in the other case the contamination was very slight.

This work can be considered an extension of the technique of fluoroscopically-triggered contrast-enhanced MR angiography that was first described a decade ago (19,20). Comparison illustrates the advances that have been made in both the speed of MR image acquisition and in computation. Riederer et al (20) acquired fluoroscopic images using a 2DFT technique with 256×128 in-plane sampling and 6 mm slice thickness, with a 625 ms frame time. The fluoroscopic images were not used for diagnostic purposes. In this current work, typical 3D fluoroscopic images were acquired with 400×320 in-plane sampling and 132 slice partitions with a frame time only 4 to 8x longer. Moreover, the real-time images themselves have diagnostic quality. In Ref. (20), 2DFT reconstruction using four individual receiver coils was done in 600 ms. In this work, a 3DFT reconstruction using 16 coil elements and incorporating SENSE unfolding and homodyne phase correction was done in 910 ms (Fig. 2).

This project advances methodology for use of time-resolved imaging in conjunction with bolus-chase MRA. In prior works, acquisition of time-resolved calf arteriograms in addition to a non-time-resolved bolus-chase exam has been demonstrated using a dual contrast injection (21,22). The present work combines time-resolved and bolus-chase imaging, efficiently imaging only one contrast injection. Compared to dual injection protocols, single injection methods potentially allow reduced contrast dose, faster exam times, and improved vessel conspicuity due to lack of residual contrast. Others have previously acquired time-resolved bolus-chase arteriograms using continuously moving table methods (23,24). However, the spatial resolution of these works was relatively coarse, the best reported being 1.6 mm isotropic by Fain et al (24) compared to 1.0 mm isotropic in this study. Madhuranthakam et al (23) used real-time reconstruction of 3D image updates with a 2.5 second frame time to trigger table motion, much like this work. However, the image quality was degraded due to poor spatial resolution (at best $2.3 \times 2.3 \times 6.2 \text{ mm}^3$).

Arguably, the greatest challenge of the technique presented in this work is to achieve high image quality in the proximal station, particularly given the need for high frame rates to precisely trigger table motion to avoid venous contamination in the distal station. To achieve both a high frame rate and diagnostic spatial resolution requires significant image acceleration. However, image acceleration degrades SNR, which can be particularly problematic in the proximal station where variation in patient size presents a challenge for receive array development for parallel imaging. Additionally, rapid bolus transit through the

proximal station may lead to incomplete filling of k-space, causing vessel blur. Further work is needed to determine how best to trade off spatial and temporal parameters for this type of acquisition.

This study has several shortcomings, a number of which are primarily engineering-related and potentially correctable. First, the FOV and SENSE acceleration were fixed for both stations due to software limitations. This led to increased and unnecessary sampling in one or both stations, negatively impacting temporal resolution. Tailoring the FOV and SENSE acceleration to each station, as has been done by others for non-time-resolved imaging (5,7,8), would reduce the acquisition time and improve temporal resolution in both stations in this work. Second, the length of the receive array elements used at each station was 27 cm, whereas the longitudinal FOV was 40 cm. Drop-off of element response longitudinally between stations was reduced by overlapping the station FOVs by 10 cm. However, longer receive elements would improve upon the 70 cm longitudinal coverage. Third, the receive arrays for the thigh station might be improved with respect to 2D SENSE performance by better accounting for the asymmetric A/P vs. R/L FOV dimensions using design principles previously applied to the calves (14). Lastly, any reduction in the six seconds required to move the table could be used for extended image acquisition time.

In addition to allowing the FOV, SENSE acceleration, and receive arrays to be different at each station, future work will focus on extending the method to three or more stations. Challenges include developing a system of multiple receive arrays for high image acceleration at all stations, acquiring sufficient data at each station to ensure diagnostic quality, and having a fast image update time for precise triggering of table motion. The speed and flexibility of the CAPR technique, combined with the ability to make real-time decisions based on reconstructed 3D CAPR image updates, adds new degrees of freedom to bolus-chase imaging, moving the methodology toward more robust, patient-specific, and potentially automated acquisitions.

CONCLUSION

Two-station time-resolved bolus-chase MRA with real-time station switching has been demonstrated in imaging of the thighs and calves of volunteers. Multiple 1.0 mm isotropic resolution arterial frames can be acquired in both stations with negligible venous contamination. Real-time reconstruction of 3D CAPR image updates allows for precise triggering of table motion, eliminating the need for a priori estimation of bolus arrival and progression.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIG. 1.

a: N4 CAPR sampling pattern typically used for imaging the calves. Every image update the orange center is sampled along with one of the four vane sets (blue, green, red, yellow). **b:** N8 CAPR sampling pattern used for imaging the thighs. The orange center is decreased in size and the annular region is divided into eight vane sets, reducing the image update time relative to N4 CAPR. **c:** Typical play-out of CAPR image updates in the thigh and calf stations. Colored time blocks correspond to the colored regions in (a) and (b). The data used for reconstruction of the final four time frames at the thigh station and the first four frames at the calf station are shown and labeled I1-I8. The white arrows, corresponding to sampling of the center of k-space, indicate the time at which the frame is said to be acquired. Frames I1-I4 are reconstructed using view shared N8 CAPR with a typical image update time of 2.5 seconds. After the table moves to the calf station following frame I4, frames I5-I8 are acquired with an update time of 5.0 seconds using N4 CAPR. Full view sharing cannot be used for calf image reconstruction until frame I8 when all four vane sets have been sampled.

FIG. 2.

a: Schematic of the real-time system used to trigger table motion. Raw data is acquired using custom-built receive arrays and sent to a buffer for reading by the reconstruction cluster. The cluster rapidly processes CAPR image updates and produces coronal MIPs that are then sent to the scanner console for display on a GUI. The operator triggers table motion via the GUI. The trigger message is then relayed back to the cluster and on to the pulse sequence controller for imaging adjustment. **b:** Real-time reconstruction timing diagram. Raw data is read and fast Fourier transformed along the readout direction as the CAPR sequence is played out, identified as the FFTx line. Upon completion of data acquisition for an image update (white arrows), all raw data has been read and data reconstruction commences. After time t_0 , a reconstructed MIP is sent to the GUI. The operator has time t_1 to trigger table motion before the completion of the next image update. The CAPR image update time is t_2 . **c:** Real-time reconstruction processing times for a typical CAPR acquisition with a 2.5 second image update time. Most time is spent performing fast Fourier transforms and 2D SENSE unfolding. In this example, $t_0 = 0.9$ s, $t_1 = 1.6$ s, and $t_2 = 2.5$ s as defined in (b).

FIG. 3.

Time series of coronal MIPs for Volunteer #4 showing bolus progression in the thighs (a-d) and calves (e-h). The times at which the frames were sampled post-contrast injection are shown. Table motion was triggered upon viewing frame (c), and the table moved after completing the image update shown in frame (d). All frames have purely arterial signal and are of high quality.

FIG. 4.

a: Extended FOV coronal MIP created using frames (d) and (g) of Fig. 3. The vessel signal and background noise is continuous between frames. **b-e:** Time series of targeted MIPs at the region boxed in (a). Times shown correspond to those in Fig. 3. The sharpness of the vessels improves as additional image updates are view shared.

FIG. 5.

Time series of coronal MIPs of the thighs (a-c) and calves (d-f) for Volunteer #6 like those shown for Volunteer #4 in Fig. 3. Superficial venous contamination is visible in the third calf frame (f, arrow), but good quality arterial phases without venous signal were acquired in the first two calf frames.

FIG. 6. Similar results for Volunteer #6 as shown for Volunteer #4 in Fig. 4. The extended FOV coronal MIP was created using frames (c) and (e) in Fig. 5. Very slight superficial venous contamination is visible in the third targeted MIP (d).

CE-MRA imaging parameters. Spatial resolution was 1.0 mm isotropic for both stations for all volunteers. For each volunteer the FOV, sampling matrix, TR, TE, flip angle, bandwidth, and 2D SENSE acceleration were fixed for both stations. The number of receive elements, CAPR vane sets, image update time, and CAPR center size could be varied for each station, and values are designated in the table as “high station / calf station.”

Table 1

Volunteer	1	2	3	4	5	6	7
Age (yr), Gender	65, M	44, F	57, F	49, F	50, M	52, M	45, F
Height (cm), Weight (kg)	178, 73	175, 77	157, 59	175, 87	168, 109	180, 120	165, 102
FOV (cm) (S/I × L/R × A/P)	40 × 32 × 13.2	40 × 32 × 13.2	40 × 32 × 13.2	40 × 32 × 13.2	40 × 32.4 × 17.6	40 × 32.4 × 17.6	40 × 39.6 × 20.0
Sampling Matrix (N _x × N _y × N _z)	400 × 320 × 132	400 × 320 × 132	400 × 320 × 132	400 × 320 × 132	400 × 324 × 176	400 × 324 × 176	400 × 396 × 200
TR, TE (ms)	5.9, 2.7	5.9, 2.7	5.9, 2.7	5.9, 2.7	6.1, 2.7	6.2, 2.8	6.0, 2.7
Flip Angle (degrees)	30	30	30	30	30	30	30
Bandwidth (kHz)	±62.5	±62.5	±62.5	±62.5	±62.5	±62.5	±62.5
2D SENSE Accel. (R/L × A/P)	4 × 2	4 × 2	4 × 2	4 × 2	3 × 2	3 × 2	3 × 2
Number of Receive Elements	8 / 8	8 / 8	8 / 8	8 / 8	10 / 6	10 / 6	10 / 6
CAPR Vane Sets	N8 / N8	N8 / N8	N8 / N8	N8 / N4	N8 / N4	N8 / N4	N8 / N4
Image Update Time (s)	2.5 / 2.5	2.5 / 2.5	2.5 / 2.5	2.5 / 5.0	4.5 / 9.4	4.6 / 9.5	6.4 / 12.6
CAPR Center Radius (1/cm)	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0	1.0 / 1.6	1.1 / 1.6	1.1 / 1.6	1.1 / 1.6
Real-Time Recon Latency (s)	0.9	0.9	0.9	0.9	1.5	1.5	2.2

Table 2

CE-MRA evaluation scores for diagnostic quality

Category	Min – Max	Mean $\pm$ St. Dev.
<u>Proximal Station</u>		
Depiction of Major Vessels:	2 – 4	3.0 $\pm$ 0.6
Artifact:	2 – 4	3.0 $\pm$ 0.6
Venous Contamination:	4 – 4	4.0 $\pm$ 0.0
<u>Distal Station</u>		
Depiction of Major Vessels:	3 – 4	3.9 $\pm$ 0.4
Artifact:	3 – 4	3.6 $\pm$ 0.5
Venous Contamination:	3 – 4	3.9 $\pm$ 0.4
<u>Extended FOV Exam</u>		
Continuity of Signal:	3 – 4	3.9 $\pm$ 0.4