The Use of Real-Time MRI Techniques for Imaging an Extended Field of View in Magnetic Resonance Angiography

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Abstract – **Accurate, fast, sensitive, and safe imaging of the cardiovascular system has major societal benefits owing to the high prevalence of cardiovascular disease. This is particularly challenging in imaging the peripheral vasculature, defined as extending from the renal artery origins to the ankles, because of the long (>120 cm) superior-inferior (S/I) field of view. Contrast-enhanced MR angiography provides major advantages compared to other imaging methods because it uses no ionizing radiation, provides 3D images, and requires only a relatively benign intravenous injection of contrast material. However, such imaging has major technical challenges in that the speed of passage of the contrast-enhanced blood through the vasculature is highly variable from patient to patient and the potentially rapid enhancement of veins can interfere with the radiological interpretation of disease in the companion arteries. The purpose of this work is to describe MRI physics and engineering methods designed to rapidly acquire high spatial resolution images of the peripheral vasculature at individual table positions or "stations," and then to integrate these methods with real-time signal processing to allow interactive control of the MRI patient table, allowing it to advance in synchrony with the advancing contrast on a patient-specific basis. Results are presented with single station techniques to illustrate the potential image performance as well as in the more demanding and desired multi-station application in which the time available for data acquisition is limited at each station.**

I. Introduction

THE imaging of the interior channels or the "lumina" of the blood vessels of the body, also called "angiography" has been a major area of study for medical doctors. Early work was done developing x-ray angiography in conjunction with iodinated contrast agents as far back as the 1930s, generally in conjunction with film as the image receptor. However, in the last several decades a number of methods have been developed for performing angiography with modern technology. These include digital subtraction angiography (DSA) [1], ultrasound (US) imaging [2] possibly in conjunction with Doppler techniques, and angiography using computed tomography techniques [3] sometimes referred to as CT angiography (CTA). Along with these methods other investigators have developed MRI-based techniques for vascular imaging or "MR angiography (MRA)," and these have included methods which are based on the phase differences of the measured signal [4] as well as those due to the magnitude of the signal magnetization, otherwise referred to as "time-of-flight" [5] effects. In the mid-1990s other investigators pioneered the use of an MR contrast material for imaging the vasculature, generally in conjunction with first having made an intravenous administration of a gadolinium (Gd)-based contrast agent [6]. This general approach is referred to as "contrast-enhanced MR angiography" or "CE-MRA." The basis of the method is to inject a contrast agent into the blood on the venous side such as in the antecubital vein of the arm. The paramagnetic properties of the agent cause a marked reduction in the longitudinal relaxation time (T1) of the blood, reducing it from approximately 1100 to 100 msec, allowing significant signal enhancement. CE-MRA, particularly when performed with a three-dimensional (3D) acquisition, has many appealing properties, including applicability to all vascular regions of the body, a 3D image format permitting arbitrary direction of projection and selection of sub-volumes, lack of ionizing radiation, small dosages of the contrast material, and very small risk due to the intravenous vs. intraarterial administration. However, this is offset by the major intrinsic disadvantage of MRI, namely an extended acquisition time. In initial work the acquisition time was typically about a minute long in order to obtain imaging of the renal or carotid arteries with moderate spatial resolution. However, since the introduction of CE-MRA there has been steady improvement in the speed as well as other aspects of the technique. In addition to the desire to provide reduced acquisition time, other early technical challenges included the requirement to synchronize the MRI data acquisition to the arterial phase of the contrast bolus, and the desirability for minimal venous enhancement. These challenges were addressed with a number of improvements, including the development of short repetition time (TR) gradient echo pulse sequences, test bolus [7] and real-time MR-based [8, 9] means for accurate synchronization, and development of special purpose ordering of the acquisition of the phase encoding "views" in which the low-spatial-frequency image components are acquired earliest in the acquisition, allowing extended acquisition times well into the venous phase [10] but without objectionable venous signal. CE-MRA is now widely used for imaging many vascular regions of the body in conjunction with single-arterial-phase methods [11].

There is a broad range of arrival times from one patient to the next in the peripheral vasculature post contrast injection. This is due in part to the long vascular distance traveled by the contrast-enhanced blood, compounded by variable physiological status. This is further complicated by the

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potential for abnormal filling patterns secondary to vessel occlusion or other pathology. To accommodate all of these it is often desirable to image the time-varying nature of the contrast-enhanced blood as it advances through the vasculature. This can allow, for example, identification of the specific feeder vessels in cases of abnormal filling or vascular malformations, and choice of a target vessel if the patient is a candidate for a potential vascular graft. However, in MRI because the time spent in acquiring data for a new image might alternatively be spent in improving the spatial resolution of a single image, forming a new image necessarily prevents use of the time to sample high frequency Fourier coefficients of k-space to generate an image with high spatial resolution. This illustrates the fundamental tradeoff between spatial and temporal resolution as studied, for example, with the Time-Resolved Imaging using Contrast KineticS or "TRICKS" technique [12].

The purpose of this work is to describe how MRI physics methods and high speed signal processing can be used to generate high spatial resolution imaging of the extended peripheral vasculature. The method is based on highly accelerated time-resolved contrast-enhanced MR angiography (CE-MRA) acquisition as well as real-time image reconstruction.

II. Methods

A. MR Data Acquisition

Images for this work were generated using 3DFT data acquisition. With this method the frequency encoding or "readout" direction is performed every repetition interval along the k_X direction, and phase encoding is done along both directions of the k_Y-k_Z plane. The final 3D image is reconstructed by applying 3D Fourier transformation to the (k_X, k_Y, k_Z) or "k-space" data, generating the final image in (x, y, z) space. Sampling within the k_Y-k_Z plane is done on a rectilinear grid, and the process is referred to as "Cartesian" sampling. The specific data acquisition for this work used the method of Cartesian Acquisition with Projection Reconstruction-like sampling (CAPR) as discussed in detail in [13]. The technical properties have been studied in detail using computer-controlled phantoms [14]. Like many methods for performing time-resolved CE-MRA, the technique of view sharing is employed in which not all k-space data are replaced from one image to the next in the time series; rather some data are "shared." Also critical for the ability for short acquisition times is the use of 2D SENSE acceleration [15], with acceleration factors of R = 8 or higher. The importance of this is that 3D image sets with higher spatial resolution and requiring a shorter acquisition time are now possible vs. performance available a decade ago.

B. MRI Acquisition for Extended FOV Imaging

It is possible to characterize time-resolved MR image acquisition methods by the frame time as well as what is called the temporal footprint. This latter metric is defined as the total time required to form a single image in a time-resolved sequence. When no view sharing is done and all of k-space is freshly sampled for each image, the temporal footprint matches the frame time, the time from one image to the next in the series. However, when image frames are presented after having updated only a portion of the data k-space, the temporal footprint is longer than the frame time. In an extreme case if only a small fraction of k-space is updated every image, then the temporal footprint may be 10x or more longer than the frame time. The result is that the actual temporal resolution, or ability to distinguish phenomena occurring at different times, is not as small as the frame rate. Equivalently, the images comprising a sequence appear to have temporal blurring. Thus, view sharing is valuable for providing some increase in the frame rate but only if used in moderation.

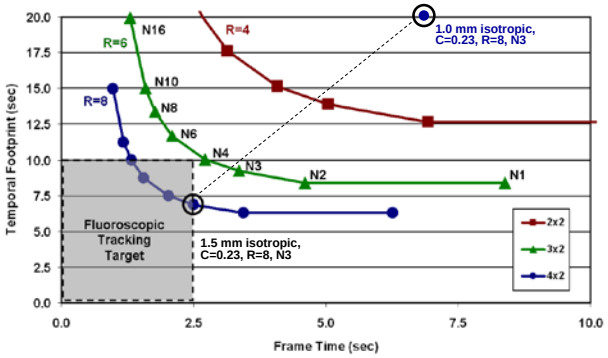


Figure 1. Plot of temporal footprint vs. frame time for imaging of the peripheral vasculature. Upper circled point corresponds to reference acquisition technique for single station imaging.

Figure 1 shows a plot of the temporal footprint vs. the frame time for a 3D FOV encompassing the legs. Various possible MR acquisition methods are designated by individual points on the plot. The level of SENSE acceleration is parameterized by the individual colored curves. As the acceleration factor R increases, the time required to form an image is reduced, leading to points closer to the origin as might be desired for high speed.

The upper circled point corresponds to a specific acquisition technique developed for imaging the calves with 1 mm isotropic spatial resolution [16]. As shown, the frame time is about 6 sec long and the temporal footprint is 20 sec. This technique works well when only a single table position or "station" is to be imaged.

The problem with imaging the extended FOV from the abdomen to the ankles is that multiple, generally three, stations are necessary. The typical speed of transit of the contrast bolus from the abdomen to the thighs and then to the calves is such that in order for the patient table advance to match the contrast bolus transit, a dwell time as short as 10 sec should be allowed at each station. Further, in order for the operator to visualize the advancing contrast bolus with adequate temporal precision to trigger table advance to match the advancing contrast, the frame time must be no longer than about 2.5 sec. These two constraints define the

shaded target zone of performance in Figure 1. To get to this target zone the original circled acquisition method was modified by allowing the spatial resolution to become somewhat degraded from 1.0 mm to 1.5 mm isotropic.

C. Receiver Coil Arrays for CE-MRA

The development of receiver coil arrays for the calves for 2D SENSE-accelerated CE-MRA has been discussed in Ref. [16]. One major finding of that work was that because the two directions of the parallel acquisition for the coronal-format CE-MRA acquisition are typically within the transverse plane, the coil elements should be placed circumferentially around the calves. This provides both good SNR and low susceptibility to noise amplification based on the algebraic SENSE unfolding. Similar coils for other regions of anatomy have also been developed, such as the brain, feet, hands, and abdomen. The design of each coil array is similar. First, a basic element size is specified, with the length chosen to allow imaging along the extent of the superior/inferior (S/I) field-of-view (FOV). The width is selected to provide moderate falloff of sensitivity in the transverse direction into the patient anatomy.

For this project this methodology was extended to having a multi-element array at each of the three stations. This setup is shown in Figure 2. At the left is a single two-element module, each 40 cm long. Six such modules are attached together side to side at the top of the figure, corresponding to the 12-element coils wrapped around the abdomen-pelvis station. The second array is comprised of ten elements and is wrapped around the thighs. The final array consists of eight elements and is used for the most distal station, wrapped around the calves.

D. Real-Time Image Reconstruction

To image the extended FOV of the peripheral vasculature accurately, provision was made to allow the operator to see the advancing contrast bolus in real time. This was done with custom image reconstruction hardware. The engineering specification was to require that the 3D data set reconstruction and all signal processing to account for 2D acceleration be performed with approximately 250 msec.

E. In Vivo Experiments

The CAPR acquisition sequence was used in conjunction with 2D SENSE parallel acquisition in imaging the peripheral vasculature of volunteers as well as in patients for whom CE-MRA was clinically indicated. The study was done under a protocol approved by the Institutional Review Board of our institution. Written consent was obtained from all volunteers. The CAPR acquisition was performed using a fast spoiled gradient echo pulse sequence with the typical parameters: repetition time (TR) 5.85 msec; echo time (TE) 2.7 msec; flip angle 30°; bandwidth ±62.5 kHz; and sampling of a full 400-point echo along the frequency encoding direction. Prior to the contrast-enhanced run a calibration scan was performed to obtain coil sensitivity data. For the contrast-enhanced run for each subject no more than 20 mL of Multihance (gadobenate dimeglumine, Bracco Diagnostics, Princeton NJ) was injected into an arm vein at a rate of 3 mL/sec followed by a 20 mL saline flush also administered at 3 mL/sec. With the three-station method the spatiotemporal resolution in the final station matches that of Ref. 16 but now high resolution arterial-phase 3D images of the two proximal stations are also provided.

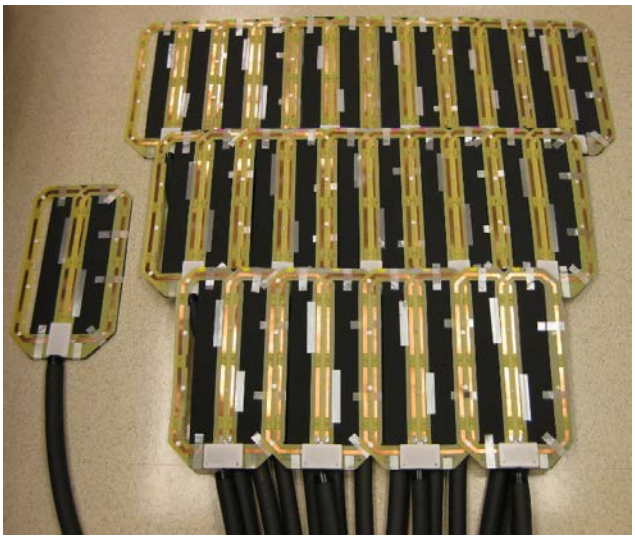


Figure 2. Receiver coil array for long-FOV MRA.

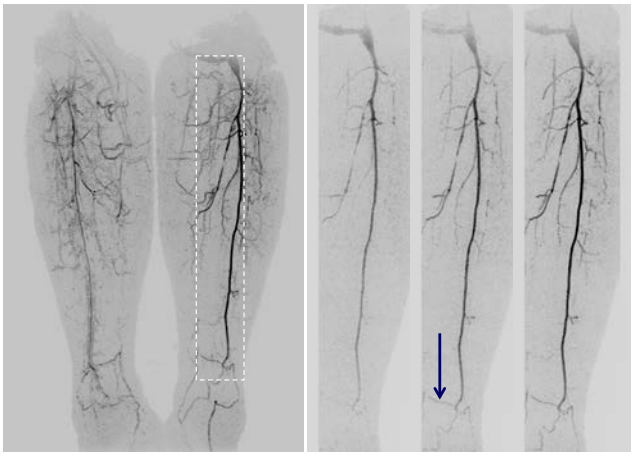
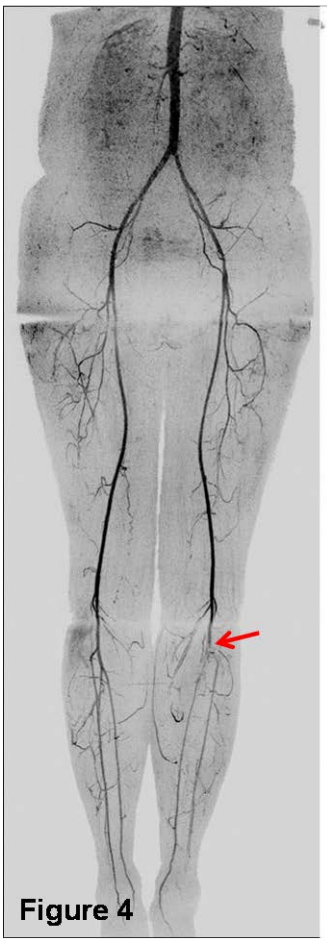


Figure 3. Image of single station (calves) with cross filling at level of ankles via perforator artery (arrow).

III. RESULTS

Sample results from a single station study are shown in Figure 3. For this subject there was considerable disease on the patient's lower left leg, and the ankle vessels were perfused by cross filling via the perforator artery. Sample results from the three-station extended-FOV technique performed with real-time reconstruction and interactive patient table advance are shown in Figures 4 and 5. Radiological evaluation using a four-point scale in over 20 three-station studies confirmed consistently high signal level and vessel sharpness.



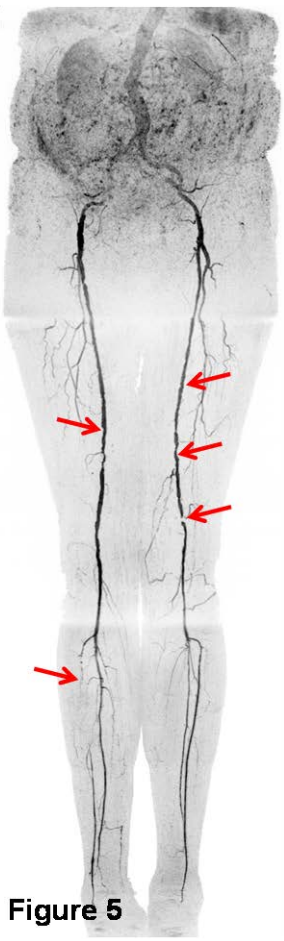


Figure 4. Image of an extended FOV using three stations and real-time table advance. Patient has focal lesion at distal end of left popliteal artery (arrow). Figure 5. Three-station study of a second patient showing bilateral atherosclerotic disease (arrows).

IV. Discussion

We have described the principal elements of a method for performing high resolution 3D contrast-enhanced MR angiography of an extended FOV ranging from the abdomen to the ankles. The method allows for interactive triggering of table advance by the operator. The principal technical enablers of the method are view sharing, 2D acceleration methods using 2D SENSE, customized modular multi-element coil arrays, and real-time image reconstruction. We have demonstrated the applicability of this method in single- and multi-station imaging of the peripheral vasculature.

Whenever acceleration of this magnitude is performed a major concern is the loss of SNR due to: (i) use of less data in the reconstruction, and (ii) any noise amplification intrinsic to the unfolding process. These appear to be well addressed by the various receiver coil arrays which can be sized and placed around the targeted vasculature.

Future directions of this work include further reduction of acquisition time using even higher acceleration factors and the potential for generating images using fat suppression methods vs. subtraction of a pre-subtraction mask image.

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