Accelerated acquisition and reconstruction of non-CPMG fast spin echo sequences

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Introduction: Quadratic phase modulation of the refocusing pulses in a fast spin echo (FSE) sequence [1,2] has been shown to sustain signal magnitude and phase regardless of the signal phase at the beginning of the echo train. This technique, also known as non-CPMG (Carr-Purcell-Meiboom-Gill) FSE, generates two sets of signals in a single echotrain, which typically are saved and reconstructed separately [1]. This requires that the echo train be twice as long as that of conventional FSE to fill the same matrix size, which extends acquisition time and causes blurring in single shot techniques. However, the two signals are related by a modulation function that varies relatively slowly in space, similar to that of low-order phase changes between shots in multi-shot diffusion weighted imaging. In this study, we present a novel concept for accelerated acquisition and reconstruction of non-CPMG FSE trains that is based on techniques used for reconstruction and phase correction of multishot diffusion imaging methods. We also implement these concepts with two applications: accelerated single-shot FSE (SSFSE) and multishot PROPELLER diffusion imaging.

Theory: The two sets of signals created in a non-CPMG echo train can be represented as:

$$S1 = (I + jQ)\exp(\varphi) \qquad S2 = (I - jQ)\exp(\varphi)$$

Where the magnitude of I and Q are proportional to the in-phase and out-of-phase components of the signal at the start of the echo train, defined as the time point half an echo spacing before the first refocusing pulse. I and Q are themselves complex values, and their relative phase varies with refocusing flip angle, from approximately 90 to 135 degrees for flip angles between 90 and 180. Since this modulation is based on the RF transmit and receive fields, the relative phase and magnitude of S1 and S2 can be assumed to be smoothly varying in space. When low order information for both signals is adequately captured within a shot, the two signals can be combined after correction of both magnitude and phase, using modified multishot phase correction techniques [3-6], or more generally, with super-FOV reconstruction [7]. Cartesian SSFSE acquisition can thus be accelerated by limiting double encoding of the non-CPMG signals to just the center portion of k-space. For PROPELLER acquisitions, no additional encoding is required, since all blades overlap at the center.

Methods: A Cartesian SSFSE sequence and a diffusion weighted split-blade PROPELLER FSE sequence [8] were modified to incorporate non-CPMG phase modulation. No data was collected during the first 4-7 echoes of each echo train, during which a stabilization scheme was implemented. The center 16 lines of k-space of the SSFSE sequence were double encoded, while the outer portion of k-space on one side was single-encoded, alternating between the two signal groups. Synthesis of complementary non-CPMG signals was performed with a modified ARC algorithm that trains one signal's data to the other [6]. Full k-space sets for both signals are then synthesized. The whole acquisition was also further accelerated by a factor of 2 using ARC [9] with external calibration data. The split-blade PROPELLER sequence acquired the even and odd echoes of the same echo train as separate perpendicular blades. Blade width was 16 lines of data, spaced to 30 lines in k-space through the use of mutual calibration [8]. 8 blades were acquired for reconstruction of a 256x256 matrix. After blade-by-blade phase correction, the low order magnitude of the two blade images in each pair were scaled to the average of the two, reducing blade-to-blade magnitude variation. An upper limit to the magnitude scaling was placed to prevent excessive noise magnification. Sequences were applied to phantoms and volunteers in a 1.5T Signa HDx imager (GE Healthcare, Waukesha, WI) with an 8-channel head coil. Images were observed for residual artifacts and overall image quality.

Results: Phantom images acquired with SSFSE are shown in figure 1. Non-CPMG acceleration removed residual N/4 artifacts that could not be removed with ARC alone. Volunteer head images acquired with PROPELLER are shown in figure 2. Magnitude correction significantly reduced aliasing artifacts without negatively affecting the overall reconstructed image.

Discussion: We have demonstrated acceleration of non-CPMG acquisitions that limits double encoding of the two signal groups to the center portion of k-space. This acceleration is compatible with further parallel imaging acceleration, using a variety of options for acquiring calibration data. While residual aliasing in PROPELLER images was reduced with magnitude correction, contrast appeared unaffected, since magnitude averaging of low order data is inherent with PROPELLER reconstruction. Non-CPMG acceleration brings the minimum echo train length of the non-CPMG sequence closer to that of conventional FSE sequences, and completely eliminates the double encoding requirement for PROPELLER.

References: 1. LeRoux P, JMR 155:278-92. 2 Murdoch JB, Proc. SMRM 1994, p 1145. 3. Miller K et al, MRM 50:343-353. 4. Liu C et al, MRM 54:1412-1422. 5. Pipe et al, MRM 47:42-52. 6. Hwang KP et al, Proc ISMRM 2007, p. 8. 7. Lustig M et al, Proc ISMRM 2005, p 504. 8. Huo D et al, Proc ISMRM 2008, p756 9. Brau AC et al, Proc. ISMRM 2006, p 2462.

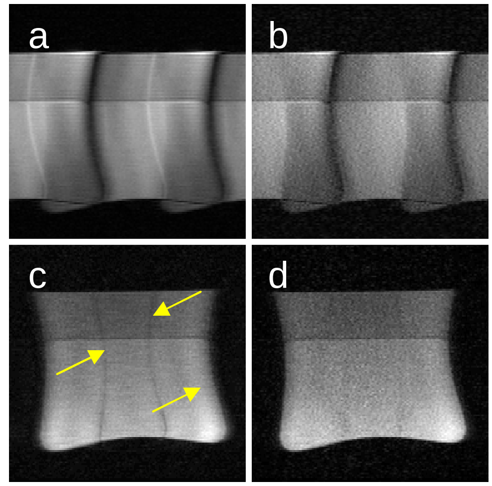

Figure 1: Phantom images acquired with non-CPMG SSFSE accelerated with both ARC and the proposed method, where only the center portion of k-space was double encoded with the two non-CPMG signals. Images are shown before synthesis with ARC (a,b) and after (c,d). Synthesis with the proposed method was applied in (b,d). Arrows note residual aliasing and increased blurring (c).

Figure 2: Diffusion weighted non-CPMG PROPELLER images, with correction (b,c) and without (a). Reduction in radial artifacts and improved conspicuity of fine structures is shown in the images window-leveled to show differences in background signal (a,b).