Estimation and Compensation of Motion-Induced Phase Error in 3D for Multi-shot Diffusion Acquisitions

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Target audience: High-resolution diffusion imaging pulse sequence developers.

Purpose: High-resolution diffusion-weighted imaging is limited to multi-shot acquisitions, which are problematic due to inter-shot phase variations caused by rigid-body (non-repeatable) and pulsatile (repeatable over the cardiac cycle) motion during the diffusion-encoding periods [1]. In diffusion-weighted SSFP (DW-SSFP) and diffusion-weighted FSE (DW-FSE) phase variations do not only hamper the combination of shots but also create incoherent echo pathways that contribute to destructive interferences of echo pathways which in turn leading to signal decay and instability. It has been proposed to *prospectively correct* this phase before the creation of the spurious pathways created by subsequent RF pulses [2,3,4]. A larger volume of k-space must be covered to make such pulse slice selective than to compensate the 3D non-linear phase error. The purpose of this work was to measure the 3D non-linear component of the phase in human volunteers and design a short-duration (<10ms) 3D RF pulse that is capable of correcting this phase.

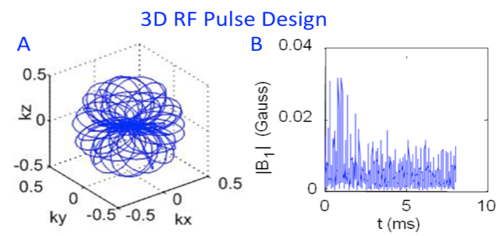

Figure 1: A) Excitation trajectory in normalized k-space with supported matrix 10^3 and FOX of 22x22x22 cm^3. The trajectory is obtained by rotating the in-plane parametric equation $\{sin(\theta)cos(\theta),\ sin(\theta)sin(\theta)|\theta|/\theta\}$, $-\pi\leq\theta<\pi$ around a normal described by the equations in [5] B) Magnitude of the RF pulse. Total duration 8.1 ms.

Methods & Results: • *In vivo phase measurement:* Phase profiles (due to brain pulsation) were measured in x, y, and z using a 4D flow sequence (VENC=10cm/s) [4] gated on 20 phases over the cardiac cycle. These displacements were used to calculate the phase accrual and tissue velocity for arbitrary diffusion preparations. Based on that velocity and the diffusion-encoding direction, the resulting non-linear phase error was estimated. Figure 2 a,c,e shows the non-linear phase for one phase of the cardiac cycle with diffusion gradients in direction A/P and equivalent *b*-value of 155 s/mm^2.

• *RF pulse design:* A 10^3 trajectory (Fig.1a) was designed which offers a good tradeoff between resolution and the drawbacks of long RF pulses (off-resonance sensitivity, relaxation effects). A 3D RF pulse for DW-SSFP (Fig. 1b) was generated to imprint the conjugate of the measured phase error pattern onto a water phantom. The 10° RF pulse *rf(t)* was obtained by minimizing the L_2 error between the desired profile *P(p)* and the DFT *E(p,t)* (small tip angle encoding matrix for a given trajectory) of the RF over a region of interest *ROI(p)* as:

$$Argmin_{rf(t)}\{|ROI(p).*[E(p,t)*rf(t)-P(p)]|_2\}.$$

No SAR restrictions were added. The phase was imprinted on a water phantom using the single channel transmit body coil and was measured at 3T by an 8-channel head coil and a 48^3 SPGR scan. A similar scan using hard pulse excitation was used to measure and remove the baseline phases (RF, eddy currents). The phase was unwrapped [6], downsampled to 10^3 and masked by the ROI (Fig. 2 b,d,f). A complex magnetization RMSE of 30% was measured. The standard error in magnitude and phase were 29% and 22 degrees, respectively.

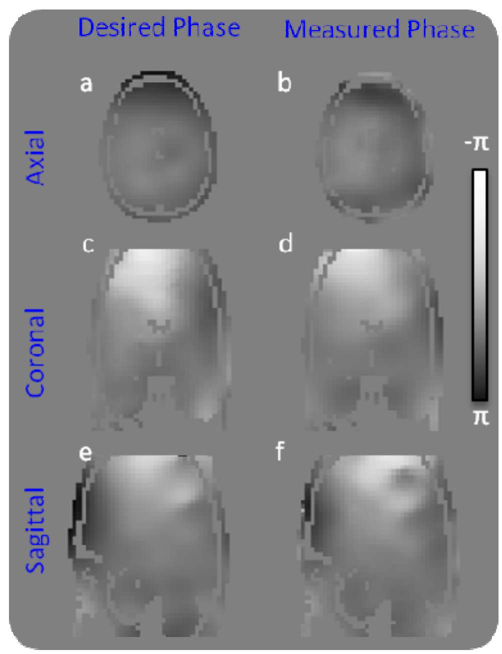

Figure 2: The desired 3D excitation phase profile (a,c,e) compared to the low-passed (10^3), measured phase profile in a water phantom (b,d,f). Note the close correspondence of the low-resolution component of the phase achieved with the short (~8 ms) RF pulse.

Discussion & Conclusion: These results suggest that a set of RF pulses can be designed to correct the repeatable non-linear 3D phase in gated diffusion acquisitions. This represents a significant step toward making alternative fast 3D diffusion-weighted sequences such as DW-SSFP and DW-FSE feasible for in-vivo use.

References: [1] O'Halloran et al., MRM 68, 2012; [2] Nunes et al, ISMRM 2011, 172; [3] Nunes et al, ISMRM 2012, 115; [4] Porter et al. US Patent 2012/0025825 [4] Markl et al. MRM 17, 2003; [5] Wong et al, MRM 32, 1994; [6] Cusak et al. Neuroimage 16, 2002

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