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

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Target audience: High-resolution diffusion-weighted imaging (DWI) pulse sequence developers.

Purpose: High-resolution DWI is limited to multi-shot acquisitions, which are problematic due to inter-shot phase variations caused by 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, leading to signal decay and instability. To remedy this problem, it has been proposed to *prospectively correct* the motion-induced phase [2,3,4, 5]. This problem is difficult, not only due to its 3D nature, but also because of the challenge of validation with repeatable motion. The purpose of this work is to measure the 3D non-linear component of the phase in a novel, pulsatile phantom with repeatable motion and prospectively correct the linear and non-linear components of this spurious phase using a 3D RF pulse.

Methods & Results: • *Pulsatile motion phantom setup:* The phantom consisted of 2 latex balloons (Fig 2). Balloon A was connected to a flow pump (Harvard Apparatus, Holliston, MA) modified so that the flow went back and forth at each beat with no net flow at a rate of about 58 times/minute. Balloon B was taped to balloon A and filled with a semi-solid mixture of sodium polyacrylate, water and gadolinium. As balloon A inflated and deflated, balloon B experienced periodic, non-rigid motion. Gating was performed by connecting the plethysmometer to a portion of the pump tube containing an air bubble. With motion of the bubble, the reflective properties of the tube change and are detected by the plethysmometer. • *Non-linear phase measurement:* The motion-induced phase (Fig 4A) was measured using a diffusion-weighted spin echo EPI scan gated to the peak motion of the pump. A b-value of 124 s/mm^2 was used to impart a phase spanning roughly a 2π range for the level of motion in the phantom. • *RF pulse design:* A 10^3 stack of spirals trajectory (Fig. 3) was chosen for the RF pulse to offer a good tradeoff between resolution and the drawbacks of long RF pulses (off-resonance sensitivity, relaxation effects). The RF pulse was generated to imprint the conjugate of the measured phase 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:

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

• *Prospective correction:* The same pulse sequence was used to test the prospective correction. First, only the linear portion of the phase was corrected using a blip gradient (Fig 4B). Then the non-linear correction was added (Fig 4C and D). The standard deviation of the phase inside the phantom was measured at 0.70 rads before correction, 0.58 rads after linear phase correction and 0.35 rads after linear and non-linear corrections. The standard deviation of the magnitude profile imparted by the RF was measured at 25% (not shown). The constant components of the phase were discarded for this experiment and air regions were masked out.

Discussion & Conclusion: These results suggest that a set of RF pulses can be designed to correct the repeatable non-linear 3D phase in gated DWI. 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. Furthermore, the phantom-based methodology developed here provides a platform upon which to test prospective phase corrections under repeatable conditions with real motion.

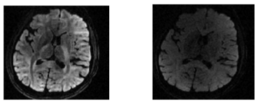

Figure 1: Effect of motion phase errors on diffusion imaging scans. Direction of low motion (left) and of high motion (right).

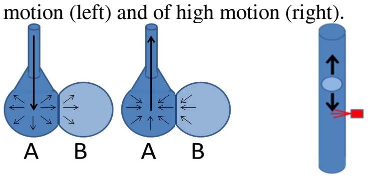

Figure 2: Non-rigid motion of Balloons A and B (left image). Placement of the plethysmometer (red) near an air bubble to allow gating (right image).

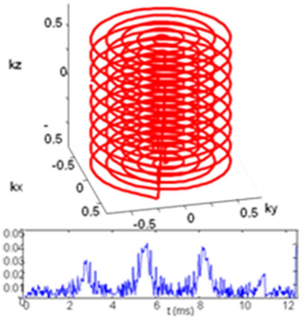

Figure 3: Excitation trajectory (red) in normalized k-space with supported matrix 10^3 and FOX of 22x22x22 cm^3 and magnitude of the RF pulse (blue). Total duration 12.1 ms.

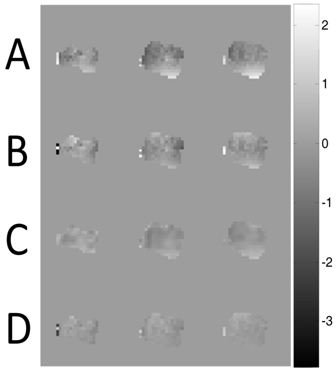

Figure 4: A) Measured phase without correction B) Measured phase with linear correction C) Conjugate phase of the RF pulse used for prospective phase correction D) Measured phase after full correction.

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, [5] Aboussouan et al., ISMRM 2013, 2084

Acknowledgements: NIH (5R01EB011654, 5R01EB008706, 5R01EB002711, P41 RR009784), the Center of Advanced MR Technology at Stanford (P41 EB015891), Lucas Foundation.