Analysis and Design of Higher-Order Motion-Compensated Diffusion Encoding Schemes for In Vivo Cardiac DTI

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Introduction: Cardiac diffusion tensor imaging (DTI) [1-3] is increasingly used to characterize myocardial microstructure and myofiber orientation in both normal and diseased hearts. Clinical applications of the technique in humans have been made feasible by employing either STEAM [4] or bipolar diffusion encoding [5] in conjunction with acquisition during the quiescent phase of the cardiac cycle to reduce the effects of motion. However, extension of *in vivo* cardiac DTI to small animals remains elusive or suboptimal due to the high heart rate, absence of cardiac quiescent phase, and insufficient gradient hardware performance. The present work conducts a systematic analysis of the effects of cardiac motion on diffusion encoding and proposes pulse sequence schemes to minimize them via higher-order motion compensation. The proposed approach is demonstrated by the feasibility of myocardial fiber orientation mapping in live rats, and is expected to benefit *in vivo* cardiac DTI in humans and other animal species.

Methods: High temporal-resolution (130 fps) FLASH-CINE images over the entire cardiac cycle were acquired on an anesthetized Sprague-Dawley rat using a Bruker 70/30 instrument equipped with 600 mT/m gradient system. Position-time relationships of selected left-ventricular locations within these images were derived and used to numerically estimate the motion sensitivity of diffusion encoding by integrating the spin phase equation. Because motion compensation was found to be more effective at reducing the spin phase contribution than increasing the gradient performance, minimum-duration schemes for nulling the second (acceleration-compensation) and third (jerk) gradient moments [6] were designed for the spin echo sequence. The schemes (acceleration compensated sequence illustrated in Fig. 1) were evaluated by performing *in vivo* DTI scans (dual cardiac and respiratory gating, 0.35 x 0.35 x 3 mm^3 voxel size, 128 x 128 matrix size, TR = 500 ms, b = 350 s/mm^2, 12 diffusion encoding directions) on rats, and compared to those obtained using non-compensated (monopolar) and velocity-compensated (bipolar) diffusion pulses. DTI scans were analyzed by generating myocardial fiber orientation helix angle maps via standard methods [7].

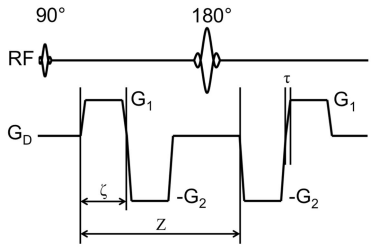

Figure 1. Minimal-duration trapezoid pulses with velocity and acceleration compensation for spin echo diffusion encoding.

Results and Discussion: Spin phase analysis reveals that motion sensitivity of diffusion encoding gradient pulses vary widely depending on the location, cardiac cycle time point, and axis of motion with respect to the encoding direction. Moreover, because the motion is not constant during diffusion encoding, significant sensitivity remains when velocity-only compensation was employed. For reducing the sensitivity, compensating for higher orders of motion was found to be most effective. For example, acceleration compensation reduces motion sensitivity by a factor of 11.2, whereas increasing gradient peak-amplitude by 2.5 times decreases the spin phase by only a factor of 2.3. Results of live animal diffusion MRI (Fig. 2) are largely consistent with the motion sensitivity analysis. As higher order motions are compensated, the appearance of the heart progressively improves, albeit longer TEs associated with higher order compensations also reduce the image SNR. A myofiber helix angle map obtained using acceleration compensation is shown in Fig. 3, which to the authors' knowledge is the first time such map of a live rat has been presented. Although demonstrated for spin-echo here, the proposed approach can be easily modified for use in other preparations and acquisitions such as STEAM and EPI.

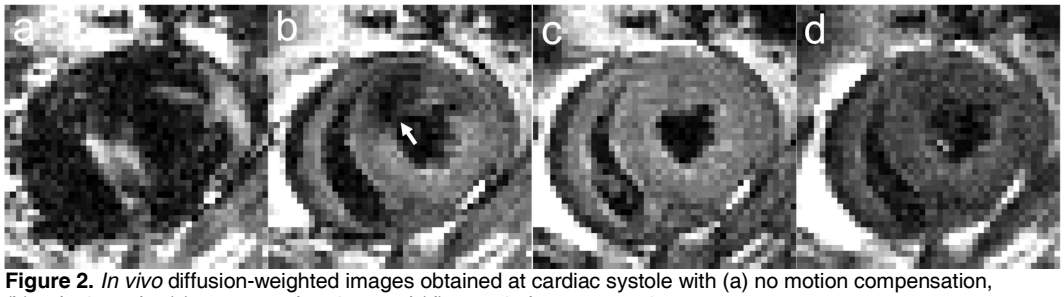

Figure 2. *In vivo* diffusion-weighted images obtained at cardiac systole with (a) no motion compensation, (b) velocity-only, (c) up to acceleration, and (d) up to jerk compensation.

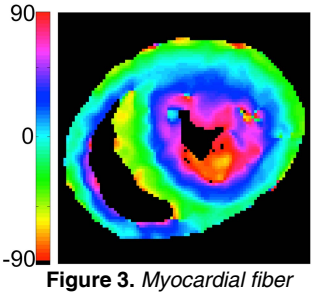

Figure 3. *Myocardial fiber* helix angle map of a live rat.

Conclusion: Diffusion encoding with up to acceleration moment nulling was found to offer the best combination of motion compensation and image SNR, which is crucial for making cardiac DTI on live rats now feasible. The ability to characterize myofiber orientation and myocardial microstructure *in vivo* is invaluable for longitudinal studies necessary in preclinical studies of cardiac development and diseases.

References: [1] Tseng WY et al, JMRI. 2006; 23:1-8. [2] Wu MT et al, Circ Cardiovasc Imaging. 2009; 2:32-40. [3] Toussaint N et al, MICCAI. 2010; 13:418-425. [4] Reese TG et al, Magn Reson Med. 1995; 34:786-791. [5] Gamper U et al, Magn Reson Med. 2007; 57:331:337. [6] Pipe JG et al, Magn Reson Med. 1991; 19:175-179. [7] Jiang Y et al, Magn Reson Med. 2004; 52:453-460.