Eddy-current-induced Artifact Suppression for b-SSFP via Through-slice Dephasing

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Introduction: Magnetic field gradients induce eddy currents (ECs) in the conductive components of the scanner. As described by Maxwell's equations, these currents create undesired time-varying magnetic fields in return. Typically, EC artifacts are addressed by the use of shielded gradient coils and model-based pre-emphasis of gradient waveforms in all major systems, and by the avoidance of phase encode (PE) ordering schemes with large jumps in k-space. EC-induced fields are particularly problematic for steady-state coherent imaging sequences such as fully balanced steady state free precession (b-SSFP), since the time integrals of applied field gradients are designed to be zero within each short TR. Given that consecutive readouts are only a few milliseconds apart, these time-varying gradient fields are strong enough to create significant signal fluctuations, disturbing any steady-state and inducing severe artifacts [1] With Cartesian b-SSFP imaging, only PE gradients vary from TR to TR. The differential in PE gradients between each TR is minimal for a conventional linear PE scheme where consecutive lines of k-space are acquired one after another, resulting in a smooth variation of the induced fields over time. However, when PE ordering schemes such as random, centric or golden-ratio based [2,3] PE techniques are used, the unwanted fields fluctuate and cause k-space signal modulation in the PE direction (Fig 1). We explore *through-slice dephasing (TSD)*[1,4], which has not been well characterized, as a means of reducing EC artifacts.

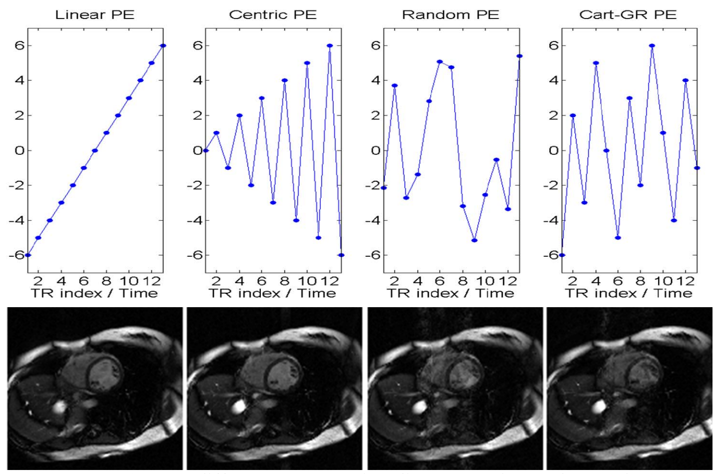

Figure 1: (Top) Four different PE strategies: linear, centric, random and Cart-GR. (Bottom) Short axis cardiac images acquired using the corresponding PE schemes. PE direction is vertical.

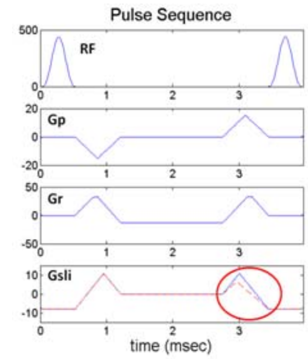

Figure 2: (blue) b-SSFP has fully balanced gradients. Through-slice dephasing decreases the area of the slice selection dephasing gradient (red oval), leading to a small amount of intravoxel dephasing in the slice direction.

Methods: A healthy volunteer was imaged on a 1.5T System (Espree, Siemens Healthcare, Erlangen, Germany) using the standard body phased-array and spine coils after informed consent was obtained. Maximum gradient amplitudes and slew rates were 33 mT/m and 120 mT/m/ms, respectively. A Cartesianized golden-ratio (Cart-GR) step ordering was introduced as a nonlinear acquisition strategy in addition to centric and random PE orderings. With Cart-GR, the resolution in the PE direction is a *Fibonacci number* (e.g. 233) and the step over the k_y-grid between consecutively acquired PE lines is the previous *Fibonacci number* (e.g. 144). Each PE line is acquired exactly once over 233 successive TRs, guaranteeing that k-space is filled without repetitions or missing lines for any arbitrary scan window. 2D b-SSFP imaging was implemented with a sequence harnessing a hardware optimized gradient design [5] for speed (TR: 3.130 msec, TE: TR/2, matrix: 233x256, FOV: 300 mm, α=35°). TSD was achieved by modifying the 0^{th} moment of the slice-selection dephasing gradient (Fig 2), creating symmetrical phase accrual at the end of each TR. The angle of dephasing used for the human studies was ±30° at voxel edges. In addition to human studies, b-SSFP simulations were run on Matlab to investigate the effect of ECs and through-slice dephasing on individual spins. ECs were modeled as sources of spin dephasing as a family of transients with time constants similar to those that are used by the scanner for pre-emphasis of waveforms. Simulation results represent spin magnetizations integrated over voxels. Transverse magnetizations were simulated at the center of every sampling window (TE) over time. Then, they were reordered to represent their PE locations in k-space to compute point spread functions (PSFs) via FFT.

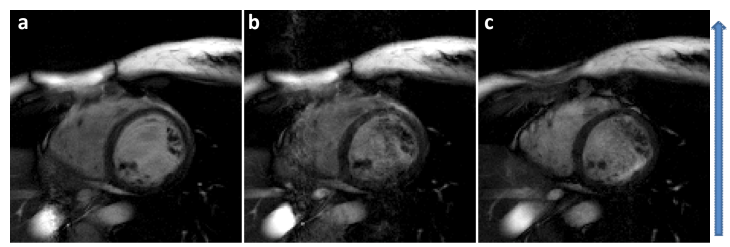

Figure 3: Short axis images acquired using (a) linear PE, (b) Cart-GR PE and (c) Cart-GR PE with 30° through-slice dephasing. TSD substantially improves image quality for Cart-GR PE. Blue arrow indicates PE direction.

Results & Discussion: Fig. 3 shows that image artifacts generated by the Cart-GR scheme are removed when TSD of ±30° is utilized. The simulations demonstrate that signal fluctuations are reduced when the same amount of dephasing is used (Fig. 4). Fig. 4 also shows that side peaks in the PSF, which yield image distortion along the PE direction, are suppressed, clarifying artifact reduction. Fig. 5 signifies that TSD will cause SNR loss, yet minimal signal drop is predicted with dephasing angles less than ±60°. However, for off-resonance spins (e.g. adipose tissue), the signal behavior is rather different as signal drops can occur with lower dephasing angles. Similarly, changes in banding artifacts are visible (Fig 3), with TSD. Changes in contrast are also expected, as demonstrated by simulations (Fig. 5).

Conclusion: Through-slice dephasing enables suppression of signal instabilities, removing image distortions with minimal SNR loss. k-space trajectories with highly variable PE orderings can be efficiently realized by using TSD. More work is needed to determine the effect of TSD on moving spins.

References: [1] O.Bieri, et al. MRM 54:129 (2005); [2] S.Winkelmann et al. IEEE TMI 26:68 (2007); [3] P.Siegler at al. ISMRM 2010; [4] B.A. Hargreaves ISMRM 2008; [5] J.A. Derbyshire, et al. MRM 64:1814 (2010).

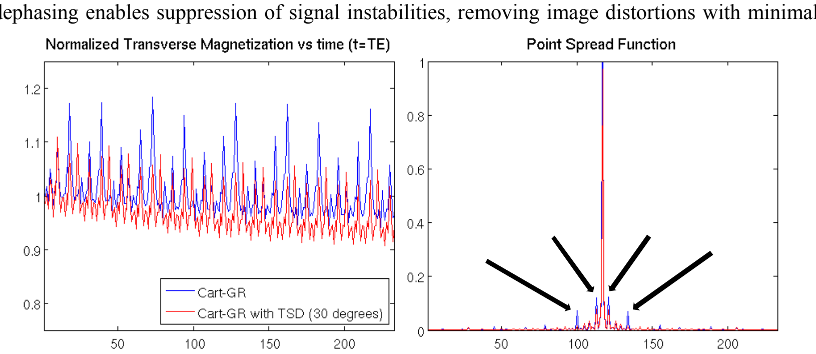

Figure 4: (Left) Transverse magnetizations normalized to theoretical steady-state signal are simulated at TEs for Cart-GR PE scheme (blue) without and (red) with a TSD of 30°. (Right) PSFs plotted with same color legend as on the left. Arrows indicate substantial side peaks (blue).

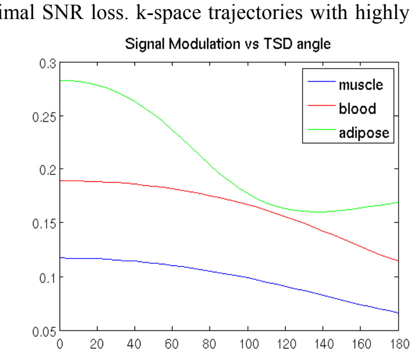

Figure 5: Signal dependencies on TSD angle for various tissues. Note extra signal loss associated with off-resonance (adipose tissue)