Single-shot spiral imaging using the gradient impulse response for trajectory prediction

Signe Johanna Vannesjo[1], Nadine N Graedel[2], Lars Kasper[1], Simon Gross[1], Christoph Barmet[1,3], and Klaas P Pruessmann[1]

[1]Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland, [2]FMRIB Centre, University of Oxford, Oxford, United Kingdom, [3]Skope Magnetic Resonance Technologies, Zurich, Switzerland

Introduction Spiral acquisition offers several advantages over Cartesian acquisition strategies, particularly in terms of efficiency of k-space coverage, flow compensation, and robustness against motion. Nonetheless, spiral imaging is hardly used in practice. One main hindrance has been imperfection of effective gradient time courses, which are harder to characterize and correct for than, e.g., in echo-planar imaging (EPI). Errors in spiral trajectories are particularly detrimental in advanced reconstruction scenarios including parallel imaging and B_0 non-uniformity correction. Previous correction methods have focused on determining a fixed[1] or variable[2] delay per k-space sampling point. Mere delays, however, do not capture the full extent of gradient waveform deviations. Full accounts of actual k-space trajectories can be obtained by concurrent field monitoring[3] which however requires dedicated hardware and adds to the complexity of measurements. As a third option, it has recently been proposed to base image reconstructions on trajectory prediction using a linear time-invariant model of the gradient system[4-6]. This approach has the advantage that, for a given system, the gradient impulse response functions (GIRFs) need to be measured only once and can then be used to predict actual trajectories for arbitrary gradient sequences. In this work, we investigate the potential of this approach to enhance the feasibility of spiral readouts. To this end we consider the challenging case of single-shot spiral imaging with long acquisition windows, parallel-imaging acceleration and B_0 correction. To gauge the consistency of gradient characterization we explore the use of GIRFs determined three years prior to the present study.

Methods Gradient system characterization as described in Ref. 5 was performed on a whole-body 3T Philips Achieva system (Philips Healthcare, Best, The Netherlands) on two occasions separated by 3 years in time. Single-shot spiral acquisitions (FOV 23x23 cm^2, res 1.35x1.35 mm^2, SENSE factor 2, TR 3 s, TE 20 ms, readout length 41 ms, angulated axial slices) of the brain of a healthy volunteer were obtained on the same system. A coil sensitivity map and a field map were additionally acquired. The imaging acquisitions were accompanied by concurrent field monitoring using 16 ^{19}F NMR field probes mounted on the receive coil. A spatial model of three linear terms and a 0^{th}-order term was fitted to the measured fields. Based on the measured GIRFs, the field response to the spiral gradient sequence was predicted by frequency domain multiplication, including cross-terms to B_0[5]. Images were reconstructed based on nominal, concurrently monitored and GIRF-predicted trajectories, using both the recent and the three-year-old GIRFs. The coil data was initially demodulated by the measured or predicted 0^{th}-order phase. Algebraic image reconstruction was performed with an iterative conjugate-gradient algorithm, including gridding, sensitivity encoding and multifrequency interpolation for B_0-correction[7-9].

Results The measured GIRFs showed a high degree of reproducibility between the two separate measurement time points (Fig. 1). Nominal spiral trajectories deviated significantly from the concurrently monitored ones, gradually drifting apart at the center of k-space. GIRF-predicted trajectories closely followed concurrently monitored trajectories (Fig. 2). Reconstructions based on concurrent monitoring yielded high image quality without conspicuous blurring or ghosting and with only rather minor residual effects of B_0-inhomogeneities at the surface of the brain (Fig. 3a). GIRF-based reconstructions were of virtually equivalent quality (Fig. 3b), whereas images based on nominal trajectories were severely compromised by blurring and signal dropout (Fig. 3c). No significant difference in image quality was observed between using the recent or the three-year old GIRFs.

Discussion & Conclusions GIRF-based trajectory prediction has been found highly effective at enabling spiral imaging in the presence of gradient imperfection. Importantly, accurate representation of gradient encoding in the signal model also added to the robustness of B_0 correction, which is paramount for spiral imaging with long readouts. According to the authors' experience, the resulting single-shot image data is of substantially higher quality than commonly accomplished with spiral readouts and on par with EPI results. These findings indicate that GIRF-based prediction may help deploy the benefits of spiral strategies for rapid readouts such as in fMRI, diffusion imaging, and ASL, as well as motion- and flow-insensitive anatomical imaging. The approach is not limited to spiral sequences, but has the potential to work as a generalized correction method for arbitrary k-space sampling. Three-year-old gradient characterization was found still effective, supporting the concept of one-time calibration.

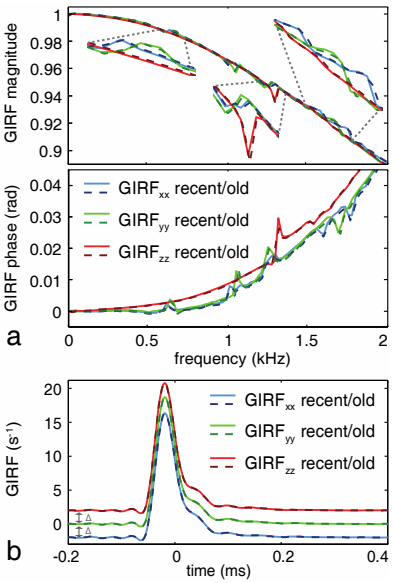

Fig. 1 *Measured self-term GIRFs in **a)** the frequency-domain (magnitude and phase) and **b)** the time-domain (offset by a constant Δ for visibility).*

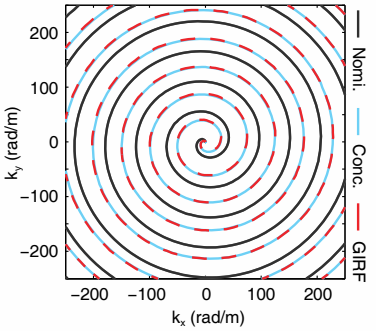

Fig. 2 *Nominal (black), concurrent (blue) and GIRF-predicted (dashed red) spiral trajectories.*

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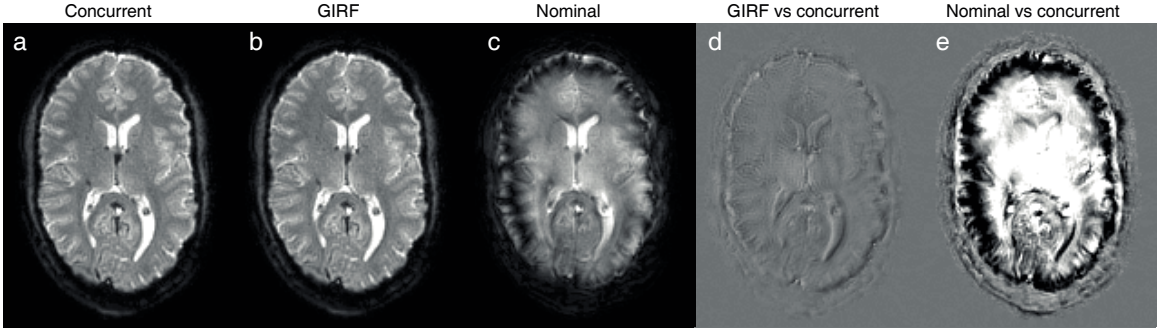

Fig. 3 *Single-shot spiral images reconstructed using the **a)** concurrently monitored, **b)** GIRF-predicted (3-year old GIRFs) and **c)** nominal trajectory. Difference images to concurrent monitoring for **d)** GIRF-prediction and **e)** nominal reconstructions are scaled to ± 20% of maximum image intensity.*