Real-time distortion correction of spiral MRI using the gradient system impulse response function

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TARGET AUDIENCE
This work will be of interest to clinicians and researches interested in performing real-time spiral MRI.

PURPOSE
MR-guided cardiovascular interventions require imaging sequences that are fast, interactive and low SAR, when using conductive devices. Spiral trajectories use fewer RF pulses with longer readouts [1], making them particularly efficient with respect to SAR and SNR. However, imperfections in magnetic field gradient waveforms are problematic for non-Cartesian readouts and can lead to image distortions [2]. In addition, blurring caused by off-resonance effects during long readouts needs to be corrected during reconstruction [3,4]. In the context of interventional procedures, these corrections must be made in real-time, and it is therefore not practical to measure true k-space trajectories and field maps in each arbitrary image orientation. In this abstract, we present a real-time spiral imaging platform for MR-guided interventions with k-space trajectory correction from a one-time measured gradient system impulse response function (GIRF)[5] and interactive off-resonance reconstruction.

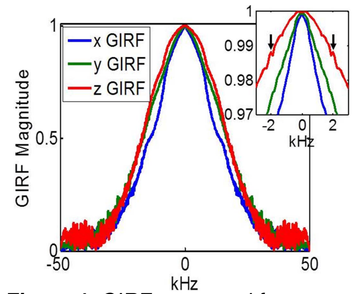

***Figure 1**: GIRF measured for x, y and z gradients.*

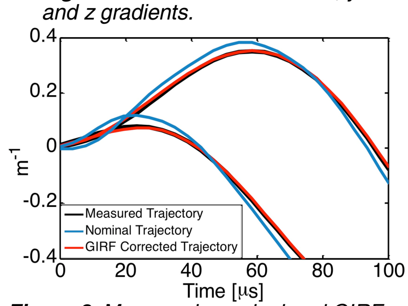

***Figure 2**: Measured, nominal and GIRF corrected k-space trajectories (first 100 μs of readout)*

METHODS
GIRF measurement: To measure the GIRF, the gradient system was probed with a series of triangular waveforms in each gradient axis independently (slew rate = 169 mT/m/s, triangle gradient amplitude =9-30 mT/m, triangle length = 50-170 μs). The nominal waveforms were compared to the true measured waveforms [2] in order to calculate the GIRF (spherical phantom, TR = 7.5 s/slice, flip angle = 90°, 1024 samples, slice thickness = 3mm, slice gap = 33mm, receiver bandwidth = 100 Hz/Px).

Trajectory correction: Variable density spiral trajectories were calculated using freely available software (http://mrsrl.stanford.edu/~brian/vdspiral/). During real-time reconstruction, nominal spiral gradient waveforms in the physical (x, y, z) axes were convolved with the GIRFs to produce corrected waveforms. Corrected k-space trajectories and regridding weights [6] were exported in ISMRMRD format (http://ismrmrd.sourceforge.net) and images were reconstructed using the Gadgetron [7].

Off-resonance reconstruction: Reconstruction frequency (*f*) was implemented as an interactive parameter, which can be modified during imaging to de-blur an area of interest. Each data point is multiplied by the phase term [$exp(i2\pi ft)$] before export to the Gadgetron.

Imaging: Imaging was performed on a 1.5T Aera MR scanner (Siemens, Erlangen, Germany). Nominal and corrected trajectories were compared to measured trajectories [2] in a phantom (4 interleaves, TE/TR = 0.86/15.51 ms, flip = 10°, matrix = 128, FOV = 300 mm, slice thickness = 5 mm). Off-resonance reconstruction was tested in a normal volunteer (16 interleaves, TE/TR =0.86/5.16 ms). *In vivo* experiments were conducted according to local ethical guidelines.

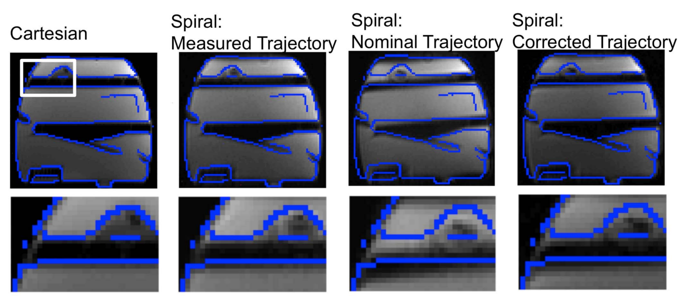

***Figure 3:** Comparison of phantom images generated with Cartesian and spiral imaging. Edges of Cartesian image are overlaid on spiral images to demonstrate reduced image distortion following GIRF trajectory correction. Zoomed-in region (white box) is shown below full image.*

RESULTS
The GIRFs (Figure 1) showed low-pass behavior and mechanical resonances (arrows) of the gradient system. Nominal gradient waveforms were found to deviate from the true measured gradient waveforms, and were corrected by convolution with the GIRF for an oblique image orientation (Figure 2). Corrected spiral k-space trajectories demonstrated reduced image distortion, compared to nominal trajectories, in a structural phantom (Figure 3). A frame rate of 12 frames/second was achieved *in vivo* and off-resonance reconstruction was shown to regionally de-blur images (Figure 4).

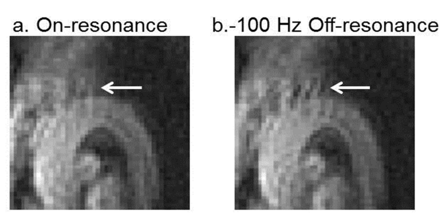

***Figure 4:** In vivo images of aortic arch generated with spiral MRI, with on-resonance reconstruction (a) and -100Hz off-resonance reconstruction (b). De-blurring of vessels is shown with off-resonance reconstruction*

DISCUSSION AND CONCLUSION
Applications of spiral imaging in MR-guided interventions have been limited due to the need for additional measurements and corrections. Here we have used a one-time GIRF measurement to correct for gradient imperfections in real-time. In addition, we have used an interactive single-value off-resonance correction to de-blur areas of interest during interventions. This platform produces distortion-free spiral images in real-time and therefore is applicable to MR-guided interventions.

REFERENCES: [1] Terashima M**,** et al, High-Resolution Real-Time Spiral MRI for Guiding Vascular Interventions in a Rabbit Model at 1.5T*JMRI* (2005) **22**:687–690. [2] Duyn J et al, Simple Correction Method for **k**-Space Trajectory Deviations in MRI. J*MRI* (1998) **132**: 150–153. [3] Noll DC et al, A homogeneity correction method for magnetic resonance imaging with time-varying gradients. *IEEE Trans Med Imaging* (1991), **10**: 629–637. [4] Man LC, Multifrequency interpolation for fast off-resonance correction. *MRM* (1997), **37**: 785–792. [5] Vannesjo S et al, Gradient System Characterization by Impulse Response Measurements with a Dynamic Field Camera. *MRM* (2013) **69**:583–593. [6] Meyer C et al, Fast spiral coronary artery imaging. *MRM*; **28**: 202–213. [7] Hansen MS and Sørensen TS, Gadgetron: An open source framework for medical image reconstruction. *MRM* (2013), **69**: 1768-77.