Image reconstruction using the gradient impulse response for trajectory prediction

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Introduction: Gradient field imperfections, as caused by eddy currents and mechanical gradient coil oscillations, are a well-known source of image artifacts. This is especially problematic for fast imaging sequences with EPI or spiral readouts, as they require strong gradient fields to be switched rapidly during the course of the readout. It has been shown that image reconstruction using gradient field evolution monitored with a dynamic field camera can greatly improve image quality [1,2]. This however requires each gradient sequence to be monitored individually, either concurrently with the imaging or in a separate calibration scan. With the assumption that the gradient chain behaves as a linear time-invariant system it is possible to determine the gradient impulse response function (GIRF) of the system as a one-time calibration procedure [3,4]. The measured GIRFs can then be used to predict the actual field evolution to any gradient sequence. In this work we performed reconstruction of EPI images based on GIRF-predicted k-trajectories and compared this approach to using nominal or concurrently measured k-trajectories.

Methods: All measurements were performed on a 3T Philips Achieva system (Philips Healthcare, Best, The Netherlands). The GIRF was determined for each gradient axis by measuring the field response to triangular input functions using a dynamic field camera with 16 transmit-receive ^{1}H NMR probes [3]. Single-shot EPI data was acquired on a spherical phantom (35 ms TE, 42 ms T_{acq}, 22x22 cm^2 FOV, 80x80 matrix) and on a healthy volunteer (31 ms TE, 32 ms T_{acq}, 22.8x22.8 cm^2 FOV, 128x128 matrix). Simultaneously, the k-trajectory (0th to 2nd order in real-valued spherical harmonics: k_0-k_8) was measured using concurrent field monitoring with 10 ^{19}F NMR probes [2]. A GIRF-based prediction of the trajectory (k_0-k_3) was obtained by a frequency-domain multiplication of the nominal gradient sequence with the measured GIRFs. Images were reconstructed based on (a) the nominal trajectory (k_1-k_3, neither eddy current-, nor EPI phase correction are applied), (b) the GIRF-predicted k-trajectory (k_0-k_3), and (c) the k-trajectory (k_0-k_3) measured with concurrent field monitoring. Image reconstruction was performed using an iterative gridding algorithm [5], including demodulation of the imaging data by the predicted/measured 0th-order field integrals $k_0(t)$. For the in-vivo images, the reconstruction was complemented by static off-resonance correction based on a separately acquired B_0-map [6].

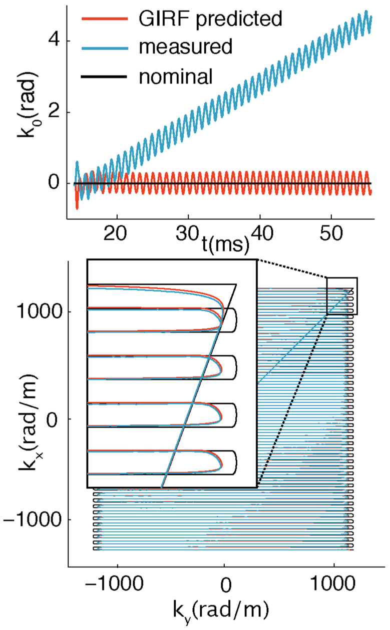

Fig. 1. **k-trajectory:** nominal, GIRF predicted and measured $k_0(t)$ (top) and parametric first order k_x - k_y (bottom).

Results: A comparison of the 0th- and 1st-order phase coefficients (k_0 / $k_{1\&2}$, Fig. 1) shows that the GIRF-predicted trajectory captures many features of the measured k-space trajectory. This manifests itself in the offset between odd and even profiles and in the turns, where the nominal trajectory deviates most from the measured one. It also accurately predicts oscillations in k_0 caused by the readout gradient. Other features however, such as a B_0 drift (linear increase of $k_0(t)$, Fig. 1) are not reproducible and therefore cannot be predicted by the GIRF. Both the phantom and the in vivo images show strong ghosting artifacts when reconstructed on the nominal trajectories (Fig. 2). The ghosting related to inconsistent odd and even profiles is largely eliminated when using the GIRF-predicted trajectories for reconstruction; drift in k_0 leads to an image shift of about 1 pixel in phase-encode direction. The residual ghosting in the GIRF reconstructed and concurrently monitored images in the phantom data is presumably due to static off-resonance. In the (B_0-corrected) in-vivo images, the GIRF reconstructed image shows some residual ghosting, whose origin might partially be explained by the k_0 drift.

Discussion and Conclusion: Image reconstruction based on GIRF-predicted gradient field evolutions can reduce ghosting in EPI images to a minimum. The GIRF method is based on a linear and time-invariant model and does not take into account non-linear gradient responses and variations over time, e.g. resulting from heating of the gradient coils and shim structures in high duty-cycle scans as well as physiologically induced fields generated by subject breathing and movement. The GIRF method can be complemented by static off-resonance correction on a case-by-case basis. Unlike concurrent field monitoring, the GIRF needs to be determined only once for a given system, hence providing a correction method for gradient imperfections without sequence-by-sequence field monitoring. For certain encoding strategies alternative correction methods exist, such as EPI phase correction. However, these correction techniques are often not sufficiently robust for routine clinical application. Moreover they do not extend to more advanced k-space encoding schemes. In contrast, GIRF-based image reconstruction is amenable to arbitrary k-space encodings without further customization.

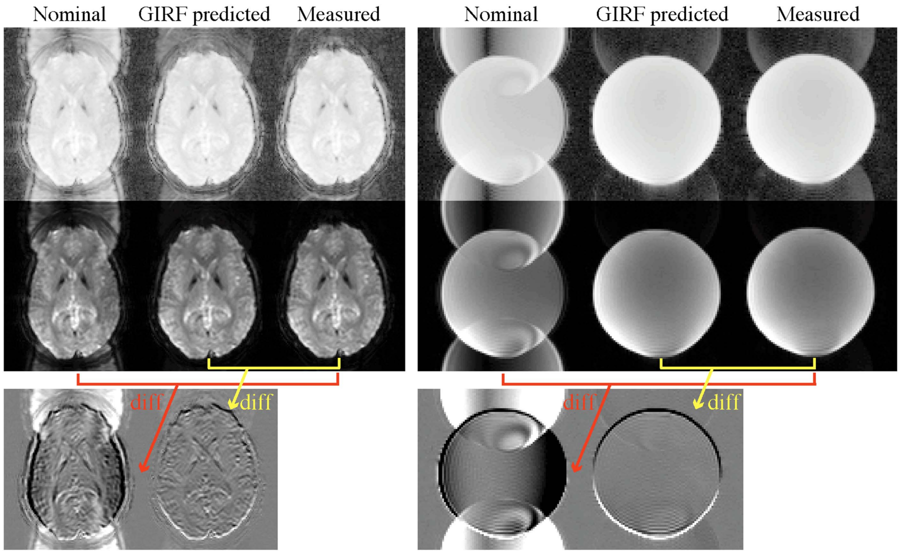

Fig. 2. **EPI in vivo (left) and phantom (right) images:** reconstruction performed using nominal, GIRF predicted and measured trajectories on logarithmic scale (top) and linear scale (middle). Difference images are shown in the bottom row.

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