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On the source of unresolved Nyquist ghosting in EPI at ultrahigh field

H. Scholten[1], I. Homolya[2], H. Köstler[1]

[1]Department of Diagnostic and Interventional Radiology, University Hospital Würzburg, Würzburg, Germany, [2]Chair of Molecular and Cellular Imaging, Comprehensive Heart Failure Center, University Hospital Würzburg, Würzburg, Germany

Introduction: Nyquist ghosting in echo planar imaging (EPI) arises from a misalignment of the forward and reversed k-space lines.[1] For human-sized 7T scanners, it has been reported that the standard navigator-based correction method[2] does not suppress ghosting sufficiently[3–5], because the shift between odd and even echoes varies over time.[3,5] We show that this is related to mechanical resonances of the gradient coils, and apply a trajectory correction, which improves ghost suppression.

Methods: We acquired single-shot EPI images of a spherical phantom in a coronal slice on a 7T scanner with two orthogonal phase encoding directions. We characterized the gradient system with the gradient system transfer function (GSTF)[6] and used it to calculate corrected k-space trajectories.[7] Dwell time differences between the GSTF acquisition and the k-space sampling points were compensated for.[8] From the corrected trajectories, we calculated the shifts between forward and reversed k-space lines.

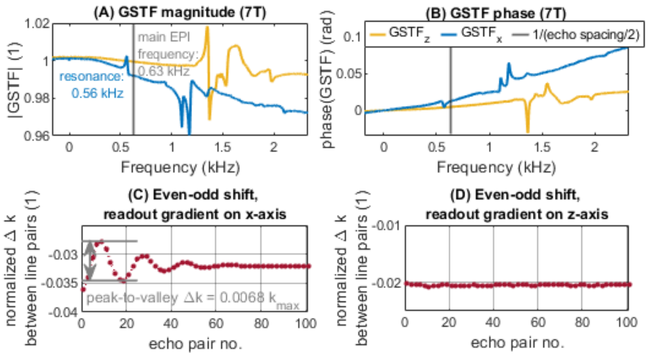

Fig. 1: (A) Magnitude and (B) phase of the GSTFs of the x- and z-axis of the 7T gradient system. (C,D) GSTF-predicted shift between center points of odd and even readouts.

Results: Fig. 1 shows that the main frequency of the oscillating EPI readout gradient, is close to a mechanical resonance of the gradient coil of the physical x-axis (A,B). The GSTF-predicted shift between odd and even readout echoes oscillates if the readout gradient is on the physical x-axis (C), but is constant with the readout gradient on the physical z-axis (D). The varying shift between echoes results in severe ghosting artifacts under the navigator-based correction (Fig. 2A,B). With the GSTF-based correction (C), both the average and maximum ghost intensity is reduced. With the readout gradient on the z-axis (Fig. 2D-F), the maximum ghost intensity is also lower with the GSTF-based reconstruction (F).

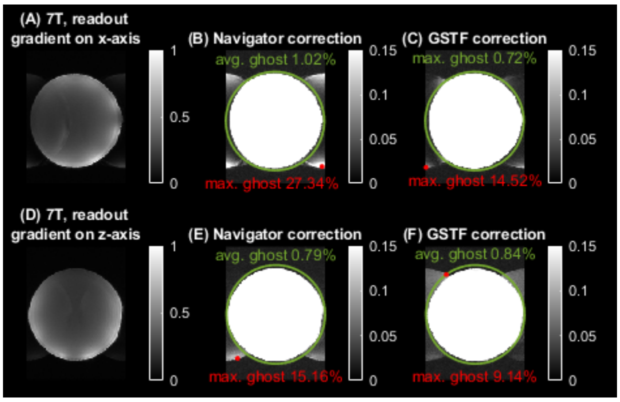

Fig. 2: Coronal phantom images. (A,B,C) Readout gradient on x-axis. (D,E,F) Readout gradient on z-axis. Average ghost intensity: outside the green circle. Red circles: maximum ghost intensities.

Discussion and Conclusion: Our GSTF-predicted trajectories replicated the oscillating k-space shifts that were previously reported for 7T systems[3,5]. We also confirmed the associated failure of the navigator-based ghost correction. We related this effect to a mechanical resonance. As shown before[7], a GSTF-based trajectory correction can reduce Nyquist ghosting, as it incorporates mechanical oscillations of the coils. Ghosting can also be reduced by shifting the axis or main frequency of the oscillating readout gradient away from any resonances. This work thus identified an additional source of residual Nyquist ghosting in EPI at ultrahigh field, and two possible alleviations.

References: [1] Bernstein, Handbook of MRI Pulse Sequences (2004). [2] Heid, US Patent (2000). [3] Poser, Proc. ISMRM (2010), [4] Josephs, Proc. ISMRM (2020), [5] Goa, Proc. ISMRM (2021), [6] Scholten, Magn. Reson. Med. (2023), [7] Vannesjo, Magn. Reson. Med. (2016), [8] Scholten, NMR Biomed (2024)