On the feasibility of single-shot EPI during higher-order shim settling

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Introduction: Field inhomogeneities due to susceptibility differences within an imaging object is a major source of artefacts in MRI, causing image distortions and signal drop-outs. The problem is especially severe in long read-out sequences at higher field strengths. Active shimming up to third order in space is a commonly used strategy to improve local field homogeneity. However, the underlying field profile is generally not smooth, and cannot be well compensated for over larger volumes with third order approximations only. To achieve locally optimised shimming while still being able to image larger volumes one method is to use dynamic shimming, i.e. to update the shim current settings between acquisition of different slices or subvolumes [1,2]. This puts high requirements on the switching characteristics of the shim system, to fit into the timing of the imaging sequence. Changing the currents in the shim coils will inevitably lead to eddy currents in conductive structures of the scanner, producing magnetic field effects. The linear shims generally share hardware and therefore also timing characteristics of the gradient system, with the ability of performing rapid switching. Here the dynamic effects of setting the 2nd and 3rd order shims are investigated and reconstruction is performed on imaging data acquired during eddy current settling.

Methods: Imaging data of a round water phantom doped with $CuSO_4$ was acquired on a 7T Philips Achieva system (Philips Healthcare, Cleveland, US). A single-shot EPI of one slice through the center of the phantom was performed repeatedly with 200 ms TR (matrix 80x80, voxel size 2.5x2.5 mm, slice thickness 6 mm, TE 21 ms). During the time course of the scan the higher order shim currents were set to a value specified manually, and after 6 seconds set back to zero. The shim values were chosen based on the scanner's PB-volume shimming algorithm, performed on a volume covering the center of the phantom. The linear shims were kept at zero for clear delineation of the dynamics of the higher order shims. The same sequence, including shim settings, was performed while monitoring the field evolution with a dynamic field camera consisting of 16 NMR probes distributed on a 20 cm sphere. The phase of the probes can be fitted to dynamic phase coefficients up to 3rd order in space with microsecond resolution [3]. Real-valued spherical harmonics were used as basis functions, which up to a scaling factor were the same as used by the scanner for shimming. Imaging data at different stages of the scan was reconstructed based on the monitored trajectories and compared with reconstructions based on a nominal trajectory. The nominal trajectory was chosen as a trajectory in a stable phase, when all eddy currents due to the switching of the higher order shims had died out. All reconstructions were corrected for B_0-inhomogeneities by means of multi-frequency interpolation, using a B_0-map (ΔTE 1 ms) acquired without shimming [4]. For the monitored reconstructions, measured higher-order field effects were included in the B0-map.

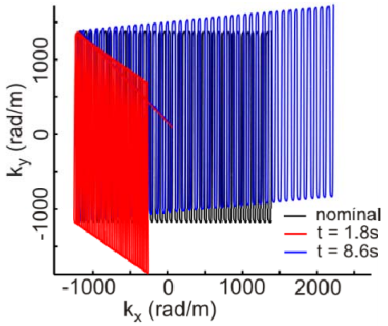


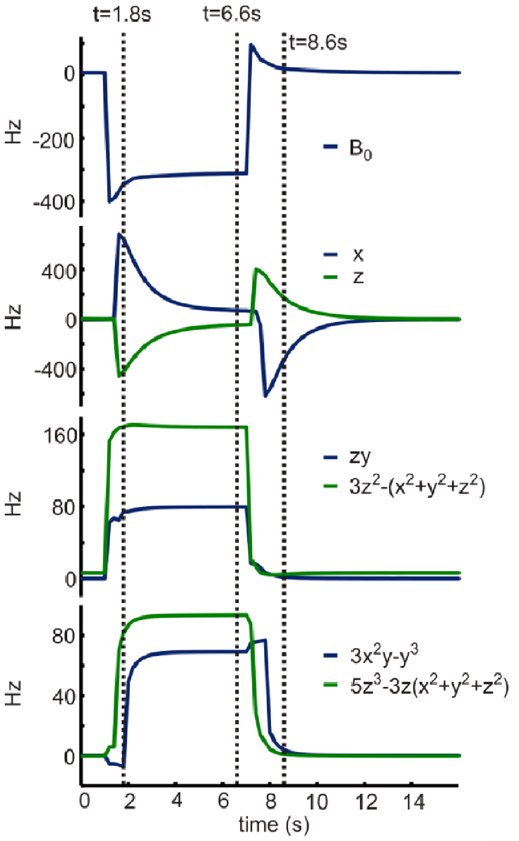
***Fig 1:** Monitored k-space trajectories*

Results: The switching of the higher order shims produced significant eddy currents, living for several seconds, and there was a marked shift in B_0 (Fig 2). The strong eddy current effects in the first orders lead to considerable distortions of the k-space trajectory (Fig 1). Figure 3 shows reconstructions of the phantom based on nominal (top) vs. monitored (bottom) trajectories, at different stages of the shim switching. The nominal reconstructions show strong distortions of the imaged phantom. Using monitoring and including measured higher order effects in the B_0-correction enabled geometrically stable reconstructions through the larger part of the eddy current settling time. Right after setting the shims however, the trajectory was compressed in the phase-encoding direction to a degree that the center of k-space was never reached during the read-out, and consequently the image could not be satisfactorily reconstructed. After turning off the shims the trajectory was stretched, giving rise to a larger Δk, corresponding to a diminished FOV in the image domain.

Conclusion: The higher-order shims produced long-living eddy currents of a size significant for image quality. Including monitored data in the reconstruction allowed for geometrically accurate reconstructions of images acquired during eddy current settling. Right after shim setting however, there were distortions of the k-space trajectory stronger than could be compensated for by reconstruction strategies alone. A future approach could include real-time compensation of the eddy currents, based on measured eddy current characteristics.

References:

[1] Blamire et al., 1996 Magn. Res. Med. 36:159-165 [2] Koch et al., J. Magn. Res. 180:286-296 [3] Barmet et al., 2008 Magn. Res. Med 60:197 [4] Man et al., 1997 Magn. Res. Med. 37:785-792



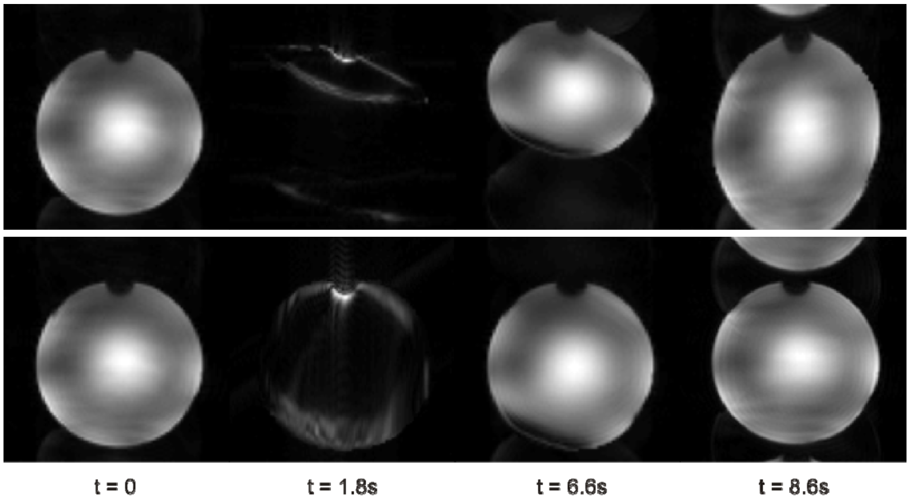

t = 0 t = 1.8s t = 6.6s t = 8.6s

***Fig 2 (top):** Measured fields, scaled to maximum phase within a 20 cm sphere.*

***Fig 3 (left):** Reconstructed phantom images based on nominal (top) and monitored trajectories (bottom).*