Numerical investigation of nonlinear, spatially-varying pulsed magnetic fields

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Introduction
Curved spatially-varying magnetic fields have a strong impact on MRI, especially in the context of correcting magnetic field inhomogeneities (shimming) [1]. Conventional methods are well established, but new progress from hardware and sequence development intends to overcome certain limitations, e.g. by the use of higher-order shim coils or the application of spatially-selective dynamic shimming [2]. Beyond field corrections, curved field gradients are currently also under discussion for region-specific zoomed spatial encoding with reduced hardware demand and peripheral nerve stimulations at higher switching rates [3]. However, the gains from such strategies depend on many factors and are hardly predictable without simulations [2,3]. Here, a framework for exact numerical MRI simulations is presented; it easily enables the simulation of nonlinear spatially-varying pulsed magnetic fields in a wide variety of experimental setups.

Methods
The numerical Bloch equation simulator JEMRIS [4] was extended by the ability to spatially shape any involved pulsed gradient through a user-defined analytical formula. This was achieved by utilising the C++ library GiNaC [5] for symbolic mathematical calculation. The object-oriented approach of JEMRIS allowed the extension to be implemented on the abstract level of a general pulsed gradient waveform. In this way, the functionality of arbitrary nonlinear gradient shapes directly applies down to each explicit gradient module of the framework. The approach is demonstrated for two different types of applications: i) Shimming was performed with JEMRIS. The object was given by the MNI human brain phantom [6] with susceptibility-induced field inhomogeneities mimicking 9.4 Tesla. EPI acquisitions were simulated for the cases of the homogeneous B_0 field, the uncorrected inhomogeneous field, and shim-corrected inhomogeneous fields up to 2nd and 3rd order ellipsoidal harmonics [7], respectively. The correction fields were optimized to dynamically mitigate field inhomogeneities during the pulse sequence, thus, different correction terms were pulsed during frequency and phase encoding, respectively. ii) Encoding with nonlinear gradients is performed in 1D-imaging simulations for zoomed spatial-dependent resolution. Since JEMRIS is fully capable of parallel RF receive, this example may be easily extended to exact full Bloch equation simulations of the PatLoc approach [3].

Results
Fig.1 depicts the EPI simulations with and without field inhomogeneities and dynamic shim corrections, respectively. The results enable exact prediction of shim performance, here shown for the case of EPI at 9.4 Tesla. Fig. 2 shows 1D imaging simulation for a box-car spin distribution. The same simulated gradient echo sequence was repeated with different gradient fields: linear encoding, cubic encoding, arc-tangent encoding, and a Rayleigh function, respectively, where the latter resembles a PatLoc encoding field [3]. Except of linear encoding, the resolution properties of the 1D images are region specific. The arc-tangent is an artificial example as no coil design is currently available producing such spatial field dependence.

Conclusions
Curved magnetic field gradients have a huge field of applications in MRI, especially for shimming the main magnetic field, which becomes even more important at ultra high magnetic field strength (>=7T). Here, new strategies involve new hardware development, which should be subject to preceding extensive simulations in order to maximise application-specific efficiency of the concepts. The presented approach allows such simulations with few limitations on the complexity of the physical processes: it enables simple definition of spatially arbitrarily-shaped, non-linear gradient pulses in combination with the most general numerical Bloch equation simulations. Such an approach may lead to new developments in MRI; that is, simulation–driven development of MRI hardware which then feeds directly into the development of new techniques.

References:
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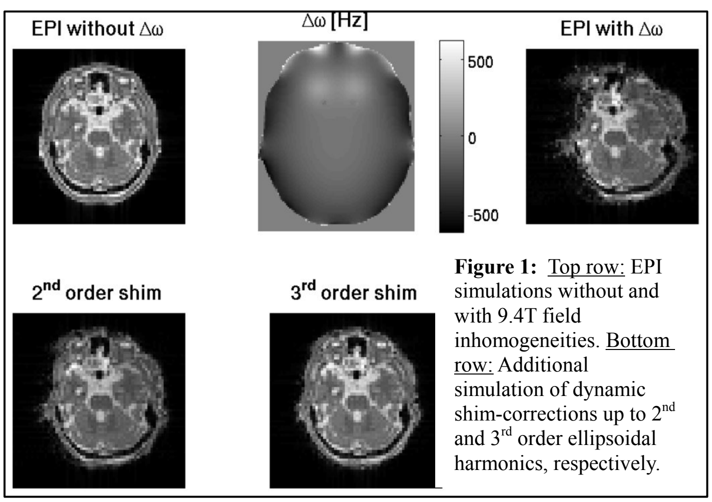

Figure 1: Top row: EPI simulations without and with 9.4T field inhomogeneities. Bottom row: Additional simulation of dynamic shim-corrections up to 2nd and 3rd order ellipsoidal harmonics, respectively.

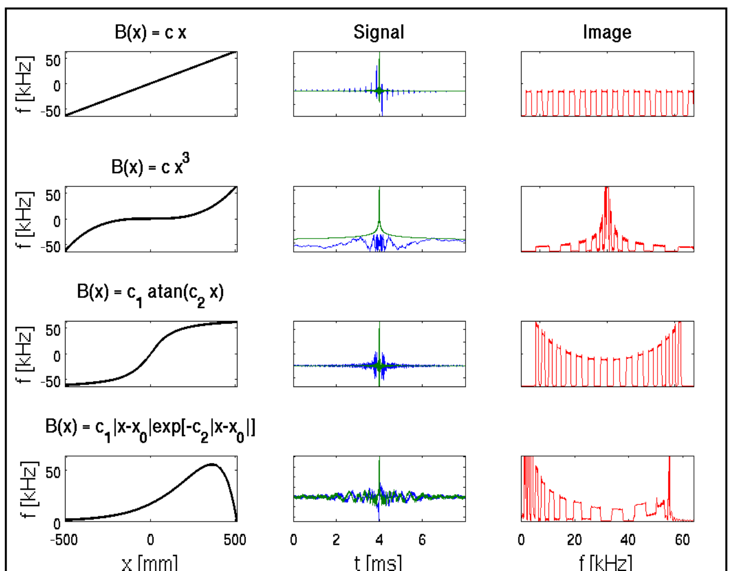

Figure 2: Simulation of position encoding with various curved magnetic fields results in region-dependent resolution properties of the encoding. Spatial encoding functions from top to bottom row: Linear; Cubic; arc-tangent; Rayleigh.