

Coping with Off-Resonance Effects and Gradient Imperfections in Parallel Transmission Experiments

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Introduction: Parallel transmission has proven to provide good results for spatially selective excitation with reasonable RF-pulse durations [1]. For best spatial definition, exact matching of RF-pulses with a simultaneously played out gradient waveform, which defines a k-space position for every point in time, is crucial. However off-resonance effects and gradient imperfections may lead to distortions in the excited pattern. In this study several approaches are presented and compared which allow the mitigation of the impact of such inaccuracies by measuring and pre-calibrating the k-space trajectory and by basing the RF pulse calculation on such measured data.

Theory: In the small-tip-angle regime the excited transverse magnetization $M(\mathbf{x})$ can be calculated by Eq. 1a. It is determined by the $B_{1,n}^+$ -fields generated by N coil elements ($1 \leq n \leq N$) and by the phase evolution $\phi(\mathbf{x}, t)$. The phase is not only given by the nominal k-space trajectory k^{nom} but also by experimental imperfections which can be accounted for by adding correction terms to the phase evolution (Eq. 1b): linear, separable trajectory differences Δk_i and non-separable phases ϕ_{AG} produced by deviations in the gradient's amplitude and additional phases ϕ_{ABO} resulting from B_0 inhomogeneities may occur. Furthermore overall timing inaccuracies are taken into account by introducing delays τ_i between the RF-pulse and the gradient channels ($i=x, y, z$). If the phase contributions can be measured, they can be compensated for by pre-corrections via gradient and shim adjustments or by including the actual phase evolution into the pulse calculation (inverse problem of Eq. 1).

$$\text{Eq.1} \quad (a) \quad M(\mathbf{x}) = \sum_n \int_0^T B_{1,n}^+(t) \cdot e^{i\phi(\mathbf{x}, t)} dt \quad (b) \quad \phi(\mathbf{x}, t) = \sum_i x_i [k_i^{nom}(t + \tau_i) + \Delta k_i(t)] + \phi_{AG}(\mathbf{x}, t) + \phi_{ABO}(\mathbf{x}, t)$$

Materials and Methods: The parallel transmit experiments were carried out on an 8-TX-channel 9.4 T, 30 cm bore BioSpec system (Bruker BioSpin MRI GmbH, Ettlingen, Germany) [2] in combination with an 8-element transceive volume array with elements in classical loop design and a spherical phantom with T1-doped saline water solution. As k-space trajectory a constant density, constant angular velocity spiral was chosen (Fig. 1b) and spatially selective RF-pulses were calculated using the conjugate gradient method described by Graesslin et al [3]. A checkerboard-like target pattern was defined (Fig. 1a) to be excited by pulses with an acceleration-factor of 2.67 and durations of 4 ms.

To demonstrate the effect of the phase contributions Δk_i , ϕ_{AG} and ϕ_{ABO} , a nearly perfectly calibrated trajectory was manually distorted in a reproducible way by reducing the y channel's amplitude to 90%, delaying the x channel by 5 μ s, adding a global delay between RF and gradient pulse of 5 μ s and by changing the shim-offsets what resulted in the trajectory described by the solid curve in Fig. 1b and an off-resonance field distribution with a maximum of about 180 Hz. The order of magnitude of these values is typical for uncalibrated trajectories generated at the gradient system's speed limits.

For measuring the phase contributions in Eq. 1b, 3 specific methods were used: (I) To measure the trajectory produced by each gradient channel, a variant of the method described in [4], assuming global, non spatially dependent trajectories and spatially linear gradient terms was used: A thin slice (0.5 mm) is excited and signal is acquired while playing out the gradient waveform on the channel perpendicular to the slice simultaneously. The experiment is performed twice for each gradient channel, once with and once as reference without playing out the waveform. Subtracting the phase evolution of the two measurements yields the k-space trajectory $[k_i(t + \tau_i) + \Delta k_i(t)]$ generated by the actually played out gradient waveform. (II) B_0 off-resonance maps leading to ϕ_{ABO} were calculated from the phase evolution between two echoes of a multi gradient-echo imaging method. (III) A more precise method which determines all phase affecting contributions simultaneously was a spatially resolving method similar to the approach of Papadakis [5]: After slice-selective excitation the signal is phase-encoded in two dimensions and the acquisition is done simultaneously while playing out the gradient waveform on all three channels. After the Fourier transform, to each imaging pixel the corresponding phase evolution can be assigned.

Data from the global trajectory measurement (method I) was used for (A) pre-calibration of the gradient waveform. Either (A1) global amplitude scaling factors and time delays were calculated or a (A2) point-wise calibration was performed by shifting each gradient coordinate to a value compensating for the deviations. In order to compensate for residual phase deviations either (B1) the actual global trajectory data (method I) [6] in combination with the measured B_0 map (method II) were included in the pulse calculation or (B2) the spatially resolved trajectory measurements (method III) covering all phase effects were used as RF-pulse calculation basis.

Results and Discussion: Applying the manually distorted trajectory together with the RF pulse calculated for the nominal trajectory, the excitation of the desired pattern, to be seen in Fig 1a, resulted in strong distortions and artifacts, as shown and described in Fig 2a.

The pre-calibration step (A) has proved to be necessary in those cases in which the trajectory deviations were so strong that the k-space trajectory did not satisfy adequate k-space coverage and the Nyquist sampling criterion, which are conditions for which the pulse calculation cannot compensate. For globally deviating trajectories the use of global correction factors (A1) turned out to be sufficient, but in cases of time- or current-depending damping effects of the gradient system, the resulting trajectory deformations could only be corrected by the point-wise calibration (A2) which yielded new calibrated gradient waveforms. With this method, initial deviations of 5.1% between actually measured and nominal trajectory amplitudes could be reduced to only 0.1% allowing high excitation precision, if off-resonance effects could be neglected.

In most cases of significant residual distortions or strong off-resonance effects, an excellent removal of the artifacts was achieved (Fig. 2b) by basing the pulse calculation on the globally measured (possibly already pre-calibrated) trajectory and the off-resonance map (B1) (To demonstrate the compensation efficacy we used the uncalibrated, distorted trajectory of Fig. 2b). In some cases the global trajectory measurement method (B1) failed, in particular when strong off-resonances caused in-slice dephasing or hampered phase unwrapping for the off-resonance maps or when spatially varying eddy current effects and gradient cross talk effects occurred, which cannot be determined by approach (B1). Including the spatially resolved measured phase evolution in the pulse calculation, i. e. approach (B2), was the best choice in these cases. Since the actual phase evolution has been measured for every single pixel and all phase contributions could be determined simultaneously with this method, it turned out to be very reliable and led to very precise excitation patterns, as depicted in Fig. 2c. However, the measurement time was prolonged to about 5 minutes compared to some seconds for the global trajectory measurement.

In most applications a combination of pre-calibration and trajectory-adapted pulse calculation yielded best results which led to robust measurement protocols, also for in-vivo experiments where arbitrary target patterns could be excited with accurate spatial definition and efficient outer volume suppression (Fig. 3).

Conclusion: This study demonstrates that the sensitivity of parallel spatially selective excitation to gradient imperfections and off-resonance effects can be efficiently met by pre-calibration of the k-space trajectory and / or including measured k-space trajectory data into the calculation of the RF pulses. It is shown that choosing a suitable measurement and correction method, depending on the degree of setup imperfections to be compensated for, the excitation precision required and the time available for the adjustments, allows robust and very precise parallel spatially selective excitation in phantoms as well as in-vivo experiments.

References and Acknowledgement: 1. Ullmann P et al. (2005) MRM 54:994 // 2. Ullmann P et al. (2008) Proc ISMRM 2008:684 // 3. Graesslin et al. (2006) Proc. ISMRM 2006:2470 // 4. Duyn JH et al. (1998) JMR 132:150 // 5. Papadakis et al. (1997) MRI 15:578 // 6. Ullmann et al. (2008) Proc ISMRM 2008:1313 // This work is part of the INUMAC project supported by the German Federal Ministry of Education and Research. Grant #13N9207

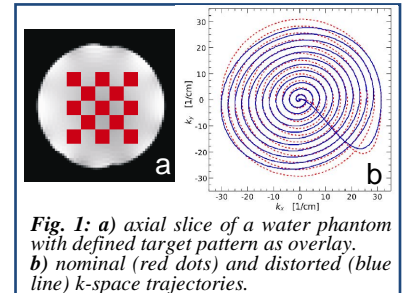


Fig. 1: a) axial slice of a water phantom with defined target pattern as overlay. b) nominal (red dots) and distorted (blue line) k-space trajectories.

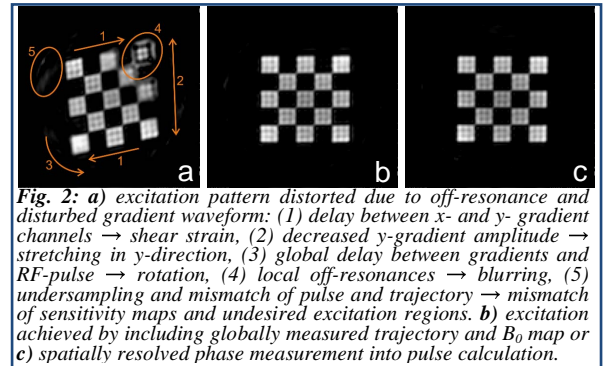


Fig. 2: a) excitation pattern distorted due to off-resonance and disturbed gradient waveform: (1) delay between x- and y- gradient channels \rightarrow shear strain, (2) decreased y-gradient amplitude \rightarrow stretching in y-direction, (3) global delay between gradients and RF-pulse \rightarrow rotation, (4) local off-resonances \rightarrow blurring, (5) undersampling and mismatch of pulse and trajectory \rightarrow mismatch of sensitivity maps and undesired excitation regions. b) excitation achieved by including globally measured trajectory and B_0 map or c) spatially resolved phase measurement into pulse calculation.

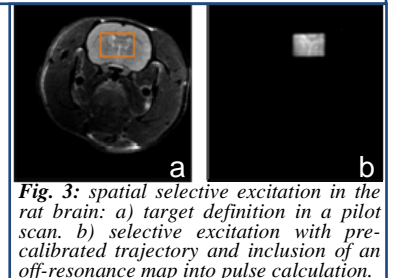


Fig. 3: spatial selective excitation in the rat brain: a) target definition in a pilot scan. b) selective excitation with pre-calibrated trajectory and inclusion of an off-resonance map into pulse calculation.