Parallel Excitation Experiments Using a Novel Direct Calibration Technique for RF-Pulse Determination

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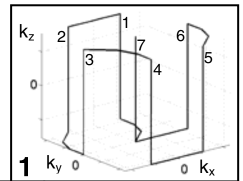
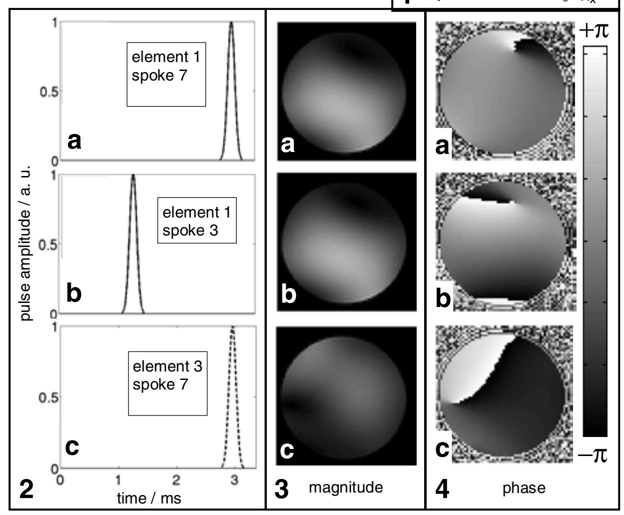
Introduction: The concept of Parallel Excitation or Transmit SENSE [1-6] has shown its potential to reduce several problems of single channel excitation, e. g. off-resonance or transverse relaxation effects, due to its pulse shortening capabilities. However, despite the shorter pulse lengths these deficiencies cannot be compensated completely. In this study a convenient and very general approach to determine Parallel Excitation pulses is presented, which not only further reduces the mentioned effects but also inherently compensates for other experimental imperfections, such as deviations of the real *k*-space trajectory from the desired one. Experiments of B_1-inhomogeneity compensation and inner volume excitation in a phantom and in a fixed rat demonstrate the feasibility of this approach.



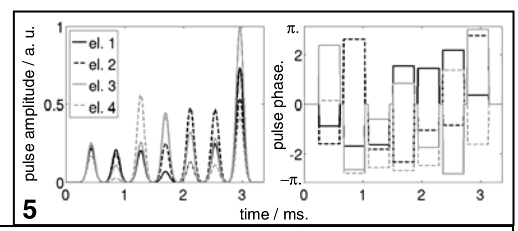
Theory: The basic equation for parallel excitation in the small tip-angle regime, taking off-resonances ω_{off} and T_2^*-relaxation into account, is given by (see also [3,7])

$$M(\mathbf{x}) = i\gamma M_0 \sum_n S_n(\mathbf{x}) \int_0^T B_{1,n}(t)\, e^{i[\mathbf{x}\cdot\mathbf{k}(t)+\omega_{\text{off}}(\mathbf{x})(t-T)]+T_2^*(\mathbf{x})(t-T)}\, dt \qquad (1)$$

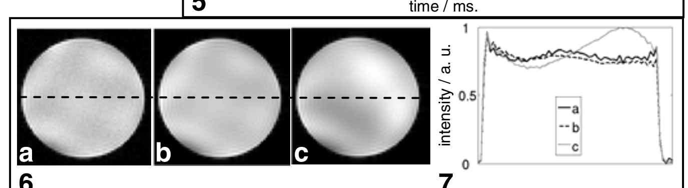
Using the direct discretization approach by Grissom et al. [7] one can theoretically incorporate all effects of off-resonance, transverse relaxation and *k*-space-trajectory deviations into the pulse calculation, but detailed maps of B_0 and T_2^*, which can be difficult to measure under in-vivo conditions, and a measurement of the *k*-space trajectory, which is difficult to achieve for the excitation case, are required. We have developed a novel method for the determination of RF-pulse profiles, using a procedure we named Direct Calibration, which is based on the fact that the above mentioned imperfections do not affect the linear relation between B_1 and M in the small-tip angle regime (see eq. 1). The principle of this approach is to first select an application specific excitation *k*-space trajectory. For our experiments of slice selection with B_1-inhomogeneity correction we chose a so-called spokes-trajectory, as proposed by Saekho et al. [8] (see Fig. 1). Secondly, a set of basic pulse profiles has to be selected and a series of experiments has to be carried out where the basic profiles are subsequently used for excitation and a series of images is acquired, the so-called basic patterns. It is important that the acquired images have a linear dependence of the generated transverse magnetization which is the case since the MR signal equation is linear. In the case of spokes-trajectories such a set of basic profiles could be composed of pulses which present a single slice selective sub-pulse at one spoke in one coil. Thus, the set would consist of (number of spokes) x (number of array elements) basic profiles corresponding to the same number of calibration scans. In the present case this calibration effort is acceptable because all above-quoted experimental imperfections are inherently measured and no sensitivity-, B_0- and T_2-maps have to be acquired. Finally, the target pattern is approximated by a linear combination of the basic patterns using an arbitrary optimization algorithm with an arbitrary cost function. When the "best" combination of basic patterns is found the desired pulse profiles are given by the identical linear combination of the corresponding basic profiles.

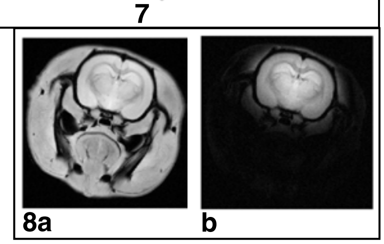


Materials and Methods: The experiments in this study were carried out on a 9.4 T BioSpec animal scanner (Bruker BioSpin, Ettlingen, Germany) using a 4-element volume TX/RX-array coil driven by 4 independent transmit channels. For excitation we used a 7-spoke k-space-trajectory as in [5] and for acquisition a standard gradient echo sequence (TE=2 ms, TR=100 ms, to keep linearity, the excitation angle must be much smaller than the Ernst angle for the chosen TR). Reception was performed with the 4 array elements separately. For simplicity, the signals were numerically combined to emulate a birdcage-mode reception, in order to obtain single complex images as basic patterns. The patterns, acquired on a 64 x 64 matrix, were fitted to the desired pattern using a least squares optimization. Where necessary, too large intermediate flip angles were suppressed by applying some regularization, in order to keep sub-pulse amplitudes moderate. The nominal calibration time is 3 min, which could be further reduced by parallel acquisition. However, a relatively low filling factor of the array in the present setup required averaging which increased calibration time. This can be avoided by further optimizing the coil setup.



Results: Fig. 2 shows three examples (a,b,c) of basic profiles each featuring one Gaussian sub-pulse in a single array element during a single spoke. The corresponding basic patterns acquired in a doped water phantom (FOV 5.5 x 5.5 cm, slice thickness 3 mm) are displayed in Fig. 3 and 4. The figures show nicely that when transmitting with the same coil but on different spokes, there is a major change only in the phase pattern, apart from some small changes in the magnitudes due to relaxation effects. In contrast to that, both amplitude and phase change completely when transmitting with different coils. Fig. 5 displays the calculated pulse profiles for the 4 array elements when fitting the basic patterns to a homogeneous target pattern. It should be noted that this fitting directly leads to a globally homogeneous image and not necessarily to a homogeneous excitation, since large-scale inhomogeneities of the reception-mode and the object are compensated inherently, too. In Fig. 6 the numerical combination (6a) of the basic patterns using the weights determined in the fitting process is compared to the real parallel excitation experiment using the determined profiles (6b) and to an experiment based on classical pulse calculation without consideration of off-resonances, relaxation and trajectory deviations (6c). Fig. 6a,b demonstrate that a very satisfactory homogeneity of the image is achieved with this 7-spoke trajectory and only 4 array elements using the Direct Calibration approach and an excellent correspondence between the numerical superposition and the experimental data is shown in the image profiles along the dashed lines (Fig. 7). Furthermore, it is shown that incorporating experimental imperfections into the pulses using Direct Calibration yields a significant benefit compared to classical pulse calculation. Fig. 8 finally shows an example of B_1-inhomogeneity compensation in a fixed rat (8a) using Direct Calibration (FOV 3 x 3 cm, slice thickness 1 mm), as well as an experiment of using the spokes-trajectory for feature-specific excitation of the brain area with simultaneous slice selection (8b).





Discussion and Conclusions: The study shows that Direct Calibration is a convenient and powerful method to determine optimized RF pulse profiles for single- and multi-channel excitation and demonstrates its potential to inherently cope with experimental imperfections such as off-resonances, transverse relaxation and *k*-space trajectory deviations. It proves to be particularly useful for applications with low spatial resolution requiring a high fidelity in the excitation patterns such as B_1-correction and inner volume imaging.

References: [1] U. Katscher et al., MRM 49:144-150 (2003); [2] Y. Zhu, MRM 51:775-764 (2004); [3] P. Ullmann et al., MRM 54:994-1001 (2005); [4] Y. Zhu et al., Proc. ISMRM 2005, p.14; [5] K. Setsompop et al., MRM 56:1163-1171 (2006) ; [6] I. Graesslin et al.; Proc. ISMRM 2006, p. 129; [7] W. Grissom et al., MRM 56:620-629 (2006); [8] S. Saekho et al., MRM 55:719-724 (2006)