Large Tip Angle Parallel Excitation Using Nonlinear Non-Bijective PatLoc Encoding Fields

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Introduction

Nonlinear encoding fields have recently been proposed [1] for anatomically tailored spatial encoding. Localized “PatLoc” encoding fields can replace or add to conventional linear encoding fields with constant gradient. Compared to purely linear encoding, it has been demonstrated [2] that PatLoc fields allow for a locally increased image resolution due to the locally varying gradient strength. For spatially selective excitation (SSE) using PatLoc encoding fields, parallel transmission [3,4] has turned out to be a necessary requirement to manipulate magnetization unambiguously in non-bijective fields [5]. In this work, a design algorithm for pulses with arbitrary tip angles for parallel excitation using nonlinear non-bijective encoding fields is described. It is demonstrated that PatLoc fields permit to realize magnetization patterns with increased resolution in specific regions of interest.

Methods

For this simulation study, the conventional x- and y-gradients were replaced by nonlinear encoding fields as depicted in Fig. 1a) and b). These fields vary as $F_1=x^2-y^2$ and $F_2=2xy$ across the field of excitation (FOX), respectively. Their local gradients are therefore still orthogonal at every point in space. However, as the gradient varies spatially it is no longer possible to define a corresponding transmit k-space to globally represent the field encoding for the calculation of selective RF pulses. The optimal control algorithm for arbitrary tip angle selective excitation as presented in [6, 7] was therefore modified as follows. The field encoding was based on a Cartesian 64x64 sampling scheme $A_j(t)$ (j=1,2) that would result in an EPI trajectory through transmit k-space for linear fields. The resulting nonlinear encoding field then reads

$$\Delta B_0(t,\mathbf{r}) = \sum_j F_j(\mathbf{r}) A_j(t)$$

replacing $\mathbf{G}(t)\cdot\mathbf{r}$ in the Bloch equations and all derived expressions of the algorithm. Correspondingly, the terms $\mathbf{k}(t)\cdot\mathbf{r}$ occurring e.g. in the initial small-tip angle pulse design are replaced by the phase

$$\varphi(t,\mathbf{r}) = -\gamma \int_t^T dt' \sum_j F_j(\mathbf{r}) A_j(t)$$

that is being accrued by the magnetization at location **r** from time t up to the end of the pulse with duration T. For a fair comparison the maximum encoding field strength at the border of the FOX was chosen equally for linear and nonlinear fields. Two-dimensionally selective RF pulses with a flip angle of 90° were then designed for a target pattern (Fig 2a), representing gray matter in a region close to the visual cortex, based on segmented brain data from [8].

Results

For a single-channel RF pulse and a homogeneous B_1 profile the simulations in Fig. 2b show aliasing due to the non-bijective PatLoc encoding, preventing the reduction of the FOV to the region of interest. When using parallel transmission with B_1 profiles as depicted in Fig. 1c, the encoding ambiguities are resolved (Fig. 2c). The capability of PatLoc encoding to resolve structures of size FOX/96 (i.e. the resolution of the target pattern) in the periphery, as opposed to conventional linear encoding fields, is demonstrated in Fig. 3. Simulations for acceleration factors 2 and 3, corresponding to 64x32 and 64x21 encoding steps, are shown in Fig. 4. Although for PatLoc encoding additional RF degrees of freedom are needed for resolving ambiguities, decent acceleration of the pulses is still possible.

Conclusion

A generalization of pulse design algorithms for SSE with arbitrary tip angle to the regime of nonlinear and non-bijective encoding fields has been presented. With these generalized encoding fields a locally increased precision in manipulating the magnetization can be achieved. Vice versa, for a given resolution and given peripheral nerve stimulation limits, PatLoc fields can be switched faster than linear fields, shortening the RF pulse duration.

References

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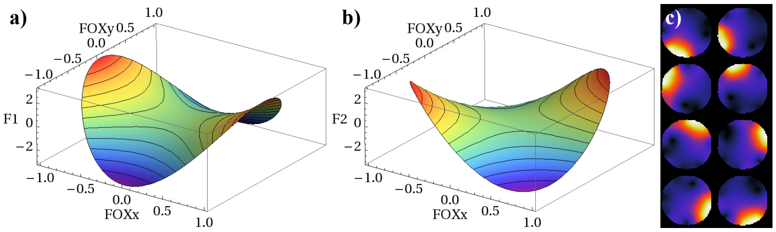

Fig. 1: Spatial encoding fields for selective excitation. a), b) Quadrupolar PatLoc fields for two-dimensional “gradient” encoding during transmit, replacing the x- and y-gradients. c) 8-channel B_1 transmit profiles for additional RF encoding.

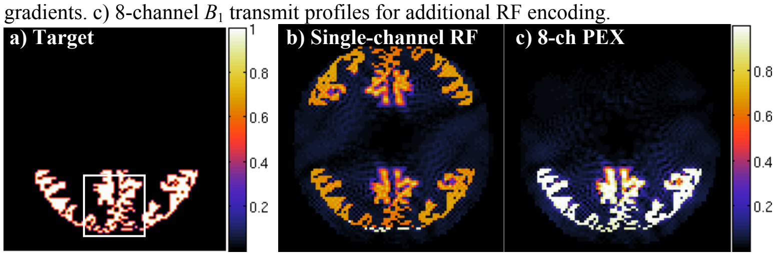

Fig. 2: a) Target pattern (96x96) for selective excitation. b) Simulated transverse magnetization for single-channel RF excitation. Unwanted aliased magnetization appears due to ambiguities in the PatLoc encoding. c) 8-channel parallel excitation resolves the ambiguities leading to the desired excitation.

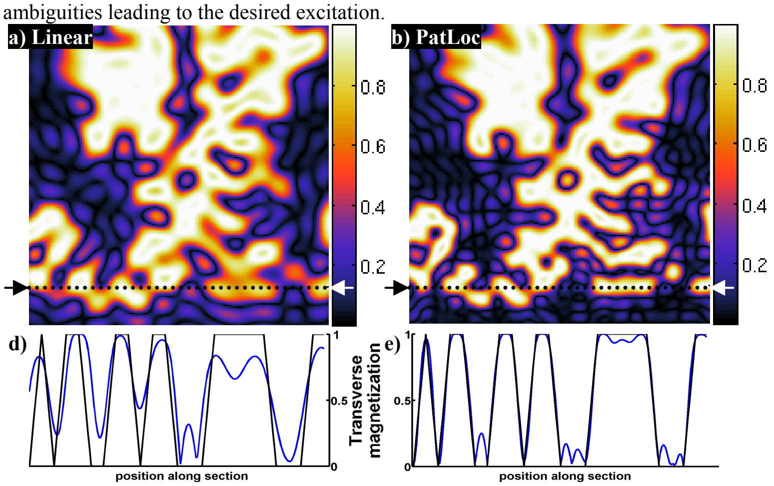

Fig. 3: Transverse magnetization of a simulated 90° selective excitation with 64x64 field encodings and 8-channel parallel transmit, evaluated on a grid with 4-fold target resolution inside the box shown in Fig. 2a. 3a), d) Linear encoding fields; 3b), c) PatLoc encoding fields. Lower row: Sections along the lines indicated by the arrows in the upper row; Blue line: Transverse magnetization; Black line: Target pattern.

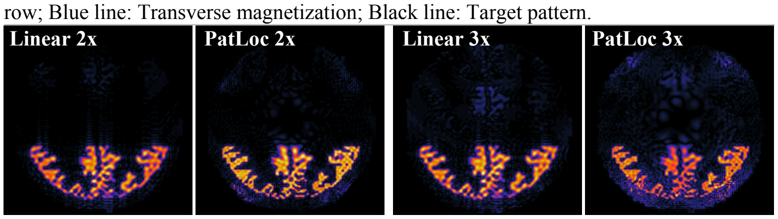

Fig. 4: Accelerated parallel excitation (64x32 field encoding steps for 2x, 64x21 steps for 3x) for linear and PatLoc encoding fields. The higher resolution in the periphery also results in higher frequency Gibbs ringing in the case of PatLoc encoding.