T2*-compensated Transmit SENSE RF pulses

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Introduction

Selective excitation in more than one dimension is plagued by effects that are due to the long duration of the RF pulses and gradient trajectories needed. B_0 off-resonances, for example, dephase magnetization contributions created at different points in time during the excitation process. As a consequence, these contributions do not add up consistently which causes artifacts in the final excitation pattern. In addition, magnetization can decay already during the transmission of a long selective pulse. Parallel transmission [1-3] helps to alleviate these problems by reducing the total duration of selective pulses. Furthermore, approaches how to inherently account for off-resonances during the RF design have been described [4,5]. In this work, the issue of transverse (T_2*) relaxation of magnetization during RF transmission is addressed. It is shown that a T_2* relaxation map can be described as the imaginary part of an off-resonance map, and that therefore, the compensation of transverse relaxation is a straightforward extension of existing off-resonance correction schemes into the complex domain. Longitudinal (T_1) relaxation during RF transmission is neglected in this study, which is justified by the longer timescale of this relaxation process.

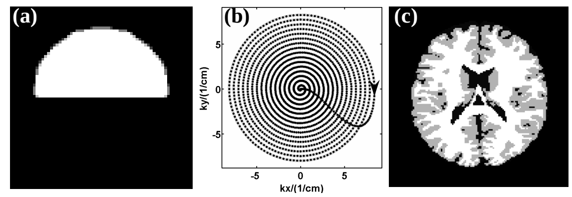

Fig. 1: (a) Half-brain excitation target pattern; (b) 2x accelerated k-space spiral trajectory; (c) T_2* map used for the pulse design and the simulations. The T_2* values are approximated as $T_2/2$ at 3T as given in Ref. [8]: White matter (T_2*=69 ms / 2), gray matter (99 ms / 2) and CSF (2000 ms / 2).

Methods

Starting from the Bloch equations with off-resonances and transverse relaxation, i.e. including T_2* decay of the x- and y-components, one obtains for the complex transverse magnetization $M_\perp$ in the rotating frame and small tip angle approximation:

$$M_\perp(\mathbf{r}) = i\gamma M_0(\mathbf{r}) \int_0^T dt \sum_l S_l(\mathbf{r}) I_l(t) \exp\left[i\mathbf{r}\cdot\mathbf{k}(t) + i\tilde{\omega}_{\text{off}}(\mathbf{r})(T-t)\right] , \qquad (1)$$

where S_l denotes the coil transmit profiles, I_l the corresponding RF wave forms and $\mathbf{k}(t)$ the excitation k-space trajectory. T is the total pulse duration and the generalized off-resonance map is defined as

$$\tilde{\omega}_{\text{off}}(\mathbf{r}) = \omega_{\text{off}}(\mathbf{r}) + i\frac{1}{T_2^*(\mathbf{r})} . \qquad (2)$$

The imaginary part of ω_{off} generates a real and negative exponent. Thus, for magnetization components excited at time t the remaining off-resonance phase angle $\omega_{\text{off}}(T\text{-}t)$ and the relaxation factor $\exp[-(T\text{-}t)/T_2^*]$ are taken into account in the forward problem. The RF pulse design is then performed by a conjugate gradient solution in the image domain [6] of the discretized Eq. (1). Clearly, the presented relaxation compensation only works in the small transverse magnetization regime [9]. In contrast, for 90° excitation angles the algorithm generally cannot generate any extra transverse magnetization such that at the end of the pulse $M_\perp = M_0$. In this case, using an adapted optimal control algorithm, either a given flip angle distribution or a downscaled transverse magnetization distribution can be achieved, but not both simultaneously. Also, selective RF pulses still need to be shorter than the shortest T_2* inside the object of interest, otherwise the relaxation compensation cannot converge.

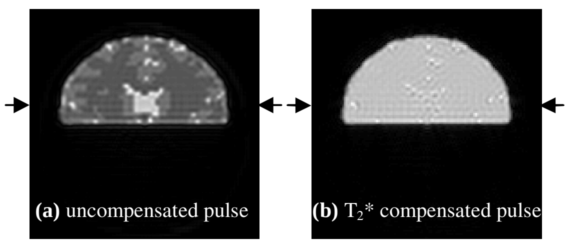

Fig. 2: Simulations of the transverse magnetization resulting from (a) a standard small tip angle RF pulse, showing T_2* contrast (duration is 20.5 ms) and (b) a T_2* compensated pulse.

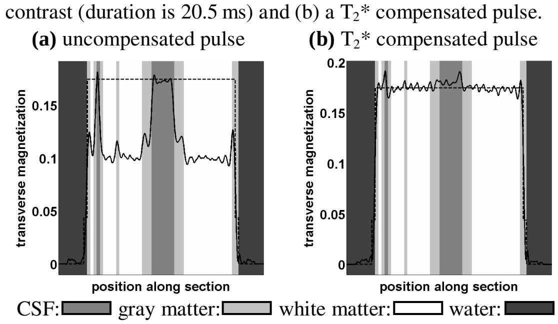

Fig. 3: Sections of transverse magnetization along the direction indicated by the arrows in Fig. 2 after excitation with (a) an uncompensated and (b) a T_2* compensated RF pulse. The dashed line indicates the target magnetization. The background gray level represents the tissue at the particular location.

Results

A four-channel RF pulse of 20.5 ms duration was designed as described above on a 2x accelerated k-space spiral, with a half-brain target pattern defined on a 64x64 grid, see Fig. 1. A T_2* map on the same grid was taken into account, which was created from a transversal slice of the healthy BrainWeb dataset [7]. Literature values for T_2 at 3T [8] divided by two were used as an approximation for T_2*. The effect of the RF pulses was simulated using the full Bloch equations including transverse relaxation on a 128x128 grid. Fig. 2(a) shows the resulting transverse magnetization for an uncompensated pulse, clearly exhibiting the expected loss of signal intensity in regions of short T_2*. The T_2* compensated pulse removes this contrast as shown in Fig. 2(b). A quantitative comparison with the target pattern along left-right sections is given in Figs. 3(a) and (b), demonstrating good agreement for the compensated pulse. Note that the k-space spiral used [see Fig. 1(b)] is running from the k-space center outward. For this reason, the relaxation effects in low-frequency spatial components of the image are strong. Inward-running spirals produce much less artifacts in the total signal level, but seriously affect the achievable resolution of the target pattern instead. The latter artifacts are more difficult to visualize, however the presented method equally well compensates for these.

Conclusion and Outlook

A method for small tip angle Transmit SENSE RF design has been described that takes into account arbitrary T_2* maps. The additional T_2* contrast generated by a long selective pulse can therefore be removed, if it is not desired. Because T_1 increases with increasing B_0 strength, neglecting the longitudinal relaxation will remain a good approximation. As T_2 values decrease with increasing B_0, the compensation of transverse relaxation will become more important in future high-field systems.

References

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