Decreasing SAR of a multi-dimensional central brightening inhomogeneity correction pulse using nonlinear gradient fields and VERSE

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Introduction

In most MRI applications, there is an inclination towards higher fields because of higher SNR. However, usage of ultra high field (UHF) MRI scanners for clinical purposes is hampered by high SAR. At UHF regime, decreasing wavelength causes inhomogeneity effects during transmission [1]. Correction methods such as B1 shimming and multi-dimensional pulses increase homogeneity, but also increase the SAR. When this increase accumulates with the quadratic increase of SAR with the field strength, SAR becomes a limiting factor at the UHF regime.

The technique of variable-rate selective excitation (VERSE) decreases the SAR by casting the gradient waveforms time dependent and adjusting the RF envelope accordingly [2]. On the other hand, we recently proposed using fields with nonlinear variation in space in order to reduce the SAR [3]. In this study, we assume a central brightening inhomogeneity, which is widely seen at the UHF regime [4], and correct this inhomogeneity using three-dimensional spoke excitation. While designing the RF pulses, we compare and combine these two techniques to observe their effects on SAR.

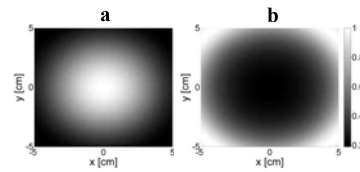

Figure 1: Central brightening inhomogeneity (**a**) and its inverse (**b**), simulation.

Theory

The RF pulse design approach in its most general form starts by expressing the desired excitation profile and taking its Fourier transform, which results in the excitation k-space. By tracing the excitation k-space using gradient fields, and sampling the excitation k-space along the path, the RF envelope is obtained. Although gradient waveforms are trapezoidal in conventional techniques, the technique of VERSE utilizes time-varying gradient waveforms in order to reduce the SAR [2]. On the other hand, when nonlinear gradient fields are used for excitation, the mapping from the excitation profile to the excitation k-space becomes a nonlinear Fourier transform [3] and hence the excitation k-space changes. Therefore, the RF envelope and the SAR are altered.

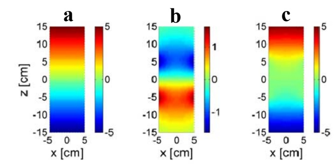

Figure 2: All fields are in mT units and on the xz-plane. **a:** z-gradient, **b:** Field of the Maxwell coil, **c:** Total field for the proposed solution.

Methods

Although the method aims to reduce the SAR for the UHF, because of the lack of a UHF MRI scanner, the initial experiments are performed on a 3T Siemens scanner to investigate the results. Simulations are performed in Matlab (Mathworks, Natick, MA, USA). In order to get a homogeneous excitation profile in the presence of the central brightening effect (Fig.1a), the aimed excitation profile is selected as the inverse of the inhomogeneity (Fig.1b). For the reference solution, the x-, y-, and z-gradient fields are used (z-gradient: Fig 2a) whereas for the proposed solution, the field given in Fig.2c is used by using a custom-built Maxwell coil (radius:8cm, distance between turns:10cm) together with the z-gradient.

For both methods, 5-spoke RF excitations are designed (Fig.3a,c) using trapezoidal gradient waveforms. Then, the VERSE algorithm is applied to both methods (Fig.3b,d) using an amplitude limit of 40mT/m and a slew rate limit of 140mT/m/msec (the limits correspond to a Siemens 3T TimTrio scanner with software version vb15). To account for the shorter pulse duration (τ) for the VERSE pulses, and possible numerical errors in the flip angle (α), the SAR values are normalized using $SAR_n = SAR\,\tau/\alpha$. To compare the solutions, the root-mean-squared error between the aimed and obtained excitation profiles are calculated.

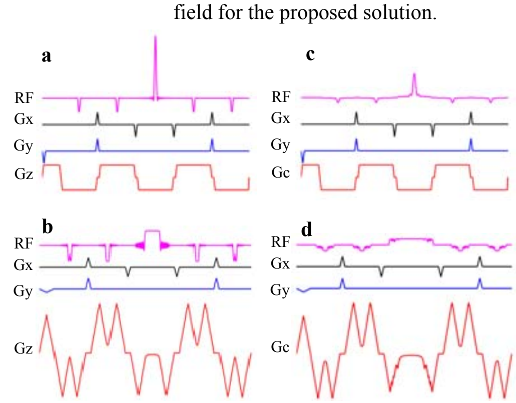

Figure 3: RF and gradient waveforms for the reference (**a**, **b**), and proposed solutions (**c**, **d**). (b, d: with VERSE). RF pulses are doubled in scale for (b, d). Gc denotes the field given in Fig.2c.

In the experiments, 3D encoding is made for both methods. Using a custom monitoring system, the z-gradient waveform is read and is fed through an audio amplifier to the produced Maxwell coil. A relay, triggered using the scanner, is added to the chain, so that during encoding, the Maxwell coil is turned off. Because the current needed for the VERSE sequence was out of the range of the amplifier, the sequence given in Fig.3d could not be implemented.

Results

For both methods, the excitation profiles obtained computationally and experimentally are given in Fig. 4a-d. All SAR values are calculated in reference to the RF sequence shown in Fig. 3a and listed in Table 1. It can be seen that for the studied case, using a nonlinear gradient field and applying VERSE yielded very similar SAR reductions. However, when VERSE is applied together with the nonlinear gradient field, the reduction becomes 91% which is approximately 65% lower than applying the two methods separately. Note that, as these reductions are obtained by changing the RF envelope, they apply to both local and whole-body SAR. The profile error for the nonlinear gradient case is slightly higher than the linear gradient field case with 6% as opposed to 3%.

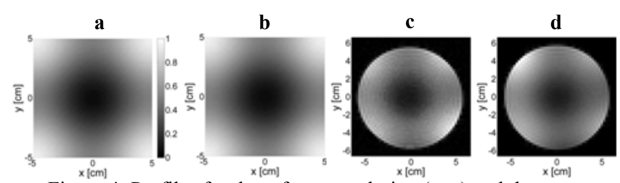

Figure 4: Profiles for the reference solution (**a**, **c**) and the proposed solution (**b**, **d**), using 5 spokes each. (**a**, **b**): simulation, (**c**, **d**): experiment. FOV is slightly larger in the experiments. Color ranges are the same for all figures.

	SAR_n
Linear gradients without VERSE	1
Linear gradients with VERSE	0.26
Nonlinear gradients without VERSE	0.24
Nonlinear gradients with VERSE	0.09

Table 1: SAR reduction values for all designed sequences. The values are calculated with respect to the linear gradient case without VERSE applied.

Discussion & Conclusion

Nonlinear gradient fields change SAR by altering the relation between the desired excitation profile and the excitation k-space, whereas VERSE reduces SAR by modifying the relation between the excitation k-space and the RF envelope. As these two techniques act on different parts of the chain from the excitation profile towards the RF envelope, the two techniques can be combined to yield further SAR reductions. It is shown that when the two techniques are used together, the reduction in SAR is higher than those provided when the techniques are used single-handedly. Therefore, we believe nonlinear gradients will be a powerful tool for inhomogeneity correction at UHF MRI.

References: [1] Wiesinger F et al. *NMR Biomed* 2006;19:368-378. [2] Conolly S et al. *J Magn Reson* 1988;78:440-458. [3] Kopanoglu E et al. *Proc. ISMRM 19th, Montreal,* 2011;p1848. [4] Vaughan JT et al. *Magn Reson Med* 2001;46:24-30.