SAR reduction by k-space adaptive RF shimming

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Introduction

Parallel transmission allows compensating for transmit field inhomogeneities in high field MRI by means of RF shimming, i.e. by the optimization of the amplitudes and phases of a multi-element RF array [1]. Moreover, the RF transmit power can be simultaneously reduced by regularization techniques. This allows for a reduction of the specific absorption rate (SAR) and hence reduces thermal stress for the patient. Unfortunately, the regularization approach leads to a conflict of objectives between image homogeneity and SAR reduction [2] and a compromise has to be found.

So far, the RF transmission has been considered independently from the sampling process. It is well known, that the center of the receive k-space determines the image contrast and uniformity. This has been used for dynamic studies by employing the 'keyhole' concept [3]. For parallel transmission, this relation offers a new degree of freedom in the sequence design: Instead of using a fixed RF pulse for all phase-encoding steps, several different pulses can be applied [4]. This k-space adaptive approach to RF shimming avoids the trade-off between contrast and SAR. In the present work, this technique is discussed theoretically and proof-of-principle is given based on phantom and *in vivo* images.

Methods

Imagine the 2D phase-encoding space of a 3D imaging sequence as shown in Fig. 1. In the central k-space, highly uniform, but relatively SAR-intensive RF pulses are to be used to achieve optimal contrast in the image domain. When sampling the outer k-space, the B_1^+ homogeneity requirement can be relaxed to achieve a reduced average SAR.

Since MR imaging is highly sensitive to phase inconsistencies, it is important to avoid deviations in the excitation phase when switching between different RF pulses. Therefore, a hybrid optimization method was developed: The central RF pulse is calculated using a magnitude least-squares (MLS) optimization that does not constrain the image phase [5]. The outer pulses are computed by a least-squares (LS) optimization, using the Tx-phase obtained from the MLS step as the target phase.

Experiments were performed on a 3T scanner (Philips Healthcare, Best, The Netherlands) equipped with an 8 TX-channel body coil [6] using a cylindrical water phantom (Ø40 cm) and *in vivo* on five average-sized volunteers in the abdominal region. B1-maps were acquired during breathhold for all Tx-channels using the actual flip angle (AFI) sequence with all-but-one channel transmitting to avoid regions of low flip angles [7]. RF-power (sum of the squared amplitude scaling factors) of the central pulses was slightly regularized to avoid exceedingly high drive voltages. Using the hybrid optimization method, additional pulses were calculated while step-wise tightening the RF power regularization. All pulses were normalized to give the same average flip-angle as the quadrature drive. Finally, the actual images were acquired using a 3D FFE Cartesian sequence for all calculated RF shim-sets.

The combination of the acquired raw data in the k-space was performed off-line. The center of the k-space was filled with samples from the image with the MLS-optimized pulse, the outer k-space data were replaced with samples from the maximally regularized LS optimized raw data at different mixing ratios *r*. For the *in vivo* data, the whole-body SAR was calculated using an FDTD simulation.

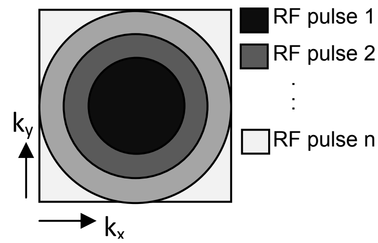

Fig 1: 2D phase-encoding space
RF excitation pulses are varied depending on the phase encoding step (k_x,k_y). Dark colors indicate a more homogeneous B_1^+ excitation, but requiring higher RF power.

Results and Discussion

Fig. 2 shows the RF-power plotted over the NRMSE (normalized root mean square error) of the effective B1 maps. The quadrature case is shown as a reference. Starting from a pure MLS-optimized excitation (*r* = 0%) and increasing *r*, the k-space adaptive design shows a strong reduction of RF-power, whereas homogeneity is almost completely maintained up to r = 80%. The corresponding images are shown in Figs. 3 and 4. When compared to the optimally shimmed images (a), the traditionally shimmed, low RF-power images (b) show a loss of contrast in the center. The k-space adaptive results (c) show an image quality comparable to the optimal results, while RF-power and SAR are almost halved.

Conclusion

A SAR reduction by k-space adaptive RF shimming is feasible without significant loss of image homogeneity. The conventional trade-off between the error and the RF-power can be overcome. In practice, using several RF pulses should allow for a smooth transition in the k-space when imaging in the steady-state. Furthermore, the proposed k-space adaptive shimming concept could be extended to all kinds of magnetization preparation RF pulses in more sophisticated imaging sequences such as TFE to further reduce the average SAR.

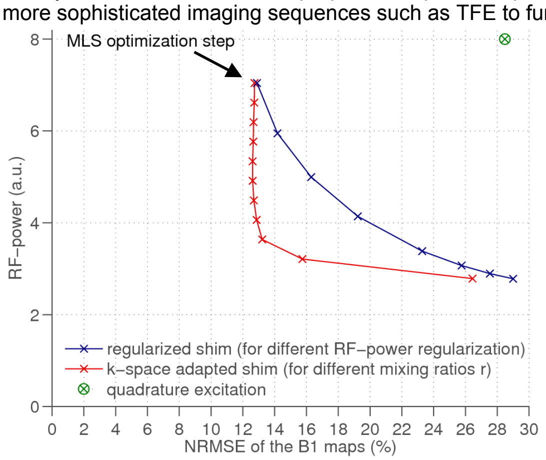

Fig 2: Comparison of the trade-off between RF-power and the B_1 homogeneity error for the water phantom: The new method (red curve) outperforms the conventional regularization (blue curve).

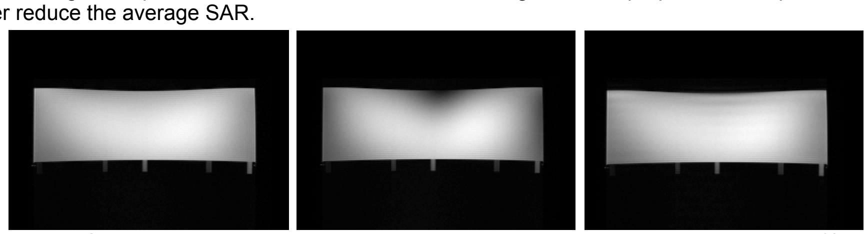

Fig 3a) Optimal shim result: RF power = 6.7 (100%)
b) Max power constraint: RF power = 2.8 (42%)
c) k-space mixture r = 80%: RF power = 3.6 (54%)

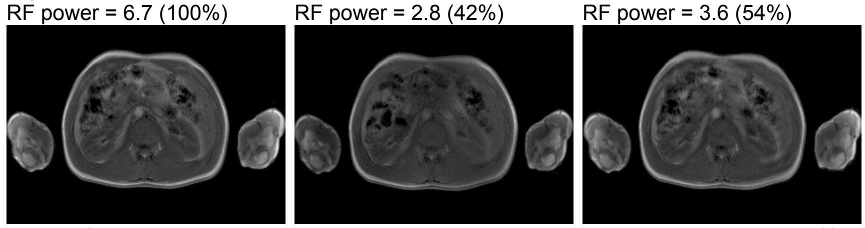

Fig 4a) Optimal shim result: RF power = 9.9 (100%) Whole-body SAR: 100%
b) Max power constraint: RF power = 4.0 (41%) Whole-body SAR: 44%
c) k-space mixture r = 80%: RF power = 5.2 (53%) Whole-body SAR: 56%

References [1] Ibrahim TS, MRI 18:733 (2000) [2] Katscher U, Proc. ISMRM 2009:2607 [3] van Vaals JJ, JMRI 3:671 (1993) [4] Börnert P, Proc.ISMRM 2009:2600 [5] Setsompop K, MRM 59:908 (2008) [6] Vernickel P, MRM 58:381 (2007) [7] Nehrke K, Proc. ISMRM 2008:353