Local SAR constrained Hotspot Reduction by Temporal Averaging

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Introduction With increasing field strength the local specific absorption rate (SAR) becomes a limiting factor for many MR imaging applications. Minimal SAR RF pulses can be selected from the large solution space due to the extra degrees of freedom in the RF pulse design [1-4]. This paper extends the recently proposed temporal averaging approach for local SAR reduction [5] with multiple local SAR constraints. It successively applies multiple RF pulses with similar target excitation patterns, but different spatial SAR distributions, for averaging out local hotspots. The concept was validated by simulations and initial experiments on an 8-channel TX MRI system.

Methods For an N-channel transmit system, the excitation pattern can be written in matrix notation as m=Ab [6,3,2], where m describes the target excitation pattern, A the sensitivity matrix, and b the concatenated RF pulses b_n ($1 \leq n \leq N$) of the individual TX elements. The currents driving the field lead to a linear superposition inside the subject, so that the SAR can be expressed in a quadratic form in the pulse samples $b^\dagger Q b$, where † denotes the conjugate transpose. Q is a block-diagonal positive definite matrix resulting from a solution of Maxwell's equations, which is a specific subject volume [3]. The problem designing a pulse b being as close as possible to a desired target excitation m, while meeting K maximum SAR constraints s_i in body regions defined by the matrices Q_i is expressed as the Quadratically Constrained Quadratic Programming problem (QCQP): optimize $\|Ab - m\|_2$ = min subject to $Q_i^T b Q_i \leq s_i$, i=1…K. As proposed in [1], this QCQP problem can be solved by being transformed in a Second-Order Cone Programming (SOCP) problem [7], using a SOCP solver [8] with MATLAB (MathWorks, Natick, WA). For the efficient calculation of this large-scale constrained optimization problem, a re-orthogonalized Lanczos algorithm [9] is used by an iterative decomposition of the matrix A into a lower rank approximation.

During a multi-shot imaging sequence, usually the same RF excitation pulses b_n are repeatedly applied. In this investigation, the sequence is partitioned into L different sections, and for each section, different excitation pulses b_n^l ($1 \leq l \leq L$) are used. As input for the subsequent optimization of the temporal averaging, different pulses are selected with desired target magnetization patterns m_l as similar as possible, however, with different critical hotspot locations. The optimal time partitioning for the pulses b_n is given by dividing the total scan time T into L time intervals t_j (j=1…L) so that minimal maximum SAR values are obtained. Time intervals were calculated according to the non-linear optimization problem max{Sx} = min subject to $x_j \geq 0$ and $\sum_j x_j = 1$. x_j equals to the non-linear optimization problem max{ST/t_j} = min. S contains the SAR values of all body cells in the columns for each pulse b_{nl}. This problem is solved using a generic optimizer [10]. A real-time SAR calculation according to [11] was used. The experiments were carried out on an eight-channel transmit 3T MRI system [12] (based on Achieva, Philips Healthcare, The Netherlands). In a first step, L=8 different 2D Transmit SENSE RF pulses [13], transmitting very similar target patterns, were calculated using the above described algorithm (32×32 FOX pixel, reduction factor R=7, spiral k-space trajectory). In a second step, also some pulses with a higher deviation from the target pattern were used according to Fig. 1.

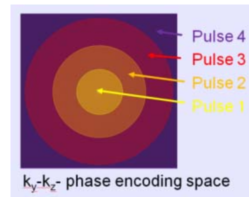

Fig. 1: Individual parallel transmit RF pulses for 4 different ky- kz- encouding plane segments.

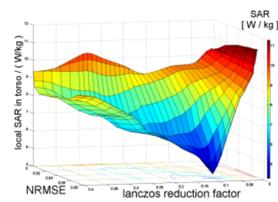

Fig. 2: Local SAR in torso vs. different Lanczos reduction factors and NRMSE.

Results and Discussion The individual spatial SAR distributions for the different RF pulses that were calculated iteratively using the algorithm above are shown in Fig. 4. The SAR of the initial RF pulse and the results of the local SAR reduction by temporal averaging are shown in Fig. 3. It was possible to reduce the limiting SAR hotspot in the torso region up to 55%, while meeting the SAR limits [14] in all other regions. A further reduction was achieved by using RF pulses with different excitation quality up to additional 25%. The use of the Lanczos algorithm enabled the calculation of the RF pulses within a few seconds making this iterative optimization procedure feasible.

Conclusion A recently proposed temporal averaging approach, exploiting the temporal degree of freedom of multi-shot imaging sequences, was extended using an SOCP based minimization technique incorporating local SAR constraints. Thus it is being able to reduce local SAR hotspots iteratively. Further SAR reduction was achieved by using pulses of different excitation quality.

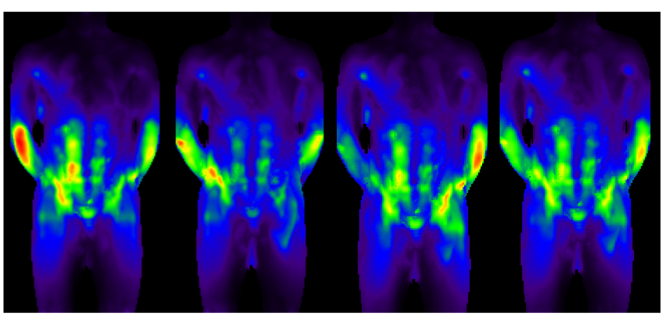

Fig. 3: SAR (MIP) resulting from individual local Q- matrices constraint RF pulses (a) and the SAR reduction by temporal averaging (b).

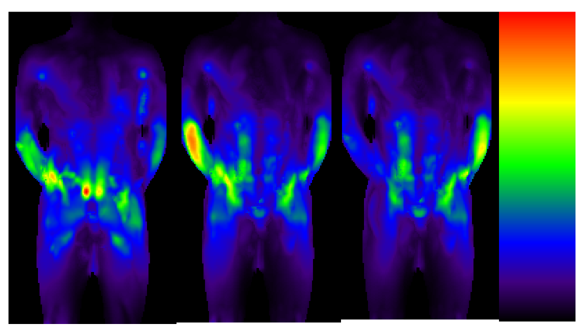

Fig.4: SAR resulting from different RF excitation pulses with similar magnetization patterns and individually critical hotspot locations.

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