SAR Hotspot Reduction by Temporal Averaging in Parallel Transmission

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Introduction

The local specific absorption rate (SAR) becomes a limiting factor for many MR imaging applications with increasing field strength. However, tailoring of the underlying electric fields (E-fields) in the RF pulse design process is possible when using parallel Tx systems. Different approaches exist to reduce SAR in parallel transmission. Minimal SAR RF pulses can be selected from the large solution space due to the extra degree of freedom in the RF pulse design [1-4]. This paper presents a novel approach for local SAR reduction by exploitation of the temporal degree of freedom of multi-shot imaging sequences. It is based on successive application of RF pulses with the same target excitation pattern, but different spatial distributions of SAR, levelling out by time averaging.

The concept was validated by simulations. Both computation of RF pulses and spatial SAR distributions were significantly accelerated implementing it on a graphics-processing unit (GPU). The local SAR calculation was carried out in real-time for a whole body bio-mesh according to [5].

Methods

For an N-channel Tx 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. Provided that the RF field inside the subject responds linearly to the currents driving the field, the SAR can be expressed in a quadratic form in the pulse samples $b^\dagger Qb$, where $\dagger$ denotes the conjugate transpose and Q is a block-diagonal positive definite matrix resulting from a solution of Maxwell's equations and corresponding to a specific subject volume [3].

Recently, a method for local SAR hot-spot reduction was proposed [7]. This method was based on incorporating knowledge about the spatial SAR distribution of an initial RF pulse into Q and relaxed minimization of the equation $b^\dagger Qb$ s.t. $m=Ab$. This was achieved by introduction of real weighting factors $\{ q_i \}$ into the problem, which are specifying a trade-off between different hotspot regions. Using an initial RF pulse that is optimal with respect to global SAR, reduction of a single hot-spot was achieved via $Q = Q_{global} + q\, Q_{region}$. While it was shown that this approach enables reduction of a local hot-spot, it may also be applied for spatial translation of a local SAR hot-spot. Therefore, a weighting factor q has to be found that moves the local SAR hot-spot to a desired, non-critical region.

Usually, the same RF excitation pulses b_n are repeatedly applied during a multi-shot imaging sequence. In this study, different excitation pulses b_n^l ($1 \leq l \leq L$) are applied in L different partitions of the sequence. The different pulses are chosen from the large solution space corresponding to the desired target magnetization pattern m, but different critical hotspot locations. Exploiting this temporal variation, the pulses may be chosen with the goal of minimal temporally averaged SAR.

To this aim, E-fields were calculated for an ideally decoupled 3T 8-channel body coil [8], according to [9]. A bio-mesh (Philips Medical Systems, Cleveland) of the "Visible Human Male" with about 750k cells was used. The pre-calculated E-fields were averaged according to [10], and the SAR calculation was highly optimized and parallelized on a high performance graphics card (EVGA GeForce GTX280, EVGA® Corporation, USA) with 240 processors that allows for a real-time calculation of the SAR. Then, L=5 different 2D Transmit SENSE RF pulses [6], transmitting the same target pattern, were calculated using the above described algorithm (32×32 FOX pixel, reduction factor R=4, spiral k-space trajectory). The desired spatial locations of the SAR hot-spots of these pulses were chosen to be separated from each other. Parts of the calculation were optimized and parallelized to run on a second high performance graphics card (EVGA GeForce GTX280, EVGA® Corporation, USA), both of which were integrated into an eight-channel transmit 3T MRI system [11] (based on Achieva, Philips Healthcare, The Netherlands). This allows for an accelerated RF pulse calculation by a factor of 5 at the scanner console.

Results and Discussion

Fig. 1 shows the individual spatial SAR distributions for the different RF pulses. The SAR of the initial RF pulse and the results of the local SAR reduction by temporal averaging are shown in Fig. 2. The limiting hotspot (pelvic region) in Fig. 2a was reduced to 68% (Fig. 2b), while meeting the SAR limits in all other regions according to [5]. It is worth mentioning that the potential of the presented method highly depends on the excitation pattern, the reduction factor, the patient model, and its position within the coil. The method has the potential of higher SAR reduction, as the time averaging dimension offers additional freedom compared to other approaches, as, e.g., calculation of a single SAR optimal pulse. Furthermore, instead of using identical target patterns for the calculation of the individual pulses, also slightly varying patterns may be used, thus creating an even larger solution space for the RF pulses and possibly enabling higher SAR reduction performance.

Conclusion

An RF pulse design technique was proposed, which exploits temporal partitioning of multi-shot imaging sequences for reduction of local SAR. This additional degree of freedom has never been used before for RF pulse design for parallel transmission. An optimized implementation of the algorithms on a GPU allowed for a fast calculation of the RF pulses and local SAR. SAR reduction is very important for SAR limited scans, e.g., Transmit SENSE with high reduction factors at higher field strengths.
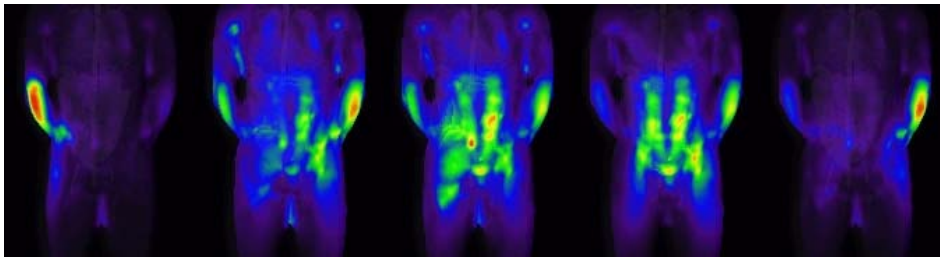

Fig. 1: SAR comparison (MIP, increasing values from blue to red) of the L=5 different RF pulses used for temporal averaging. The images are scaled individually.
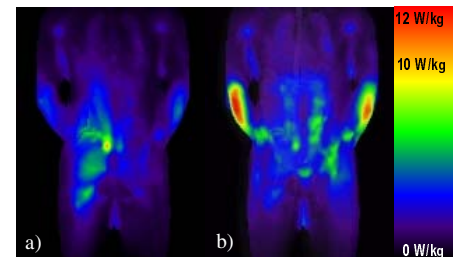

Fig. 2: SAR (MIP) resulting from the initial RF pulse (a) and SAR reduction by temporal averaging (b). Note that higher allowed local SAR limits exist for the extremities.

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