Fast non-linear pTx pulse design with integrated peak local RF energy minimization

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Introduction: For ultra-high field strengths of 7T and above and especially for parallel transmission, tissue heating due to RF field exposure is a dominant limiting factor for high performance human imaging. However, most pulse design methods use a constraint on forward RF energy or global RF energy deposition in the subject to find a trade-off between excitation quality and RF energy deposition. Both quantities can be represented by a single quadratic form. One cause for missing peak local RF energy constraints is that the model describing the spatial RF energy distribution contains one quadratic form for each voxel of the human model and thus is not efficient for the use in RF pulse design. Only recently, a compression method was shown [1] to reduce the model size to a fairly small number of "virtual observation points" (VOP). Based on this approach, a method was shown to optimize the local RF energy of an RF pulse for parallel transmission by iteratively repeating a linear pulse design [2]. In every iteration the local RF energy constraints are adapted. However, this approach is limited to low flip-angles and has no possibility to design completely non-linear pulses like composite pulses [3]. Also, this method iterates over the VOPs during the optimization which is computationally expensive for a larger number of VOPs. The goal of this study is to optimize the flip-angle distribution of non-linear high flip-angle RF pulses, such as composite pulses for parallel transmission, and to minimize the peak local RF energy at the same time in one run of a non-linear solver.

Methods: The algorithm to optimize local RF energy deposition of RF pulses for parallel transmission is based on a non-linear pulse design method we presented earlier [4]. This method solves a system of non-linear equations where each equation describes magnetization dynamics for one voxel in the field of view using the full Bloch equation.
The proposed algorithm adds additional quadratic equations to this system considering local RF energy dissipation. Each equation uses one VOP to describe the peak local RF energy of a large set voxels in the human body. To minimize the peak local RF energy, the sum of squares of the RF energy of all VOPs is minimized together with the excitation error. To trade off flip-angle homogeneity with RF energy performance, a scaling parameter is added. The resulting extended system of equations is minimized by a non-linear solver based on the Levenberg-Marquardt algorithm witch uses a CUDA capable graphics processing unit.
For pulse design, B1- and E-field distributions were calculated with CST Microwave Studio using the human model HUGO positioned in an 8 channel 7T head coil. The RF energy distribution was compressed into 423 VOPs with a maximum overestimation of 5%. High flip angle 180° composite pulses for homogeneous excitation as well as spokes pulses were designed with different trade offs between spatial fidelity and local as well as global RF energy. All calculations were done on a Workstation equipped with an Intel Xeon Processor with 3.6GHz and a NVIDIA GeForce GTX 285.

Results: In figure 1, peak local RF energy is plotted versus root mean square excitation error of the achieved flip-angle distribution. This is shown for the proposed local RF energy constrained algorithm (blue) and the global RF energy constrained algorithm (red). Figure 1a shows the results for a three sub-pulse composite pulse, figure 1b shows the results for a spokes pulse with three spokes. All pulses have a total length of 3ms. The maximum spatial fidelity is achieved without any RF energy constraint and is therefore independent of the used algorithm (top left point). In all cases, the local RF energy constrained algorithm shows equal or lower peak local RF energy. For the spokes pulse, the reduction is up to 30%, for composite pulses up to 20%. For very strict RF energy limits (bottom right points), the homogeneity gets close to the homogeneity of RF shimming. The total pulse calculation time including the peak local RF energy optimization was less than 100ms for all shown pulses which, on average, is approximately 10% longer compared to the original pulse design algorithm.

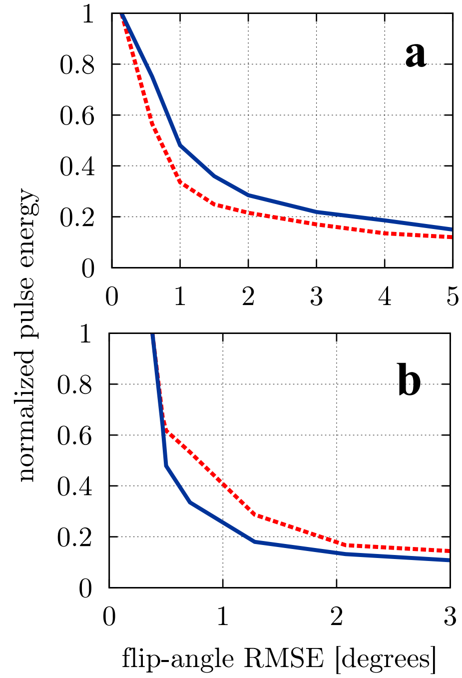

Fig 1: normalized peak local pulse energy vs. flip-angle root mean square error for composite pulses (a) and spokes (b) using a global RF energy limiting algorithm (orange) and a local RF energy limiting algorithm (blue)

Conclusion: We demonstrated the design of 180° composite pulses and spokes pulses for B1+ inhomogeneity mitigation that yields a significant reduction in local RF energy deposition compared to a design using global RF energy limits only. Depending on the pulse type and desired flip-angle homogeneity, the peak local RF energy deposition was reduced up to 30%. The used algorithm includes local RF energy constraints directly into the pulse design with no significant impact on calculation time by extending the system of non-linear equations that describes the optimization problem. The results for both algorithms is identical in the case of best flip-angle homogeneity which shows that the data is not biased by differences in the B1+ mitigation performance of both algorithms. The local RF energy constraint pulse design was implemented on a graphics processing unit to ensure fast pulse calculation times. For all shown pulses, the design time was less than 100ms. The proposed method can directly be applied for other pulse types used for parallel transmission, like transmit SENSE or spectral-spatial pulses.

References: [1] Eichfelder et al. MRM 66(5):1468-1476 (2011), [2] Lee et al. ISMRM 2010, 422 , [3] Collins et al. MRM 57:470-474 (2007), [4] Gumbrecht et al. ISMRM 2010, 101