Local and global SAR constrained large tip angle 3D kt points parallel transmit pulse design at 7 T

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Target Audience: MR physicists and users needing 3D uniform tip-angle parallel transmission (pTx) excitations.

Purpose: pTx pulses have been shown to mitigate B1+ inhomogeneity at high-field for both small and large tip angle excitations with slice-selection [1] (spokes) and for 3D [2] (kt points). At small tip angles with spokes trajectory, it has been demonstrated that the control of pulse power does not explicitly control local SAR and simultaneous constraints of pulse power and local SAR are required to yield optimal pulses satisfying system and regulatory limits [3]. To our best knowledge, none of the existing large tip angle pTx pulse design methods are capable of controlling local SAR directly. We extend the small tip angle approach to large tip angle and incorporate local SAR, global SAR and pulse power constraints in the design of 3D kt point large tip angle excitation pulses at 7 T. We demonstrate that the excitation fidelity of the large tip angle pulses improves significantly when local SAR constraint is imposed directly rather than via the control of the peak RF power.

Methods: We design large tip angle pulses in two steps. First, an LCLTA pulse [4] with the desired target tip angle is designed using the following least squares optimization algorithm: $\min_x \|Ax^* - \theta\|_2^2$ subject to $\|x\|_\infty < RF_{max}$, $xS_n^{local}x^H < S_{max}^{local}\ \forall n$, $xS^{global}x^H < S_{max}^{global}$ where A is the gradient design matrix, x is the RF pulse, θ is the target tip angle, RF_{max}, S_{max}^{local} and S_{max}^{global} are maximum RF voltage, peak local SAR (LSAR) and global SAR (GSAR) limits and S_n^{local} and S^{global} are the LSAR and GSAR matrices. The LSAR matrices could be hundreds of thousands many depending on the resolution. We compress them into a smaller set (a few hundreds) of virtual observation points (VOPs) for faster optimization [5]. To satisfy the Hermitian symmetry condition of LCLTA pulses, the kt points are restricted to be located symmetrically around the origin in pairs. This LCLTA pulse is then used as the initial point of a second least squares optimization that uses the Bloch equations as the forward model [6,7] and that includes explicit constraints for LSAR, GSAR and RF power as well. We use the full Bloch equations to calculate the objective function and its gradient rather than linearizing the Bloch equations as in the fast optimal control approach [8].This second optimization step is performed in the spinor domain as opposed to the magnetization domain [9]. We evaluated our pulse design strategy using electromagnetic simulations of a 7 T, 8-channel transmit array loaded with a 33 tissue types body model [10].

Results/Discussion: Fig.1 shows the tradeoffs between LSAR, GSAR, peak RF voltage and the excitation fidelity for 90° excitation and 180° refocusing pulses. We observe in Fig.1 that constraining the RF peak power did not constrain SAR (local or global) directly and it resulted in higher excitation error than a SAR constrained design with the same SAR level (e.g. RMMSE of point a in Fig.1 is 17% and the RMMSE of point b is 34%). The RMMSE versus peak RF voltage plots in Fig.1 suggest that this improvement in the excitation fidelity is because the SAR constrained pulses were able to decrease SAR while keeping the RF peak voltage at or close to the hardware limit whereas RF power constrained pulses need to lower it for the same purpose. The difference between the excitation fidelities of LSAR and RF peak power constrained pulses for the same LSAR level became more obvious for spin echo pulses. Fig.2 shows this difference in terms of the tip angle maps along with the LSAR maps of the slices through the SAR hotspot for two specific pulses (indicated as a and b) on the L-curves in Fig.1.

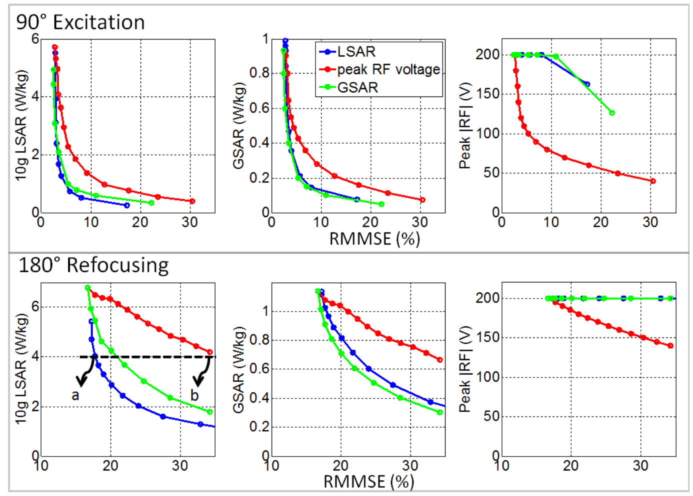

Figure.1: Blue, green, red curves are obtained by varying LSAR, GSAR, peak RF voltage, respectively while keeping the other two constraints at the safety and hardware limits (LSAR: 8W/kg, GSAR: 3W/kg, peak RF voltage: 200V). The resulting LSAR, GSAR and peak RF voltage values of all three cases are plotted for 90° excitation (9 kt points, 5.8 ms, uniform target tip angle) and 180° refocusing (12 kt points, 5.8 ms) pulses designed for a 6.4 cm thick slab. A duty cycle of 10% was assumed for all pulses.

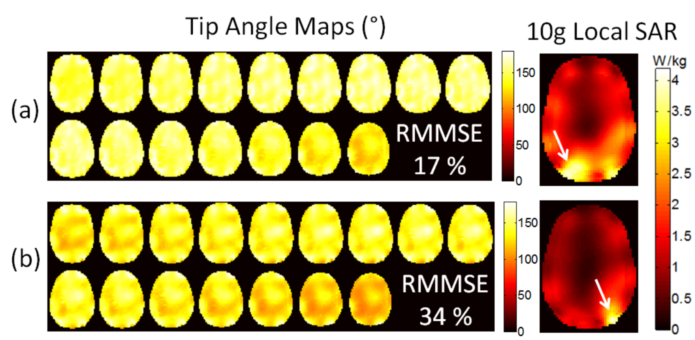

Figure.2: Comparison of the two pulses at point a and b in Fig.1 (Left) Tip angle maps of the slices inside the 6.4 cm thick slab. Point a: LSAR constrained with max resulting phase variation 15°/mm, point b: RF power constrained with max resulting phase variation 23°/mm. (Right) 10g local SAR maps of the slices through the local SAR hotspot.

Conclusion: We developed a large tip angle pulse design algorithm that explicitly constrains LSAR, GSAR and RF peak voltage simultaneously rather than assuming a worst case SAR scenario or experimentally finding a Tikhonov parameter that ensures the safety and system limits. This way both more optimal and practical pulses can be designed at large tip angle to mitigate B1+ inhomogeneity using pTx at 7 T.

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