Peak RF power constrained pulse design for multi-band parallel excitation

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Introduction: The use of multi-band (MB) RF excitation along with subsequent unaliasing via parallel imaging principles leads to significant acceleration in volume coverage along the slice direction [1-5]; this approach is becoming increasingly common and has recently been demonstrated with significant success in functional and diffusion-weighted imaging studies of the brain [2-5]. Conventionally, the total RF energy and *peak* RF power required in slice accelerated MB imaging increase linearly and approximately quadratically, respectively, with the MB factor that defines the number of simultaneously excited slices. This increase can easily limit the maximum MB factor, especially when spin echo acquisitions are required and/or high magnetic fields are employed. We demonstrated, experimentally and through simulations, that the total RF energy can be constrained for MB pulses using parallel transmit (pTx) [6]. In this study, we introduce a novel formulation for optimum peak power constraint using also MB pTx pulse design based on spoke RF pulses; in this design, we simultaneously target improved B1+ inhomogeneity. The formulation incorporates the interaction of the base pulses of individual bands by taking into account the final summed pulses. The new formulation is validated using B1+ maps simulated in a human whole body model and is shown to result in larger reduction of peak RF power than the conventional formulation for pTx pulses used for optimizing single-slice or sequential multi-slice excitation [7].

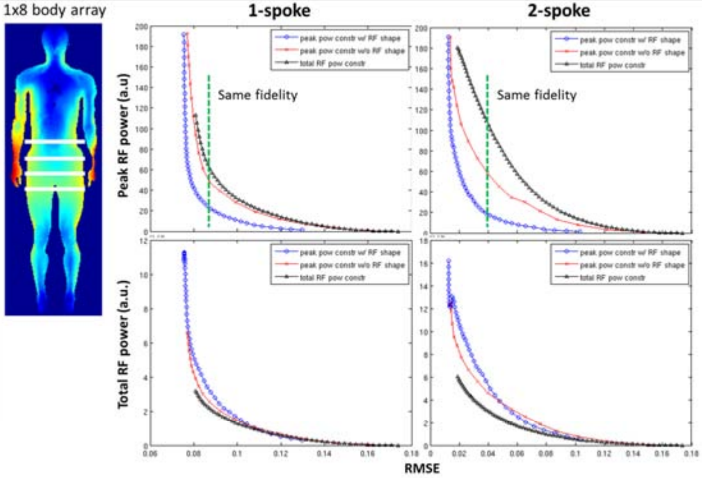

Fig. 1. L curves characterizing tradeoffs between RF power and excitation errors, calculated for conventional (red) and proposed (blue) peak power constraints, and for total RF power constraint (black).

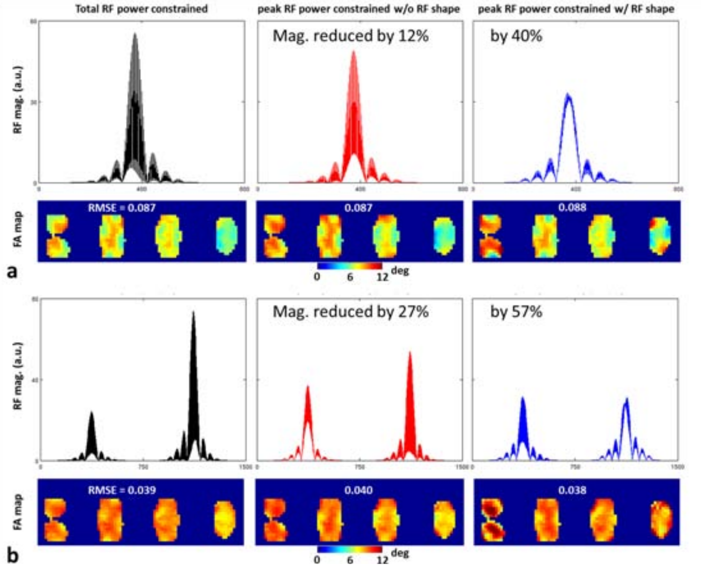

Fig. 2. RF pulse shapes of peak power for 1- (a) and 2- (b) spoke design, obtained with total power constraint (black), peak power constraint using conventional (red) and proposed (blue) methods, when targeting the same excitation fidelity as indicated by green dashed lines in Fig.1. Corresponding flip angle (FA) maps in the desired slices were also simulated to show the comparable FA homogenization.

Theory: In MB pTx, we seek to find a different set of RF magnitude and phase modulations (i.e. RF shim values) for each of the *M* simultaneously excited bands so as to mitigate B1+ inhomogeneities [6]. For this, the pulse design along with an explicit constraint upon peak RF power can be formulated as: $\min_w \|Aw - 1\|_2$ s.t. $\|[C_1, C_2, \ldots, C_M]w\|_\infty \leq \sqrt{100P_{\max}}$ (1). Here $A = \mathrm{diag}(A_1, A_2, \ldots, A_M)$ is a block diagonal matrix with A_m being the system matrix for the *m*-th band, $w = [w_1^T, w_2^T, \ldots, w_M^T]^T$ is a concatenated vector with w_m containing RF shim values for the *m*-th band, $[C_1, C_2, \ldots, C_M]$ is a combined matrix with C_m consisting of the base pulses of individual channels for the *m*-th band, and $P_{\max}$ is the peak power limit. Note that the term, $\|[C_1, C_2, \ldots, C_M]w\|_\infty$, gives the real maximum RF magnitude of the final composite MB pulses of individual channels.

Materials and Method: Electromagnetic (EM) field maps of an eight-channel body array, centered at the pelvis of a human whole body model (Duke, virtual family, 5mm isotropic), were simulated at 3T using the XFDTD software (Remcom, USA). The proposed peak RF power constraining strategy was compared to the conventional approach which uses $\|w\|_\infty \leq \sqrt{100P_{\max}}$ as the constraint. In addition, total power controlled RF pulses were designed using the constraint of $\|w\|_2 \leq \sqrt{100P_{\max}^{\mathrm{t}}}$ with $P_{\max}^{\mathrm{t}}$ being the total power limit, and were compared to those obtained with peak power constraint. One- and two-spoke RF pulses were designed to simultaneously excite four slices encompassing the pelvic area. The slice thickness was 6 mm and the inter slice distance 10 cm. To solve problem (1) we used CVX, a package for specifying and solving convex programs [8,9]. L curves quantifying the tradeoff between peak RF power and excitation errors (defined as the root mean square error (RMSE)), as well as between total power and excitation errors, were generated by varying the power limit in pulse design. All calculations except for EM modeling were performed in Matlab (Mathworks, USA).

Results and Discussion: For both 1-spoke and 2-spoke pulse design, using our proposed peak RF power constraint resulted in much larger reduction of peak RF power than the conventional formulation (Fig. 1). Both peak power controlling strategies outperformed the total power constrained case in suppressing the peak power, but at a cost of an increase in the total RF energy especially near the corner of the L-curve where a good balance between peak power suppression and excitation fidelity can be found (Fig. 1). More quantitative analyses revealed that when achieving the same excitation fidelity, the peak RF power reduction was improved from 23% (1 spoke) and 47% (2 spokes) for the conventional formulation, to 64% (1 spoke) and 82% (2 spokes) for the proposed constraint, as compared to the total power control case (Fig. 2). The total RF energy increase, however, was elevated from 18% (1 spoke) and 50% (2 spokes) for the conventional constraint, to 50% (1 spoke) and 83% (2 spokes) for the proposed method. It is important to note that this increase in the total RF energy as a result of peak power control is a unique feature of MB pTx and is not observed in single channel applications where the total RF energy remains unchanged given Parseval's theorem [6]. The reason for the total RF energy increase in MB pTx is most likely due to the pulse design algorithm which tends to increase the RF magnitudes to compensate for the degradation of the excitation fidelity due to RF phase adjustments required for peak power reduction. It will also be interesting to investigate whether peak local SAR management in MB pTx using virtual observation points would benefit from incorporating the final summed pulse shape into the constraint. In conclusion, we have introduced and demonstrated a novel formalism for constraining peak RF power in MB pTx, which gives rise to a major peak power reduction as compared to the conventional approach.

References: **1.** Larkman et al., MRI 13:313-17(2001). **2.** Moeller et al., MRM 63:1144-53(2010). **3.** Feinberg et al., PLoS 5:e15710(2010). **4.** Smith et al., PNAS 109:3131-36(2012). **5.** Setsompop et al., MRM 67:1210-24(2012). **6.** Wu et al., submitted to ISMRM 2013. **7.** Guerin et al., ISMRM 2012 p642. **8.** CVX Research, Inc. CVX: Matlab software for disciplined convex programming, version 2.0. http://cvxr.com/cvx, April 2011. **9.** Grant et al., Lecture Notes in Control and Information Sciences, Springer, 2008, p95-110.

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