RAPID ONLINE MULTIBAND RF PEAK POWER MINIMIZATION FOR CAIPIRINHA AND PTX-MULTI-SLICE SHIMS BY INTER-SLICE PHASE RELAXATION

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Target Audience MRI physicists and engineers.

Purpose Current multi-slice excitation schemes are based upon the superposition of single-band RF waveforms[1,2]. The different frequencies corresponding to different slice excitations, can constructively interfere, resulting in high peak powers. Through relaxation of the phase of the target magnetization profile, it is possible to minimize the constructive interference and thus to obtain lower peak amplitude[3]. A minimization problem has to be solved that considers the phase of each slice as part of the optimization. The algorithm from [3] requires a large amount of restarts (5000) and the minimization over a CAIPIRINHA phase cycling scheme and/or a pTx amplitude/phase shimming settings is not taken into account. In this work, we cast the problem as a linear objective function with quadratic equality and inequality constraints. This can be solved on the fly. Furthermore, the achieved peak power is lower than the existing phase relaxation method[3] and control of RF peak power over the whole CAIPIRINHA excitation scheme and/or a whole multi-channel transmit system with channel/slice dependent amplitude/phase shimming settings is obtained.

Theory Given a single band RF pulse waveform $b(t)$, the RF waveform that excites N slices at locations z_n (n indicates the slice) is given by Eq. (1). If a CAIPIRINHA phase cycling scheme, or a pTx channel system are employed, there are P pulses, each for a given phase cycling pattern or channel, respectively. The index p denotes the phase scheme or the channel for, respectively, the CAIPIRINHA and pTx case. Denoting by $\psi_{p,n}$ the desired phase (for each pulse p and each slice n), and by ϕ_n the interslice phase relaxation, the resulting p-th pulse is given by Eq. (2). Note that in Eq. (2), $\alpha_{p,n}$ denotes the amplitude shimming setting, thus for the CAIPIRINHA setup: $\alpha_{p,n}=1$. The minimum peak RF problem is then given by Eq. (3) and it returns a vector of optimal inter-slice phases $\phi=[\phi_1 \ldots \phi_N]$. This can be rewritten in matrix/vector form (Eq. 4) where $\mathbf{u}$ is the complex vector whose arguments are the inter-slice phases and $\mathbf{A}$ include all the given terms b, G, z_n, $\psi_{p,n}$ and $\alpha_{p,n}$. This particular problem can be rewritten as a linear program with quadratic inequality and equality constraints[4] given by Eq. (5). The vector $\mathbf{y}$ contains the real and imaginary part of $\mathbf{u}$ and thus the inter-slice phases. For lack of space, the details are omitted.

$$f(t) = \sum_{n=1}^{N} b(t) e^{i\gamma G t z_n} \qquad (1)$$

$$f^p(t) = \sum_{n=1}^{N} \alpha_{p,n} b(t) e^{i\gamma G t z_n} e^{i(\psi_{p,n}+\phi_n)} \qquad (2)$$

$$\arg\min_{\phi} \max |f^p(t)| \qquad (3)$$
$$\text{for } t \in [0,T] \text{ and } p = 1,\ldots,P$$

$$\arg\min_{\mathbf{u}} \max |\mathbf{A}\mathbf{u}| \qquad (4)$$
$$\text{with } |u_j| = 1$$

$$\begin{aligned} &\text{minimize } \mathbf{c}^T\mathbf{y} \qquad (5)\\ &\text{such that } \mathbf{y}^T\mathbf{Q}_i\mathbf{y} \le 0, \quad \forall i\\ &\qquad \mathbf{y}^T\mathbf{P}_n\mathbf{y} - 1 = 0, \quad n = 1,\ldots,N \end{aligned}$$

$$\Psi = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{\pi}{2} & \pi & \frac{3\pi}{2} & 0 & \frac{\pi}{2} \\ 0 & \pi & 0 & \pi & 0 & \pi \\ 0 & \frac{3\pi}{2} & \pi & \frac{\pi}{2} & 0 & \frac{3\pi}{2} \end{pmatrix} \qquad (6)$$

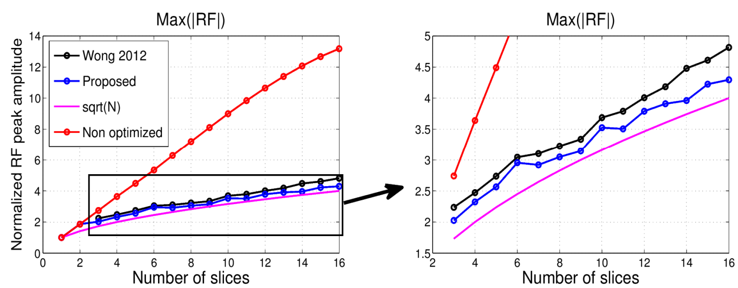

Fig 1 *Exp.1: peak amplitudes for multi-band configurations corresponding to N =2,… ,16. Values are normalized with respect to the peak amplitude of N = 1. For reference, also the theoretical minimum value √N is shown.*

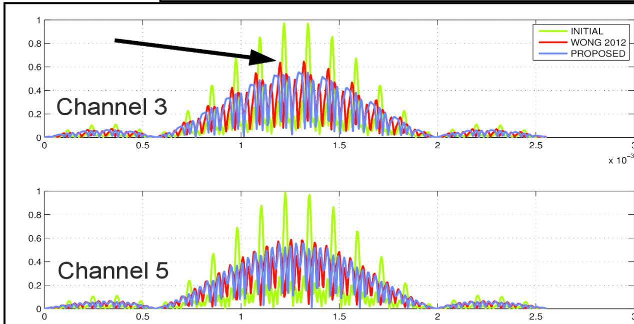

Fig 2 *Exp.3: The RF waveforms. Green: standard, Red: with inter-slice phase from [3], Blue: proposed.*

Methods We perform three inter-slice phase design experiments: *Exp.1:* multiband excitation for N = 2,3,…,16 (same as [3]), *Exp.2*: a CAIPIRINHA excitation scheme for phase cycling schemes given by the matrix $\Psi(p,n)=\psi_{p,n}$ given in Eq. (6); *Exp.3:* a Dynamic RF shimming problem for an 8 channel birdcage head-coil at 9.4T. The amplitude/phase shimming settings are optimized per channel p per slice n for a ROI covering the back of the brain (see Fig. 3). We consider a 6 slice excitation (SMS factor = 6), 3-lobes sinc pulse, 2mm slice thickness, slice distance: 16mm. Computations are carried out with Matlab on a desktop PC.

Results *Exp. 1:* Figure 1 shows the peak amplitudes for experiment 1. The computation time of each configuration is in the order of seconds and never longer that 10s. In the same figure, also the values obtained by Wong in [3] are reported. The proposed method achieves lower peak amplitude values for each multi-band excitation experiment and it approaches the √N curve. *Exp 2:* The peak amplitude corresponding to the CAIPIRINHA phase cycling scheme Ψ is 12.1μT. For comparison, the peak amplitudes obtained by the standard RF pulses for the same cycling scheme is 23.4μT. A reduction of approximately 50%. *Exp 3:* Finally, two of the eight RF waveforms for the pTx setup are shown in Fig. 2, normalized to the maximum peak of the standard (no phase relax) setup. Also the waveforms obtained by the phase relaxation from [3] are shown. The RF peak amplitude is reduced by 45% with respect to the standard setup. As indicated by the arrow, a 15% reduction is achieved with respect to the RF waveforms from [3]. To check the scanner implementation, the images obtained from the two phase relaxation methods are shown in Fig. 3. They look indeed the same, as they are supposed to be.

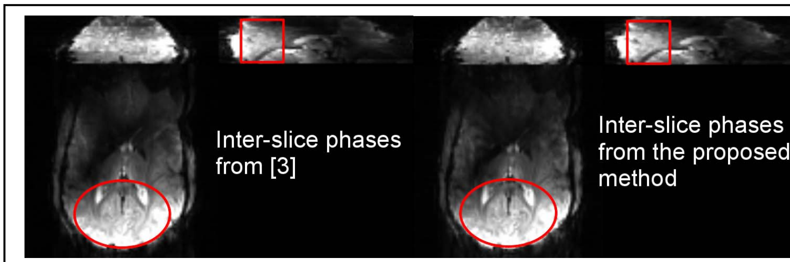

Fig 3 *Exp.3: Obtained images. Shimming is optimized for the indicated ROI (red)*

Discussion The minimum peak RF problem is generalized to the CAIPIRINHA and pTx setups. The reduction in peak RF is drastic with respect to standard design and larger than obtained in [3]. The compact formulation allows for quick computation and thus online implementation. This is essential for patient specific amplitude/phase shimming settings and CAIPIRINHA scans.

Conclusion Inter-slice phase relaxation is cast as a linear program with quadratic constraints and applied to more general setups as CAIPIRINHA and pTx shimming obtaining on-the-fly and patient-specific optimal inter-slice phase settings. **References** [1] Muller S. Magn Reson Med 1988. [2] Breuer FA et al. Magn Reson Med 2005, [3] Wong E. ISMRM 2012 p. 2209. [4] Boyd S and Vandenberghe L. Convex Optimization. 2004.