Simultaneous multi-slice parallel RF excitation with in-plane B1+ homogenization

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Introduction: Simultaneous multi-band (MB) RF excitation, along with subsequent unaliasing via parallel imaging principles, provides an effective means to accelerate volume coverage along the slice direction [1]. Recently, the approach has been exploited with significant success in functional and diffusion-weighted imaging studies of the brain [2-5]. So far this technique has only been demonstrated in the context of single channel transmit. In this study, we extend this technique to multi-channel transmit and introduce parallel transmit (pTX) MB pulse design in order to tackle the issues of B1+ inhomogeneity at high and ultrahigh field strengths, and RF power deposition. The new extension is validated in the human brain at 7T and is demonstrated capable of providing good B1+ homogenization in addition to simultaneous MB excitation without necessitating the use of higher RF energy relative to a single channel application.

Theory: Two strategies can be employed in multi-channel MB excitation to find RF magnitude and phase modulations (i.e., RF shim values) of the base RF pulse so as to mitigate B1+ inhomogeneity. One strategy, defined as *MB B1 shimming*, is to obtain a common set of RF shim values for all *M* bands that are excited simultaneously. The other strategy, defined as *Full pTX MB*, is to calculate a different set of shim values for each of the *M* bands. In *MB B1 shim*, the RF shim values can be obtained by solving $\min_{\boldsymbol{w}} \| |\boldsymbol{A}\boldsymbol{w}| - 1 \|_2^2 + \lambda \|\boldsymbol{w}\|_2^2$ where $\boldsymbol{A} = [\boldsymbol{A}_1^T, \boldsymbol{A}_2^T, \dots, \boldsymbol{A}_M^T]^T$ with $\boldsymbol{A}_m$ being the system matrix for the *m*-th band, $\boldsymbol{w} = [w_1, w_2, \dots, w_Q]^T$ with w_q being the RF shim value for the *q*-th channel, and λ is the regularization parameter. In *Full pTX MB*, one can solve $\min_{\boldsymbol{w}_{\text{full}}} \| |\boldsymbol{A}_{\text{full}}\boldsymbol{w}_{\text{full}}| - 1 \|_2^2 + \lambda \|\boldsymbol{w}_{\text{full}}\|_2^2$ where $\boldsymbol{A}_{\text{full}} = \text{diag}(\boldsymbol{A}_1, \boldsymbol{A}_2, \dots, \boldsymbol{A}_M)$ and $\boldsymbol{w}_{\text{full}} = [\boldsymbol{w}_1^T, \boldsymbol{w}_2^T, \dots, \boldsymbol{w}_M^T]^T$ with $\boldsymbol{w}_m$ containing RF shim values for the *m*-th band. It is important to note that in *Full pTX MB*, the application of final RF pulses requires full pTX hardware capable of controlling RF pulses of individual channels independently and cannot be realized simply by splitting a single channel RF pulse into different channels and imposing a channel specific phase and amplitude by a magnitude and phase controller. This is because the final RF pulse per channel is the sum of *M* different base pulses each multiplied by a different weight and thus cannot be represented simply by a channel-specific weight, w'_q, multiplied by a common pulse (Fig. 1).

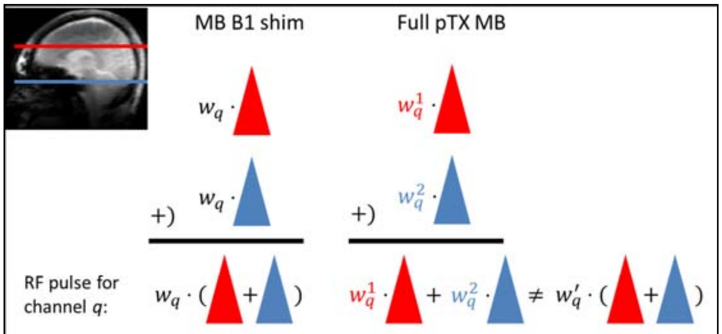

Fig. 1. Schematic illustration of MB2 B1 shimming and MB2 full pTX with single spoke. Note that due to different phase evolutions targeting band 1 (red) and band 2 (blue), the two base RF pulses are of different pulse shapes.

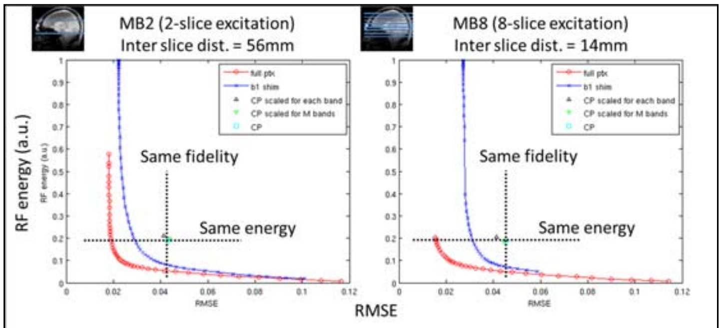

Fig. 2. L curves quantifying tradeoffs between total RF energy and excitation errors in full ptx (red) and B1 shim (blue), along with CP modes indicated by dots.

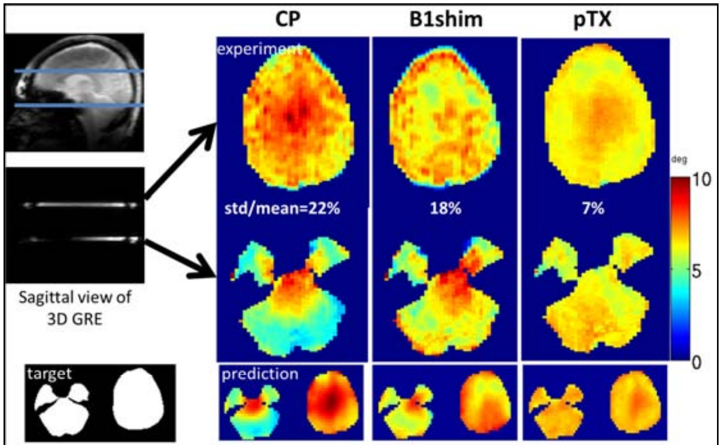

Fig. 3. MB2 RF excitation in human brain at 7T using CP mode, MB B1 shim and MB full pTX. Note good agreement seen between experiment and prediction.

Materials and Method: Experiments were conducted on a 7T whole body MR scanner driven by a 16-channel prototype pTX system (Siemens, Erlangen, Germany). B1+ maps of a 16-element transceiver array [6] were obtained within nine slices encompassing the whole brain, with a fast hybrid technique [7]. A 3D B1 phase shimming targeting a CP-mode B1+ distribution [8] was performed prior to the field mapping to avoid severe signal loss due to B1+ destructive interference. The unity target was defined as homogeneous B1+ in the desired slices by manually creating a spatial mask only covering the brain tissues in the bands. RF shim values were calculated with the variable exchange algorithm [9]. L curves quantifying the tradeoff between total RF energy and excitation errors (determined as root mean square error (RMSE)) were generated by varying λ in pulse design. For comparison, MB pulses were also assembled using the CP mode, mimicking a single channel transmit condition, where RF magnitudes were adjusted such that resulting mean flip angles averaged over the whole brain would be the same as nominal flip angles used in *MB B1 shim* and *Full pTX MB* pulse design. 3D flip angle maps were estimated for MB2 excitation with CP mode, B1 shim and full pTX RF pulses and the results were compared. The band thickness was set to 6 mm. All computations were conducted in Matlab (Mathworks, USA).

Results and Discussion: For both MB2 and MB8 design using a single spoke, *Full pTX MB* resulted in better RF performance than *MB B1 shimming*, and both strategies significantly outperformed the CP mode (Fig. 2). More quantitative analyses revealed that when using the same total RF energy as in the CP mode, the B1 inhomogeneity, measured by std/mean of B1+ maps, improved from ~25% for CP, to ~17% for *MB B1 shim* and to ~10% for *Full pTX MB* design. When achieving the same excitation fidelity, the total RF energy requirement, which in this case is proportional to total power deposited (i.e. SAR), decreased by ~58% for *MB B1 shim* and ~72% for *Full pTX MB* design as compared to the CP mode. Part of this decrease was due to a decrease in the mean flip angle. However, even accounting for this resulted in ~56% less RF energy in the *Full pTX MB* design compared to the CP mode. Fig. 3 illustrates *in vivo* experimental results of MB2 RF excitation in the human head: *Full pTX MB* strategy gave rise to best B1+ homogenization as compared to *MB B1 shim* and MB CP mode. Note that because subpulses in a composite MB pulse each have different frequencies, the use of $\|\boldsymbol{w}_{\text{full}}\|_2^2$ still gives an optimal constraint upon total RF power as indicated by Parseval's theorem [10]. However simply using $\|\boldsymbol{w}_{\text{full}}\|_\infty^2$ for peak RF power control as proposed for interleaved slices [11] would no longer be optimal, and the optimal constraint for peak power control in *Full pTX MB* would require the final summed pulse shapes of individual channels to be considered [12].

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.** Adriany et al., MRM 59:590-97(2008). **7.** Van de Moortele et al., ISMRM 2007 p1676. **8.** Schmitter et al., ISMRM 2012 p3472. **9.** Setsompop et al., MRM 60:1422-32(2008). **10.** Goelman**,** MRM 37:658-65(1997). **11.** Guerin et al., ISMRM 2012 p642. **12.** Wu et al., submitted to ISMRM 2013. **Acknowledgments:** WM KECK Foundation, P41 EB015894, S10 RR026783, R21 EB009133, R01 EB006835 and R01 EB007327.