Slab-wise parallel transmit multiband RF pulse design for simultaneous multislice imaging with volumetric coverage

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Introduction: Simultaneous MultiSlice (SMS) MR imaging using MultiBand (MB) RF pulses [1] is playing an increasingly important role in neuroimaging [2-4]. Recently, we have proposed a *slice-wise* parallel transmit (pTx) MB pulse design that can be used to improve transmit B1 (B1+) homogeneity and/or reduce RF power consumption relative to a single channel Circular Polarized mode application [5], particularly important at 7T but significantly relevant for 3T as well. However, directly utilizing this slice-wise approach and designing pTx MB pulses in a slice-by-slice fashion for all necessary imaging slices for covering a large volume of interest (VOI), such as the whole brain, is impractical within clinical time constraints because of the long B1+ mapping, pulse calculation, and sequence preparation times needed with current instrumentation, especially when using high through-plane spatial resolutions. In the present study, we propose a novel, effective and practical *slab-wise* pTx MB pulse design targeting volumetric coverage in SMS/MB imaging and describe some of its important properties by designing RF pulses based on electromagnetic (EM) modeling of a head array at 7T. The validation and utility of this new method is reported elsewhere in the context of whole brain diffusion MRI at 7T [6].

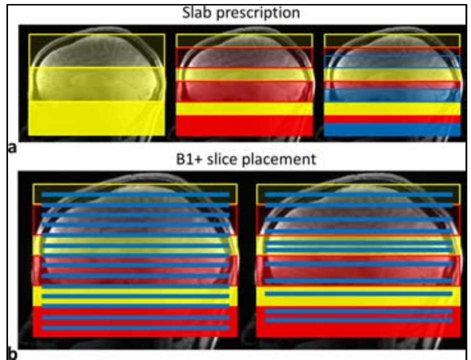

Fig. 1. (a) Example slab prescription for pTx MB pulse design with MB=3. Possible layout of the slab arrangement is depicted for one (left), two (middle) and three (right) pTx MB pulses, leading to N_{slab}= 3, 6 and 9 s, respectively. Note that it is only necessary to ensure that the slabs corresponding to a same pTx MB pulse as shown in the same color are of a constant thickness. (b) Example B1+ slice placement for designing two pTx MB3 pulses. The slices could be either equidistantly (left) or randomly (right) placed within the prescribed 6 slabs.

Two-stage design: The proposed pulse design consists of two stages: the pre-calculation stage and the calculation stage. The pre-calculation stage is to prescribe a few contiguous imaging slabs encompassing the VOI, followed by the definition of the slice placement within each slab from which B1+ maps will be acquired for the subsequent pulse calculation. Here, the slab number, N_{slab}, is given by the number, K, of desired distinct pTx MB pulses multiplied by the MB factor M (i.e., $N_{\text{slab}} = K \times M$). For example, for K=1, M=3, a single pTx MB pulse is designed with its three single band (SB) pulses optimized using the B1+ maps acquired within 3 slabs that cover the brain (Fig. 1). During data acquisition, each pTx MB pulse is applied as in the conventional MB RF excitation to excite all the imaging slices residing in its M slabs, and the K pTx MB pulses will be played out one after another to excite all N_{slab} slabs covering the entire VOI. Once the pre-calculation stage is finished, the calculation stage is conducted to obtain the RF shim sets so as to reduce B1+ inhomogeneity. Here two strategies can be considered to design each individual pTx MB pulse. One strategy, defined here as the *band-specific* design, is to find a different RF shim set for each of the M pTx SB pulses that comprise a pTx MB pulse. The other strategy, referred to as the *band-joint* design, is to find a common RF shim set for all the M pTx SB pulses constituting a pTx MB pulse. Note that both strategies will result in *K different* pTx MB pulses.

Methods: EM field maps of a 16-element RF array loaded with a human head and shoulder model (Duke, virtual family, 2x2x2.5mm^3) were simulated using the XFDTD software (Remcom, USA). Band-specific pTx MB pulses for whole brain coverage were designed using different slab numbers, so as to explore different levels of degrees of freedom. When the number of slabs is determined, the same RF shim sets calculated using the band-specific approach can actually be used to assemble various pTx MB pulse sets for different MB factors as long as M is a factor of N_{slab}. For example, the band-specific design using 8 slabs can serve for MB factors of 2, 4 and 8 (Fig. 2). By contrast, band-joint pTx MB design is dependent on the MB factor used. For comparison we designed band-joint pulses for MB=2 and MB=4 using different slab configurations. All prescribed slabs had the same thickness and B1+ information within the brain tissues from 48 axial slices was used in pulse calculation. All pulses were designed with a single spoke (i.e. RF shimming) and calculated by solving a global SAR regularized MLS problem [7], $\min_w \| |Aw| - 1 \|_2^2 + \lambda \|S_0 w\|_2^2$, where A is the system matrix, w concatenates the RF shim sets for individual pTx MB pulses, λ is the regularization parameter, and S_0 is the global SAR matrix. L-curves quantifying the tradeoff between global SAR and excitation errors (defined as the root mean square error (RMSE)) were generated for each pulse design scenario by varying λ in pulse design. SAR quantities were calculated by exhaustive search and were obtained for whole brain SMS/MB imaging with TR=1 s, 120 axial slice (corresponding to a 1-mm slice thickness), nominal flip angle=10°, and pulse duration=1 ms. All calculations except for EM modeling were performed in Matlab (Mathworks, USA).

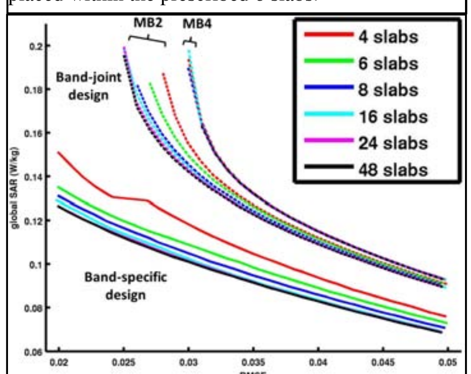

Fig. 2. Band-specific vs band-joint slab-wise pTx MB pulse design using different slab numbers. Shown are L-curves for pulses designed with global SAR control. Note that the band-specific design always drastically outperformed the band-joint approach due to largely increased degrees of freedom in pulse design, and that slab numbers had virtually no impact when designing band-joint MB4 pulses.

Results and Discussion: For all slab prescriptions considered, the band-specific design significantly outperformed the band-joint design (Fig. 2). This is due to the fact that the former has an M-fold increase in the degrees of freedom available in searching an optimum pulse solution when compared to the latter. It is important to note that the band-specific design however requires the complex and expensive *full pTx hardware* capable of synthesizing a different RF waveform for each individual channel, even when using only an RF shimming for each band. By contrast the band-joint design can possibly be achieved just by using a much *simpler and cheaper* hardware setup with an RF phase and gain controller and thus can serve as a useful tool for B1+ homogenization when only this limited pTx capability is available. Additionally, the RF performance of the band-specific pulses improved with increasing slabs until ~16 slabs for 7T whole brain coverage and then remained unchanged for larger slab numbers (Fig. 2). By contrast, the slab numbers had limited impact in the band-joint design; this is mostly due to the fact that when using a large MB factor (M>2) all K MB pulse designs are almost addressing the same global B1+ variation over the VOI, therefore yielding similar RF solution irrespective of the slab number used. Also, noticeable effects of B1+ slice placement were seen for a given slab prescription (data not shown due to limited space). All these results indicate that tradeoffs exist between design strategies, the number of desired pTx MB pulses, MB acceleration and B1+ slice placement when using the slab-wise design. In conclusion, we have presented a new slab-wise pTx MB pulse design for volumetric coverage SMS/MB imaging, described two design strategies that can be used in the design framework, and demonstrated the pros and cons of each strategy by designing respective pulses based on EM simulations at 7T. Using multiple spokes for pulse design and investigating the impact of slab numbers when designing local SAR controlled pulses are part of future work.

References: 1. Larkman et al. (2001) JMRI. 2. Moeller et al. (2010) MRM. 3. Smith et al. (2012) PNAS. 4. Setsompop et al. (2012) MRM. 5. Wu et al. (2013) MRM. 6. Wu et al. submitted to ISMRM 2014. 7. Lee et al. (2012) MRM. **Acknowledgments:** The authors would like to thank Dr. Jinfeng Tian for running the electromagnetic modeling of the RF array used in this study. This work was supported by NIH grants including P41 EB015894, R21 EB009133, R01 EB006835 and R01 EB007327.