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Optimized Amplitude Modulated Multi-Band RF pulses

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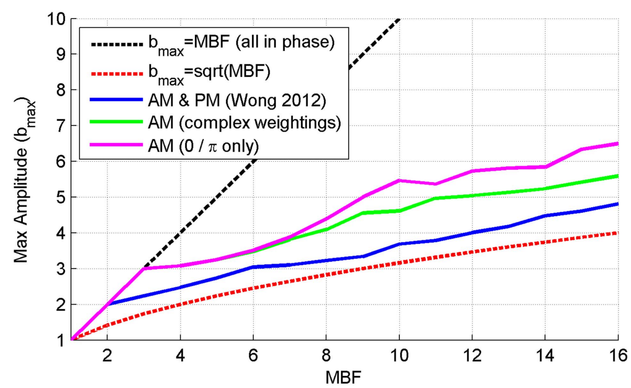
Target Audience RF pulse designers and sequence developers working with multi-band RF

Purpose Parallel imaging using Multi-band (MB) RF excitation[1] has found much recent interest for accelerated image acquisition. MB RF pulses are generally created by applying a periodic modulation function to pre-existing RF pulse waveforms, resulting in the replication of multiple aliases of the original slice profile to desired locations. A problem is that if implemented in the most straightforward way, the peak amplitude of the modulation function scales with the multi-band factor (MBF; the number of simultaneously excited slices) quickly violating peak RF power constraints of most MR systems. To mitigate this issue Wong[2] showed that the phase of each slice can be optimized independently in order to produce a modulation function whose peak amplitude is much lower than MBF. This approach has been combined with time-shifting to further reduce the peak amplitude[3,4]. An issue is that the resulting MB RF pulses have rapid modulation in both amplitude and phase. Accurate reproduction of this modulation can be problematic. Depending on the hardware, faithful reproduction of rapid phase modulation can be more error prone than amplitude modulation, especially on systems that require frequency rather than phase modulation to be defined by the pulse designer. These issues can be sidestepped if pulses are amplitude modulated (AM) only; in this work we identify optimal phases that lead to strictly AM MB pulses and compare them with the more general solutions requiring amplitude and phase modulation (AM & PM) provided by Wong.

$$b(t) = \sum_j^{MBF} \exp\left\{i\left(\gamma G x_j t + \phi_j\right)\right\} \quad \text{Eq.1}$$

Methods The modulation function b(t) required to produce slices at locations x_j with gradient G is given by Eq.1 [2]; phase offsets ϕ_j are to be optimized so as to **minimize** the maximum of the modulation function $b_{max}=\max\{b(t)\}$. Given the Fourier relationship between slices and RF waveforms, we can guarantee that b(t) will be purely real if the phase offsets have conjugate symmetry. Assuming that the slices are distributed symmetrically around a central location x=0 we can form pairs of slices that are equidistant from x=0 (if MBF is odd then the central slice is at location x=0 and is treated independently of the others). Each pair is assigned a phase offset ψ with one slice taking phase $+\psi$ and the other $-\psi$. A special case is where only real modulations are applied to each slice, in which case each pair of slices is either assigned phase 0 or π. Optimal phase offsets were computed using MATLAB's fmincon function with multiple random initializations for MBF 1 to 16.



Results The graph plots b_{max} for each MBF. Reductions in b_{max} are possible for MBF>3; the optimal phases for MBF=4 to 12 are given in the table.

Discussion & Conclusions As might be expected, the AM solutions do not reduce b_{max} as much as full AM&PM. However large reductions are still generally obtained, particularly for higher MBFs. For example for MBF=8, b_{max} can be reduced from 8 to 4.09 by using an optimized AM pulse, then further to 3.23 for optimal AM&PM modulation (49% reduction compared with 60%). For MBF>9 the reduction in b_{max} achieved with AM only pulses is greater than 50%. For low MBF (<6) it is sufficient to only offset slices by 0 or π (pink curve), while for higher factors, phase conjugate solutions are benficial. The identified optimal phases will be useful for situations where phase or frequency modulation is technically difficult or less stable than AM only.

MBF	φ / rad												b_{max}
4	0	π	π	0									3.079
5	0	0	π	0	0								3.250
6	1.691	2.812	1.157	-1.157	-2.812	-1.691							3.477
7	2.582	-0.562	0.102	0	-0.102	0.562	-2.582						3.814
8	2.112	0.220	1.464	1.992	-1.992	-1.464	-0.220	-2.112					4.090
9	0.479	-2.667	-0.646	-0.419	0	0.419	0.646	2.667	-0.479				4.553
10	1.683	-2.395	2.913	0.304	0.737	-0.737	-0.304	-2.913	2.395	-1.683			4.614
11	1.405	0.887	-1.854	0.070	-1.494	0	1.494	-0.070	1.854	-0.887	-1.405		4.974
12	1.729	0.444	0.722	2.190	-2.196	0.984	-0.984	2.196	-2.190	-0.722	-0.444	-1.729	5.045

References [1] Larkman DJ, et al. JMRI 13:313-317, 2001. [2] Wong E. Proc ISMRM 2012 p2209. [3] Feinberg DA, et al. PLoS one 5(12):e15710, 2010. [4] Auerbach EJ, et al. MRM 69:1261-7, 2013.