Optimized phase schedules for minimizing peak RF power in simultaneous multi-slice RF excitation pulses

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Introduction: For high speed single shot imaging, simultaneous excitation of multiple slices has recently been shown to be an effective means of achieving high acceleration factors (1,2). A common method for simultaneous excitation is to superimpose multiple RF pulses, each modulated to a different frequency to excite a different slice. For N slices and uniform excitation phase this method increases the peak RF amplitude by a factor of N, and the peak power by a factor of N^2. We demonstrate here that using an optimized set of excitation phases across slices allows for greatly reduced peak power, approaching a factor of N, rather than N^2.

Methods: In the small tip angle regime, the RF pulse required to give a desired excitation profile is given by the Fourier Transform (FT) of the profile. An RF pulse that excites multiple slices, each with the same profile, can be expressed as the product of a window function *A(t)* that is proportional to the inverse FT of the slice profile *M(ω)*, and a modulation function *B(t)* that replicates the pulse at different locations x_i:

$$B_1(t) = A(t)\cdot B(t) \qquad A(t) \propto FT^{-1}(M(\omega)) \qquad B(t) = \sum_i e^{i(\gamma G x_i t+\phi_i)}$$

where *G* is the slice select gradient, and ϕ_i are the excitation phases of the *N* slices. Our goal here is to optimize ϕ_i to minimize the maximum value of *B(t)* (Max(B)). For uniformly spaced slices separated by distance *d*, *B(t)* is periodic with period $\tau=2\pi/\gamma Gd$. When d is much larger than the slice thickness, as is typically the case for simultaneous multislice excitation, τ is much shorter than the overall pulse duration, and the pulse is a broad window *A(t)* multiplied by a rapidly repeating modulation function *B(t)*. It is then sufficient to minimize Max(B) over an interval of length τ. For *N*=1-16, ϕ_i were optimized using the fminsearch() (downhill simplex) function in Matlab, with random starting phases, and 5000 restarts.

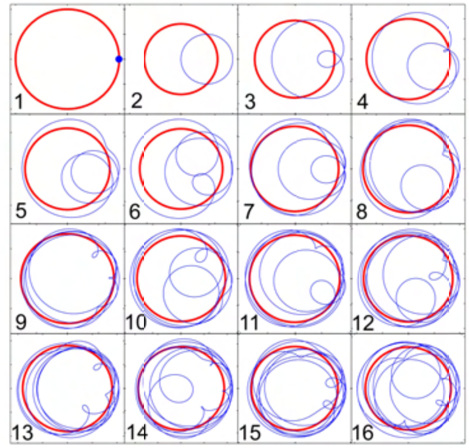

Figure 1: Optimized modulation functions *B(t)*, shown in the complex plane, in blue for *N*=1-16. For reference, the theoretical minimum value for MAX(B) is shown in red, as a circle of radius $\sqrt{N}$.

Results: For *N*=1-16, one period of the optimized B(t) in the complex plane is shown in **Figure 1**. Because the FT is unitary, $B^2(t)$ necessarily has a mean value of *N*, and the lowest possible value for Max(B) is $\sqrt{N}$. This theoretical minimum amplitude is shown as circles in red for reference. Images collected using a sinc pulse modulated with optimized ϕ_i for N=5,10,15 are shown in **Figure 2**, demonstrating that both the amplitude and phase of the excitation are as expected. Optimized phases ϕ_i are given in **Table 1**.

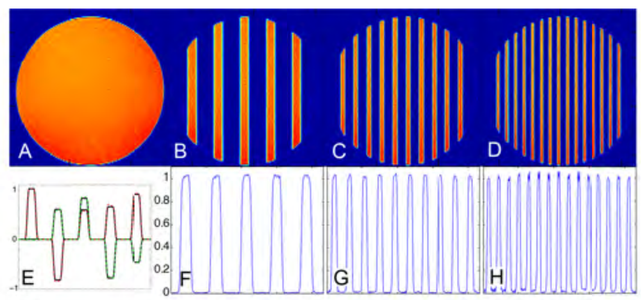

Figure 2: Images of a silicone oil phantom excited using a non-selective excitation pulse (A), and multislice excitation pulses with N=5,10,15 (B-D). Magnitude profiles are shown in F-H, and E shows separate real and imaginary components of the 5 slice excitation, with calculated profiles in black.

Discussion: By using an optimized set of excitation phases, simultaneous multislice excitation RF pulses can be designed for greatly reduced peak RF power relative to uniform phase pulses. In addition to reducing peak RF power, this combination of excitation phases also reduces the peak MRI signal, particularly across gradient encodings in Kz, allowing for more efficient use of the dynamic range of the receiver. The problem addressed here is closely related to that of discrete Fourier Transform (DFT) pairs with uniform amplitude in both domains. Exact solutions to the DFT problem exist for $N=p^2$, where *p* is prime (3). However, RF pulses constructed using these phases have the ideal $\sqrt{N}$ amplitude at only N points, but significantly higher magnitude elsewhere.

N	ϕ																Max(B)
3	0	0.730	4.602														2.236
4	0	3.875	5.940	6.197													2.472
5	0	3.778	5.335	0.872	0.471												2.737
6	0	2.005	1.674	5.012	5.736	4.123											3.043
7	0	3.002	5.998	5.909	2.624	2.528	2.440										3.102
8	0	1.036	3.414	3.778	3.215	1.756	4.555	2.467									3.225
9	0	1.250	1.783	3.558	0.739	3.319	1.296	0.521	5.332								3.337
10	0	4.418	2.360	0.677	2.253	3.472	3.040	3.974	1.192	2.510							3.686
11	0	5.041	4.285	3.001	5.765	4.295	0.056	4.213	6.040	1.078	2.759						3.789
12	0	2.755	5.491	4.447	0.231	2.499	3.539	2.931	2.759	5.376	4.554	3.479					4.007
13	0	0.603	0.009	4.179	4.361	4.837	0.816	5.995	4.150	0.417	1.520	4.517	1.729				4.182
14	0	3.997	0.830	5.712	3.838	0.084	1.685	5.328	0.237	0.506	1.356	4.025	4.483	4.084			4.479
15	0	4.126	2.266	0.957	4.603	0.815	3.475	0.977	1.449	1.192	0.148	0.939	2.531	3.612	4.801		4.609
16	0	4.359	3.510	4.410	1.750	3.357	2.061	5.948	3.000	2.822	0.627	2.768	3.875	4.173	4.224	5.941	4.815

Table 1: Optimized phases ϕ_i in radians. Optimal phases for N=1,2 are arbitrary.

References

1. Feinberg et al PLoS ONE 5(12): e15710, 2010.

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