Online SAR measurement error in high resolution slice accelerated 2D EPI

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Target Audience: Clinicians and researchers interested in high resolution slice accelerated 2D EPI.

Purpose: To reduce overestimation errors in online SAR monitoring and enable faster TRs in high resolution slice accelerated 2D EPI.

Introduction: Slice accelerated or multiband (MB) 2D EPI has recently enabled fast, high resolution, whole brain imaging [1-3]. However, as MB factors, resolution, and brain coverage increase so do the temporal frequency modulations in the MB RF pulses. For online SAR monitoring systems, which can have relatively slow impulse response functions, such rapidly modulated RF pulses can result in significant online SAR measurement errors; such that the online measured SAR is much higher than the actual SAR. In practice, this results in prematurely aborted scans even when pre-calculated SAR levels are well below (60-70%) the FDA limit. Although compromises in TR, slice profile and/or bandwidth can all reduce SAR, we found that recent methods for minimizing peak power [4,5] can also reduce the temporal frequency modulations in RF pulses thereby minimizing SAR measurement errors with little or no cost in TR or image quality – allowing acceleration gains from MB to be more fully realized.

Methods: SAR measurement error was empirically calculated for various MB factors and slice spacings by comparing the log files of the system measured 10 second average forward power to the pre-calculated expected forward power. The original, standard excitation RF pulses were then compared in Matlab (Natick, MA) to versions filtered by impulse response functions of various decay rates (τ; Fig 1C). The τ that best matched the empirical SAR measurement error was 25 µs. The SAR "error factor" for several MB factors and slice spacings was calculated as the ratio of filtered to original RF pulse power integrals (Fig 2). Phase optimized [4] and time-shifted [5] (1280ms shift for 5120ms pulses) MB RF pulses were simulated and evaluated regarding their ability to minimize SAR measurement errors. The experimental measurements were performed using a 32 channel receive and quadrature transmit coil (Nova Medical, Wilmington, MA) on a Siemens Magnetom 7T system.

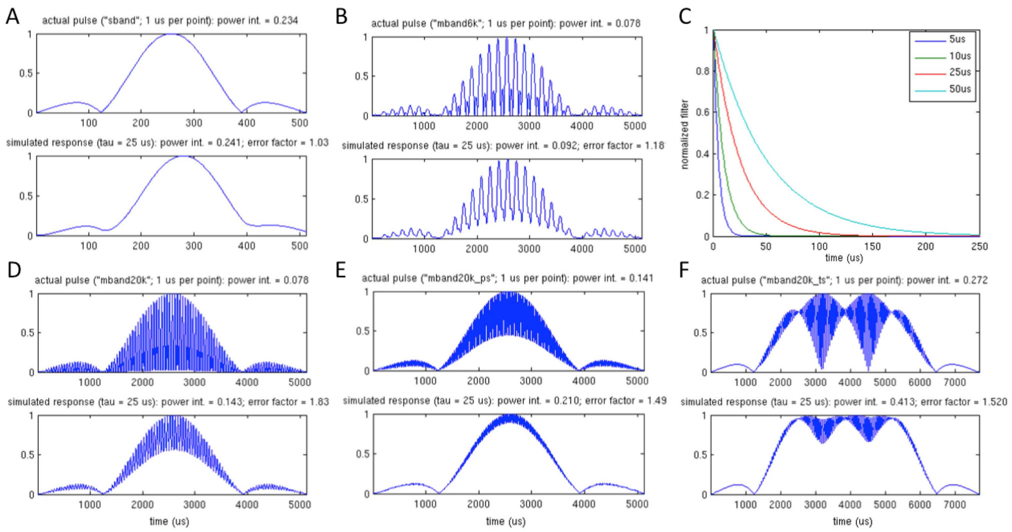

Figure 1: Original and filtered MB RF pulses. A) Original single band pulse (top), filtered pulse (bottom). B) MB=3, 6kHz slice spacing. C) Impulse response functions for various decay rates. D) MB=3, 20kHz slice spacing. E) Same as D with phase optimized pulses. F) Same as D with time-shifted pulses.

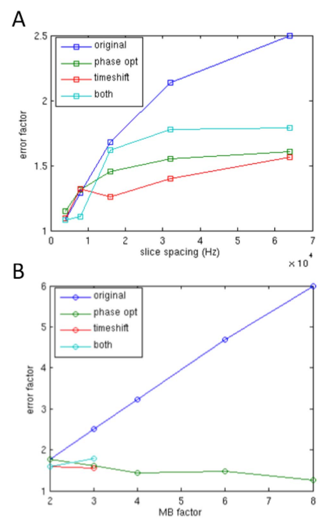

Figure 2: SAR error factors
A) As a function of slice spacing
B) As a function of MB factor

Results and Discussion: Fig. 1A compares the original single band RF excitation pulse (top) to the filtered RF pulse (bottom). In this case, SAR measurement error is negligible. Fig. 1B shows the case for MB=3 with an MB slice spacing of 6kHz. Here, the filtered version does not capture the deep troughs resulting in an SAR error factor of 1.18 (or 18% over-measurement). Increasing the MB slice spacing to 20kHz (Fig 1D) for larger brain coverage amplifies the error factor to 1.83. With phase optimization (Fig 1E) or time-shifting (Fig 1F), the SAR error factor is reduced to ~1.5 (reducing over-measurement by almost 40%). Fig 2A shows that the error factor (with MB=3) increases sub-linearly (up to a factor of ~2.5) with increasing slice spacing. Figure 2B shows that the error factor (with slice spacing = 64kz; whole brain) increases linearly with MB factor. Time-shifting was not calculated for MB>3 since RF pulses would be greater than 8ms. In both cases, the addition of phase optimization and time-shifting significantly reduced error factors, with larger reductions to be gained at larger slice spacings and higher MB factors. For MB=2, only time-shifting provides a reduction in the error factor. Nevertheless, this is still important for high field where sequences, like spin-echo diffusion MRI at 7T, tend to run near SAR limits, whereby preventing any acceleration.

Conclusion: With sluggish online SAR monitoring systems, online SAR measurement errors compound the intrinsic high SAR levels of slice accelerated 2D EPI - limiting the benefits of slice acceleration. Phase optimization [4] and time-shifting [5] reduces SAR measurement errors with little or no cost in TR or image quality. Future work will combine optimizations of individual MB RF phases with time-shifting for additional reductions in SAR measurement errors.

References: [1] Moeller et al. MRM 2010; [2] Setsompop et al. MRM 2012; [3] Ugurbil et al. NeuroImage 2013; [4] Wong Proc ISMRM 2012, 20:2209; [5] Auerbach et al. MRM 2013

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