Parallel Imaging with RASER using Multiband Frequency-modulated Excitation Pulses

T. Nguyen[1], U. Goerke[2], S. Moeller[2], K. Ugurbil[2], and M. Garwood[2]

[1]High-Field Magnetic Resonance Center, Max-Planck Institute for Biological Cybernetics, Tübingen, Germany, [2]Center for Magnetic Resonance Research, Minneapolis, Minnesota, United States

Introduction: The recently described RASER sequence is a conceptual novelty in MR imaging [1]. Based on frequency-swept excitation, and time-encoding, RASER is a rapid, pure T_2-weighted scheme without signal voids, ghosting and distortion artifacts present in conventional echo-planar imaging (EPI). These properties render it attractive for functional imaging (fMRI). However, in the previous implementation of single-shot RASER, these benefits came only at the expense of coverage and spatial and temporal resolutions. Parallel imaging (PI) can alleviate such limitations. With RASER, this must utilize unconventional approaches since the sequence does not employ conventional phase-encoding. For this, multi-band frequency-swept excitation pulses were employed, and it is demonstrated that such a PI method can be used in RASER to extend its ability for spatial coverage with reduced time demands and achieve echo times optimal for T_2-weighted blood oxygenation level dependent (BOLD) contrast in fMRI.

Theory: Spatial localization in RASER is resolved through a frequency-time relation embedded in the excitation. Hence, accelerated acquisition can be incorporated within the frequency-modulated RF pulse for simultaneous multi-band excitation. Multi-band pulses have been introduced previously, e.g. [2][3]. Adopting this concept, multi-band excitation pulses are created as a linear combination of phase-shifted copies of a basis frequency-modulated pulse by introducing a linear phase ramp:

$$P(t) = A_0(t)e^{i\varphi_0(t)}\left(1+\sum_{n=1}^{N-1} e^{i2\pi\cdot n\Delta f\cdot t}\right) \quad , \qquad \Delta f = BW = R/\tau_{p_0} \qquad \text{(Eq.1)}$$

As a basis pulse, hyperbolic secant pulses (HS*n*) have shown to have excellent profile properties [4]. For adjacent bands, the frequency shifts correspond to the basis pulse bandwidth, given by the bandwidth time product parameter, *R*, and the pulse duration, τ_p, (Eq.1). The detected RASER signal is then a superposition of spatially distinct band signals, which are not time resolved. In contrast to conventional undersampling methods, the excitation therefore yields complete spatial sampling. The aliasing is not of the same nature as with accelerated phase-encoding schemes, the signal-to-noise ratio is higher, and along with a single 1D Fourier relation, it is expected to pose better conditions for image-based PI unfolding techniques.

Methods: *Simulations:* Various multi-band pulses for optimized imaging protocols were simulated using the VNMR Pulsetool (Varian, Palo Alto) for pulse and excitation profile assessment. Other pulse implementation evaluations were executed in Matlab. *Experiments:* All experiments were performed on a 7T Siemens system using an in-house built 16-channel Tx/Rx transmission line array head coil. Human studies on 4 healthy volunteers were carried out following IRB approved procedures. The multi-band excitation pulses were implemented within the RASER sequence for on-the-flight generation, using an analytical implementation [4] of the HS20 pulse as the basis pulse, and the experimental protocol included: a quad-band, and an interleaved dual-band acquisition with a four-fold reduced FOV. The optimization of parameters with the accelerated acquisition sought to achieve the optimal echo time corresponding to T_2 while obtaining whole slice coverage. Isotropic nominal spatial resolutions were 3 mm (64x64 matrix), and 2 mm (96x96) for quad-band acquisition, and 2.7 mm (72x72) for interleaved acquisition. The FOV was 19.2x19.2 cm^2, with a slice-to-slice TR ≈ 2 sec with variable excitation pulse duration τ_p = 7.52–21.82 ms and bandwidth time product *R* = 272–552. Scans with no RF excitation (noise only detection) and corresponding full FOV scans were acquired for sensitivity profile estimations. *Reconstruction:* Data processing and reconstruction were handled offline in Matlab. A SENSE reconstruction algorithm was implemented including sensitivity profile estimations and data correction procedures.

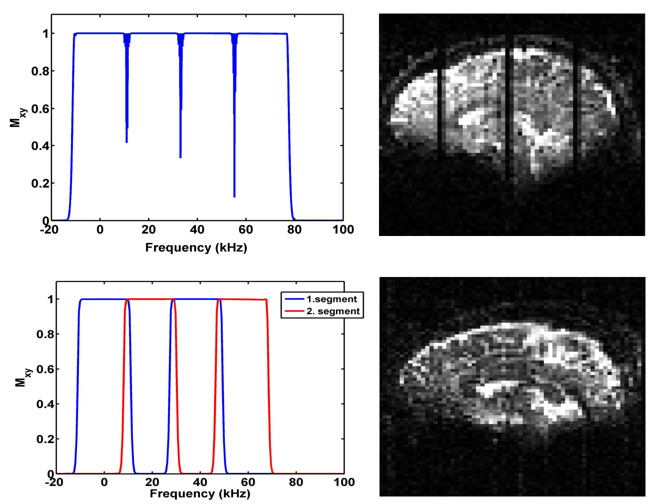

Fig. 1: *Simulated multiband RF pulse excitation profiles (Mxy: transverse magnetization) with corresponding experimentally acquired and SENSE unfolded images. Top row: Quad-band acquisition with reconstructed image, shown for isotropic 3mm resolution. Bottom row: Split quad-band interleaved acquisition with band overlap and reconstructed image with 2.7mm spatial resolution.*

Results: Multi-band frequency-modulated HS20 pulses yielded excellent excitation profiles that were optimal compared to other HS*n* pulses. SENSE reconstructed images have the expected T_2-weighted contrast and are free of ghosting artifacts (Fig.1). Single-shot multi-band images showed dropout lines of about 1 pixel width coinciding with the band ramps (Fig.1-top), while a smooth image was achieved with a two-shot dual-band interleaved acquisition (Fig.1-bottom). For quad-band protocols, a minimum echo time of TE_{min} = 40-55 ms and 72 ms was achieved for 3 mm and 2 mm isotropic nominal spatial resolution, respectively.

Conclusion: Implementation of PI in RASER was successful, achieving artifact free images covering a whole slice at an acceptable spatial resolution. Although limitations exist in single-shot multi-band excitation in the form of inevitable gapping, the tailored pulses offer great flexible options for attaining coverage as desired. Alternatively, interleaved multi-band acquisition produced excellent results for full coverage. Both schemes demonstrate the feasibility of accelerated RASER for BOLD fMRI.

Acknowledgements: We acknowledge the support of the KECK Foundation and grant BTRR - P41 RR008079.

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