Hadamard Slice-Encoding for Reduced-FOV Single-Shot Diffusion-Weighted EPI

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Introduction: High in-plane resolution and the ability to acquire a large number of slices are essential for diffusion-weighted imaging (DWI) of small structures, such as the spinal cord. Recently, a reduced-FOV method that uses 2D echo-planar RF (2D-EPRF) excitation pulses to achieve high in-plane resolution was proposed (1), with preliminary results on Hadamard slice-encoding to double the number of slices without any SNR or time penalty (2). In this work, we propose significant improvements to increase the SNR efficiency and reduce the inter-slice crosstalk for the Hadamard slice-encoding method. We validate the proposed method with *in vivo* high-resolution axial DWI of the spinal cord.

Methods: The Hadamard "multiband refocusing" scheme exploits the periodicity of the 2D-EPRF excitation profile, while maintaining the reduced-FOV in the phase-encode (PE) direction. As shown in Fig.1a-b, Hadamard 180^O RF pulses refocus two adjacent lobes to generate the following summation (S) and difference (D) images:

$$\mathbf{S} = \text{Slice1}+\text{Slice2} \quad \text{and} \quad \mathbf{D} = \text{Slice1}-\text{Slice2}.$$

The original slices can then be resolved by combining these two images (Fig.1c):

$$\mathbf{Slice1} = (S+D)/2 \quad \text{and} \quad \mathbf{Slice2} = (S-D)/2.$$

Performing this in all original slice locations doubles the number of resolved slices for the same SNR and scan time (by acquiring NEX/2 image averages for S and D). The Hadamard RF pulse pair $\{RF_S, RF_D\}$ is designed by utilizing the SLR algorithm to reduce band interference (3-4).

In this work, we propose the following improvements for the Hadamard scheme:

1. *Pulse reshaping by VERSE:* Because Hadamard pulses have twice the duration of a single-band RF pulse, they lengthen the echo time (TE) and distort the profile due to increased off-resonance and relaxation. To shorten the durations, we utilize a time-optimal variable-rate selective excitation (VERSE) algorithm (5-6) that jointly reshapes $\{RF_S, RF_D\}$, as in Fig. 2.

2. *Interleaved NEXing:* The NEXs for S and D should be acquired in an interleaved fashion (i.e., in two adjacent TRs) to avoid cumulative motion artifacts in the resolved slices.

3. *Phase-preserving reconstruction:* Preserving both the phase and the amplitude of S and D is critical to avoid interference between the resolved slices (e.g., S-D is not the same as |S|-|D|). This is a nontrivial problem for the diffusion-weighted images, which may suffer from motion-induced dephasing and signal loss. To address this issue, we have observed that the following procedure can successfully resolve the slices: Two images are reconstructed for S, without and with phase correction using central k-space data. The phase of the first image is then combined with the magnitude of the second to form a composite S image. After repeating this procedure for D, the slices are resolved using the composite S and D images.

Results: *In vivo* axial DWI images of the cervical spinal cord were acquired in healthy subjects on a 1.5T GE Excite scanner (40 mT/m gradient amplitude, 150 mT/m/ms slew rate) using an 8-channel CTL coil. 16 slices were acquired by applying the Hadamard slice-encoding scheme on an 8-slice 2D-EPRF pulse. Cardiac gating was performed to avoid pulsatile cord motion, with a total scan time of 5 minutes, 0.7x0.7 mm^2 in-plane resolution, 5 mm slice thickness, no slice spacing, 9x4.5 cm^2 FOV, b = 500 s/mm^2, TE = 63 ms and partial k_{PE} of 62.5%.

VERSE algorithm provided more than 75% reduction in RF pulse durations (Fig. 2), resulting in a 10% increase in white-matter SNR due to a shortened TE.

Figure 3 shows the results for the proposed Hadamard slice-encoding scheme. Note that there is no visible crosstalk between the resolved slices.

Conclusion: We have shown that Hadamard slice-encoding can successfully double the number of slices for the 2D-EPRF reduced-FOV method. The SNR efficiency is improved by shortening the RF pulses, while interleaved NEXing and a phase-preserving reconstruction dramatically reduce the inter-slice crosstalk. The results were validated with *in vivo* high-resolution axial DWI of the spinal cord. Note that the proposed Hadamard encoding scheme can be modified to include more lobes of the 2D excitation profile for extended slice coverage.

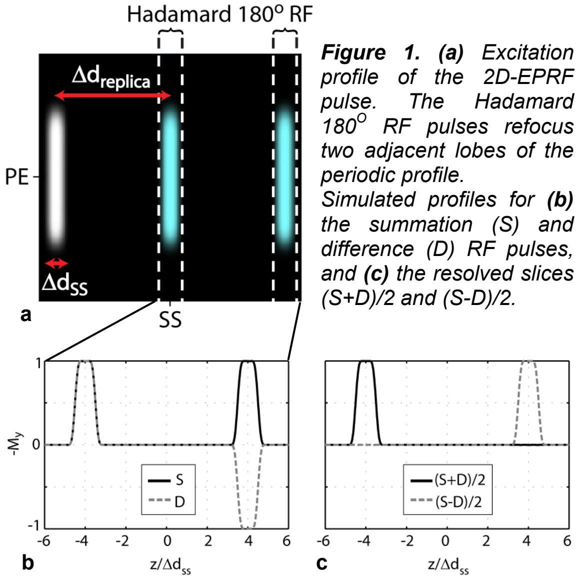

Figure 1. ***(a)*** *Excitation profile of the 2D-EPRF pulse. The Hadamard 180^O RF pulses refocus two adjacent lobes of the periodic profile.*
Simulated profiles for ***(b)*** *the summation (S) and difference (D) RF pulses, and* ***(c)*** *the resolved slices (S+D)/2 and (S-D)/2.*

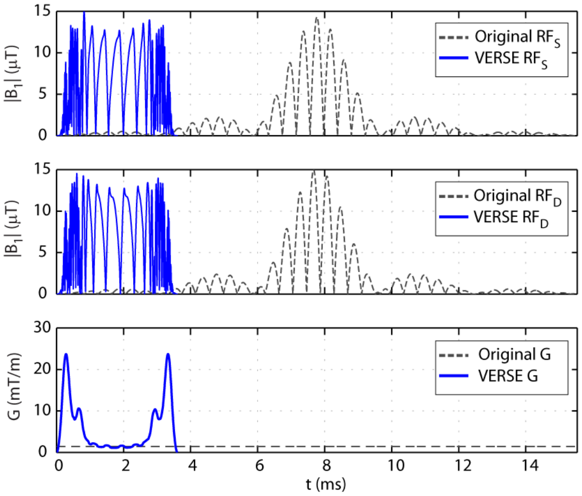

Figure 2. *The original and VERSE RF_S and RF_D pulses, along with the corresponding gradient waveform G. VERSE algorithm provides more than 75% reduction in duration (from 15.5 ms to 3.6 ms).*

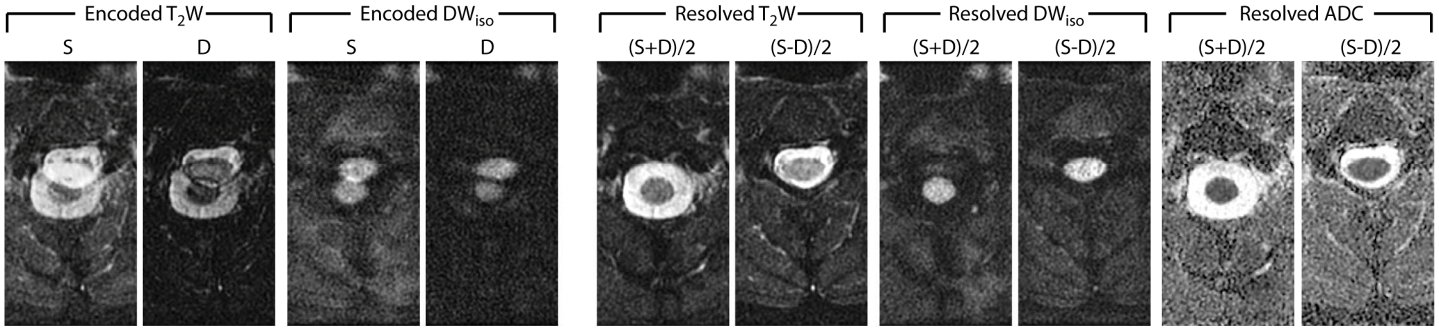

Figure 3. *Encoded (summation (S) and difference (D)) images and the resolved slices for axial DWI of the spinal cord. Only 2 out of 16 slices are displayed, and these two are 8-slice apart (i.e., the distance between two adjacent lobes as in Fig. 1a). There is no visible crosstalk between the resolved slices for the T2-weighted (i.e., b = 0) and the isotropic diffusion-weighted (DW_{iso}) images. The corresponding ADC maps are also shown.*

References:
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