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

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Introduction: A reduced field-of-view (FOV) single-shot EPI (ss-EPI) method that uses a 2D echo-planar RF (2D-EPRF) excitation has recently been proposed for high-resolution DWI [1]. This method takes advantage of ss-EPI's robustness against motion during diffusion encoding gradients. Furthermore, it allows for contiguous multi-slice imaging without the need for slice skip. However, there is a limit on the number of slices that can be imaged simultaneously, given by the number of slices that can fit between two adjacent sidelobes of the periodic 2D excitation profile (Fig. 1). In this work, we present two different Hadamard slice encoding schemes for the reduced-FOV method to double the number of slices without any SNR penalty.

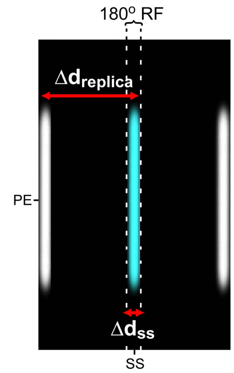

Figure 1. *Simulated excitation profile for the 2D echo-planar RF pulse. The profile is periodic in the slice-select (SS) direction. The limit on number of slices that can be imaged in a single TR is:*

$$N_{slices} = \Delta d_{replica} / \Delta d_{SS},$$

i.e., the number of slices that can fit between two adjacent sidelobes.

Methods: The excitation profile of the 2D-EPRF pulse, used in the aforementioned reduced-FOV method [1], is periodic in the slice-select (SS) direction as shown in Figure 1. A subsequent 180° RF pulse with crushers is designed to refocus only the main lobe of the excitation, suppressing the signal from the sidelobes and fat [1]. Because the adjacent slices are not excited, contiguous multi-slice imaging is compatible with this scheme. However, the periodicity of the excitation profile places a limit on the number of slices that can be imaged in a single TR. This limit is a function of the slice thickness (Δd_{SS}) and the distance between two adjacent sidelobes of the 2D excitation profile ($\Delta d_{replica}$):

$$N_{slices} = \Delta d_{replica} / \Delta d_{SS} = N_{blip} / TBW_{SS}.$$

Here, N_{blip} is the number of blips in the 2D-EPRF pulse design [2], and TBW_{SS} is the time-bandwidth product for the SS direction. Note that larger N_{blip} values (i.e., longer 2D-EPRF pulses) are needed to acquire more slices. For example, a 22 ms RF pulse is required for 6 slices for FOV of 3mm in PE direction. To achieve relatively short echo times (TE), we avoid using longer RF pulses.

For certain applications such as the axial imaging of the spinal cord, it is desirable to acquire as many slices in a single TR as possible and avoid long scan times. In this work, we use Hadamard slice encoding (i.e., multiband excitation) to double the number of slices. This method encodes two slices to generate the following images: A=(Slice1+Slice2) and B=(Slice1-Slice2). In our case, this can be achieved in two different ways:

1) Main-lobe Hadamard encoding (Fig. 2.a): The slice thickness is doubled (i.e., $\Delta d_{SS}^*=2\Delta d_{SS}$), which also doubles $\Delta d_{replica}$ due to gradient scaling. Hadamard-encoding 180° RF pulses are then applied to the main lobe to resolve two slices of thickness Δd_{SS} out of the thicker slice of $2\Delta d_{SS}$. This scheme can resolve $2\times N_{slices}$ slices.

2) Sidelobe Hadamard encoding (Fig. 3.a): Hadamard-encoding 180° RF pulses are designed to select the two adjacent sidelobes of the 2D excitation profile. This way, the main lobe and one adjacent sidelobe can be resolved, again resulting in $2\times N_{slices}$ slices.

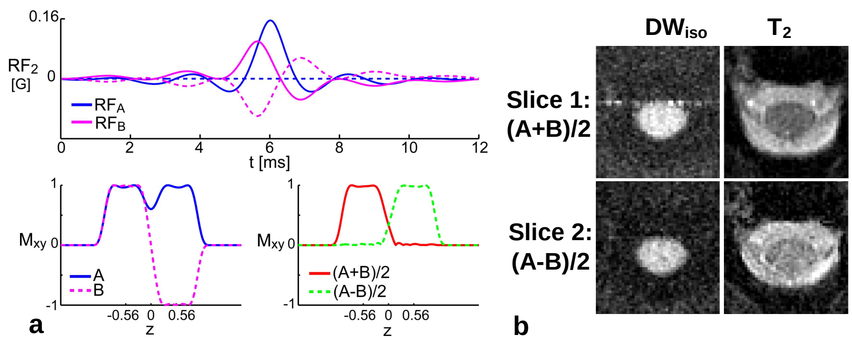

Figure 2. *Main lobe Hadamard encoding:* ***(a)*** *The two 180o RF pulses (RFA and RFB), their spin echo profiles, and the expected profiles after combining the encoded slices.* ***(b)*** *The resulting DWI images for the two resolved slices.*

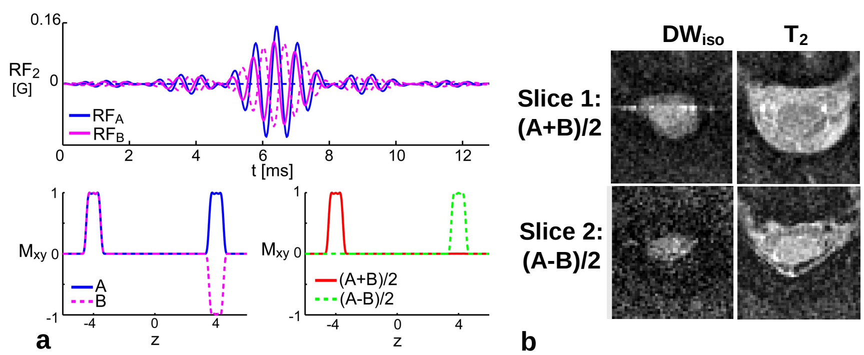

Figure 3. *Side lobe Hadamard encoding:* ***(a)*** *The two 180o RF pulses (RFA and RFB), their spin echo profiles, and the expected profiles after combining the encoded slices.* ***(b)*** *The resulting DWI images for the two resolved slices. Note that there is residual crosstalk between the slices due to imperfections in reconstruction.*

For both cases, Hadamard encoding was achieved using the method described in [2], which uses the Shinnar-Le Roux (SLR) RF pulse design algorithm [3]. The Hadamard modulation was applied to both the desired Bn(z) polynomial of the SLR transform and the corresponding RF pulses calculated by SLR transform. The β-value (defined in [3]) for both pulses were 0.4987, with TBW = 5. The main factor determining the pulse durations was the peak B_1 value of 0.16 G.

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 gradients with 150 mT/m/ms slew rates) using an 8-channel CTL coil. A 6-slice 2D-EPRF was used, which generated 12 slices with the Hadamard slice encoding 180° RF pulse in 2:52s scan time. 0.64x0.64 mm^2 in-plane resolution, 5 mm slice thickness, no slice spacing, 8x3 cm^2 FOV, b = 500 s/mm^2, TE = 60ms. A partial k-space coverage of 62.5% was used for all scans, with TR = 3.6 s and ±62.5 kHz bandwidth. Refocusing reconstruction [4] was performed, with the central 12.5% of k-space treated as the "navigator" for each single-shot data, followed by a partial k-space homodyne reconstruction [5].

Results: Figures 2.b and 3.b show the results for the two proposed Hadamard slice encoding schemes. Note that there is residual crosstalk between Slice1 and Slice2 for the sidelobe Hadamard encoding scheme. The same may be true for the main lobe scheme, as well. However, since the slices are located right next to each other, any crosstalk will be less noticeable.

Conclusion: It is shown that Hadamard slice encoding can be used to double the number of slices for the 2D-EPRF reduced-FOV method. Two unique ways of applying the Hadamard encoding are proposed. The "main lobe Hadamard encoding" has the advantage of localized crosstalk, i.e., crosstalk happens between neighboring slices, instead of a slice that is N_{slices}x Δd_{SS} away. Also, the A=(Slice1+Slice2) case for this scheme produces a useful image with twice the slice thickness, whereas the image A in "sidelobe Hadamard encoding" is not useful on its own. An improved reconstruction is needed to minimize residual crosstalk.

References:
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