Image Domain Segmented Diffusion Imaging Using A 2D Excitation RF Pulse for Distortion Reduction

Yi Sui[1,2], Frederick C. Damen[1,3], Karen Xie[3], and Xiaohong Joe Zhou[1,4]

[1]*Center for MR Research, University of Illinois at Chicago, Chicago, Illinois, United States,* [2]*Bioengineering, University of Illinois at Chicago, Chicago, Illinois, United States,* [3]*Department of Radiology, University of Illinois Hospital & Health Sciences System, Chicago, Illinois, United States,* [4]*Departments of Radiology, Neurosurgery and Bioengineering, University of Illinois Hospital & Health Sciences System, Chicago, Illinois, United States*

INTRODUCTION: Geometric distortion is a common problem in diffusion-weighted (DW) imaging using a single-shot EPI (ssEPI) sequence. The distortion, which arises from off-resonance effects (e.g., magnetic susceptibility variations, B0-field inhomogeneity, and/or eddy currents), is proportional to echo spacing *(esp)* over phase-encoding k-space resolution (Δky). To reduce distortion, *esp* can be shortened by reducing readout (kx) sampling points as employed in Short Axis PROPELLER (SAP)-EPI and Readout-Segmented (RS)-EPI (1,2), while Δky can be increased by reducing phase-encoding FOV as demonstrated in parallel imaging (3) such as SENSE and GRAPPA. The performance of distortion reduction in parallel imaging is determined by the acceleration factor R that is typically limited to 2-3 because of the signal-to-noise ratio (SNR) and artifact considerations. Recently, an image domain PROPELLOR EPI (iProp-EPI) method was introduced (4). A set of rotated blades were acquired in the image domain, rather than in k-space, using a reduced FOV. In this study, we report another approach of image domain segmented acquisition to reduce distortion in diffusion imaging using a set of parallel segments.

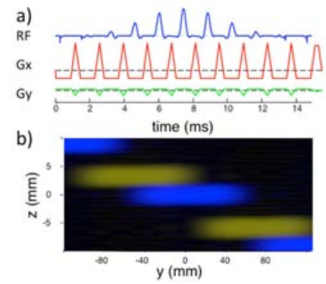

Fig. 1 A 2D RF excitation pulse (a) and its simulated excitation profile (b) showing the location of water (blue) and lipid (yellow) signals.

METHODS: To reduce distortion, the full FOV along the phase-encoding direction was divided into N parallel segments (or strips) and acquired sequentially using a 2D RF excitation pulse which is capable of simultaneous lipid suppression (4–6). These image segments were combined using a weighting function determined by the spatial excitation profile of the 2D RF pulse. This allowed a smooth transition at the interface of adjacent segments. Because image distortion is reduced in each segment due to the reduced FOV, the final combined image is expected to exhibit considerably reduced image distortion. ***2D RF Design****:* As shown in Fig. 1a, the 2D RF excitation pulse for reduced FOV was designed using tilted excitation by rotating the trajectory of excitation k-space. A fly-back echo planar gradient was adopted for robustness with RF sub-pulses playing out only during odd gradient lobes (8). The duration between two consecutive sub-pulses was set at 1.4 ms so that the lipid signal (yellow areas in Fig. 1b) was shifted outside the water profile (blue areas in Fig. 1b) and not refocused by the subsequent 180° pulse targeted at the selected slice (central blue area in Fig. 1b) in a DW-ssEPI sequence. In order to achieve a thin slice with a longer sub-pulse, the duration of the fly-back lobes was minimized by utilizing the maximal slew rate allowed by the Reilly's curve (9). Eleven sub-pulses with a time-bandwidth product (TBP) of 3.2 were modulated by an envelope pulse with a TBP of 3.3 and pulse length of 14.7 ms. The 2D spatial response $w(y,z)$ of the 2D RF pulse was simulated using Bloch equation with customized program written in Matlab (Mathworks, Natick, MA). $w(y,z)$ was subsequently used as a weighting function in image reconstruction. ***Experiments:*** MR experiments were carried out on a 3T GE MR750 scanner using a 32-channel head coil (Nova Medical, Inc., Wilmington, MA). After phantom validations, DW brain images were acquired from healthy human volunteers in 1 (i.e., full FOV), 2, and 3 segments across the FOV, respectively. For the full FOV (22×22 cm^2) acquisition, a commercial ssEPI sequence was used. For the experiments with 2 segments, each segment had a FOV of 22×12.4 cm^2 (hence 1.8 times less distortion than the 1-segment image) over a matrix of 128×72. For the experiment with 3 segments, the FOV of each segment was further reduced to 22×8.4 cm^2 (hence 2.7 times less distortion than the 1-segment image) with a matrix of 128×48. Other acquisition parameters were b=1000 s/mm^2, slice thickness = 3 mm, TR/TE = 4500/69.7 ms, and NEX = 4. ***Image Reconstruction:*** Each segmented image was reconstructed individually. The magnitude of all segments was combined to form the final image S using $S = \sum w_i(y) S_i(y) \,/\, \sum w_i^2(y)$ where w_i, S_i are excitation profile and image intensity of each segment i, respectively.

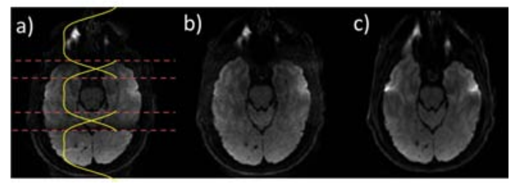

Fig. 2 (a) Three individual segments of a diffusion brain scan, RF excitation profiles (yellow), and the transition regions (red dashes) between segments. (b) Combined diffusion image from the three segments in (a) (b=1000 s/mm^2). The distortion and signal pile-up was effectively reduced compared to the full FOV image in (c).

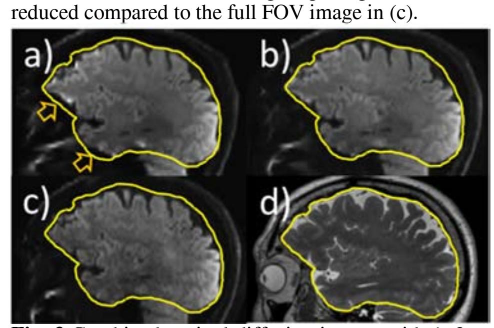

Fig. 3 Combined sagittal diffusion images with 1, 2, and 3 segments (a-c, respectively), and an FSE image as a reference (d). Note the reduction in geometric distortion in the frontal and temporal lobes (hallow arrows).

RESULTS: Figure 2a shows three individual segments of the brain, excitation profiles $w_i(y)$ (yellow) used for image reconstruction, and the inter-segment transition regions (red dashes) where intensity discontinuity is clearly visible. Figure 2b displays the combined full FOV image from the three segments in Fig. 2a, demonstrating that the abrupt transition regions were eliminated by using the simulated RF spatial profile $w_i\,(y)$. The reconstructed image (Fig. 2b) exhibited a considerably reduced image distortion and signal pile-up when compared to the corresponding 1-segmnent image (Fig. 2c). Figures 3a-c illustrate a representative result from 1, 2, and 3-segmented acquisitions in a sagittal plane, respectively. As the segments increased from 1 to 3, the image distortion was progressively reduced. This is most visible in the frontal and temporal lobes (hallow arrows) where the magnetic susceptibility variation is substantial. With 3 segments, image distortion and signal pile-up were effectively reduced, resulting in an image with similar shape as a T2-weighted fast spin echo (FSE) reference image (Fig. 3d). To assist the comparison, an identical fiducial contour (yellow line) of the brain was shown in all images in Fig. 3.

DISCUSSION: The proposed method does not involve complicated image reconstruction other than using a weighting function which can be obtained through a Bloch simulation. This method is particularly useful when multiple signal averages are needed. Instead of using multiple averages to repeatedly acquiring the same information, these "averages" can be redistributed to acquire individual segments to reduce image distortion and signal pile-up. In situations where multiple averages are not needed, the proposed technique can lengthen the scan time.

In summary, an image domain segmented DW-EPI technique with 2D excitation has been demonstrated to effectively reduce the image distortion. For brain diffusion scans, three segments appear to be adequate to reduce image distortion while maintaining an acceptable acquisition time.

REFERENCES: 1. Skare et al., MRM, 2006. **2.** Holdsworth et al., EJR, 2008. **3.** Skare et al., MRM , 2007. **4.** Skare et al., ISMRM, 2010. **5.** Finsterbusch, ISMRM 2011. **6.** Banerjee et al., ISMRM, 2013. 7. Saritas et al., MRM, 2008. **8.** Finsterbusch, JMRI, 2012. **9.** Reilly, MBEC, 1989.