Reduction of Image Distortion in Non-Axial Diffusion-Weighted Imaging Using Steer-PROP

G. Srinivasan[1,2], N. Rangwala[1,2], and X. J. Zhou[1,3]
[1]Center for MR Research, University of Illinois Medical Center, Chicago, IL, United States, [2]Department of Bioengineering, University of Illinois Chicago, Chicago, IL, United States, [3]Departments of Bioengineering, Radiology, Neurosurgery, University of Illinois Medical Center, Chicago, IL, United States

Introduction: Single-shot echo-planar imaging (SS-EPI) has been widely used for diffusion imaging, primarily due to its rapid data acquisition speed, robustness against motion, and low specific absorption rate (SAR). SS-EPI, however, not only suffers from severe off-resonance effects such as magnetic susceptibility variations but also exhibits severe distortion in non-axial planes due to concomitant gradients, also called Maxwell fields [1, 2]. The latter effect is further exacerbated with strong gradients and/or at relatively low B_0-fields (including 1.5 T). This often limits the application of diffusion-weighed EPI to the axial plane, despite the need for non-axial planes in various diffusion imaging applications. The advent of PROPELLER [3, 4] (periodically rotated overlapping parallel lines with enhanced reconstruction) imaging opens the opportunity to perform diffusion imaging in non-axial planes without considerably compromising the image quality. In order to accelerate the data acquisition speed of PROPELLER while maintaining the image quality and robustness against motion, a sequence known as Steer-PROP was recently proposed [5]. Steer-PROP is based on both gradient and spin echoes (GRASE) with ~3-5 gradient echoes acquired after each refocusing RF pulse, thereby improving the data acquisition efficiency ~3-5 times when compared to conventional PROPELLER based on fast spin echo [3, 4]. Additionally, Steer-PROP has been shown to be much less sensitive to off-resonance effects than SS-EPI sequences. The goal of this study was to demonstrate the feasibility of using Steer-PROP to obtain distortion-free diffusion images in non-axial planes in the human brain.

Methods: A diffusion-weighted Steer-PROP sequence was developed by incorporating a pair of Stejskal-Tanner gradients straddling the first refocusing RF pulse. To sample multiple PROPELLER blades after each excitation, a series of "steering" gradient pulses was added in-between the acquisition of the gradient echoes in the echo train. These steering pulses distributed the k-space lines from the N gradient echoes to N different blades. With a spin-echo echo train length (ETL) of M, this sampling scheme acquired a total of $M \times N$ k-space lines that were evenly distributed among the N blades after each excitation (or TR), thus accelerating the data acquisition by a factor of N as compared to conventional PROPELLER. The diffusion-weighted Steer-PROP sequence was implemented on a GE Signa HDx 1.5 T scanner (GE Healthcare, Waukesha, WI). Using the sequence, diffusion-weighted images were acquired from a healthy female volunteer in both axial and non-axial planes (sagittal, coronal, and oblique) with the following parameters: TR = 4000 ms, TE = 72 ms, M = 8, N = 3, matrix size L = 256, FOV = 24 cm, slice thickness = 5 mm, b = 500 s/mm^2, NEX = 2, and scan time = 2min 13sec. The oblique scan was acquired ~40° from the axial plane through a section containing both the cerebrum and cerebellum. For comparison, scans with the same planes and matching parameters were repeated using a diffusion-weighted SS-EPI sequence provided by the scanner manufacturer. The Steer-PROP images were reconstructed offline using customized programs implemented with Matlab (The MathWorks, Inc., Natick, MA), while the SS-EPI images were reconstructed using the commercial reconstruction software.

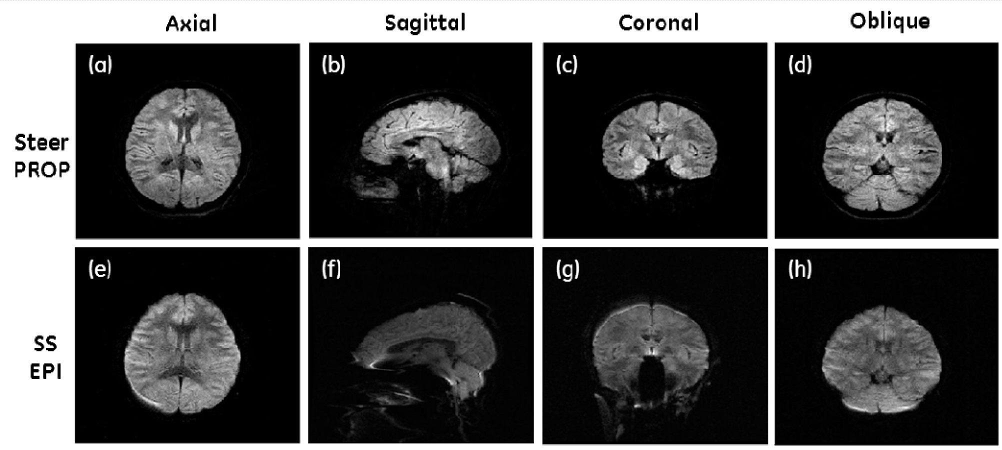

Figure 1. Diffusion-weighted images from Steer-PROP (a-d) and SS-EPI (e-h) on axial (a, e), sagittal (b, f), coronal (c, g) and oblique (d, h) planes.

Results and Discussion: Figure 1 compares a set of representative diffusion-weighted Steer-PROP (Figs. 1a-d) with SS-EPI (Figs. 1e-f) images from the human brain. The axial images (Figs. 1a,e) showed the smallest discrepancies, as expected, because of the small magnetic suspectibility differences in the specific imaging plane and the relatively small contributions from the concomitant gradient [1, 2]. For images acquired in non-axial planes (columns 2-4 in Fig. 1), Steer-PROP showed significantly less distortion than the SS-EPI images. For example, the SS-EPI image in the sagittal plane (Fig. 1f) exhibited substantial gross distortion largely due to concomitant gradient fields as well as localized distortion arising from the magnetic susceptibility differences in the frontal lobe. Both types of distortion were virtually eliminated in the corresponding Steer-PROP image (Fig. 1b). Similar improvements were also observed in coronal (Fig. 1c vs. 1g) and oblique planes (Fig. 1d vs. 1h). A downside with Steer-PROP was the longer scan time (~2 minutes) when compared to that of SS-EPI (~30 s). However, the longer scan time was still considered clinically acceptable and contributed to the improved signal-to-noise ratio (Figs. 1a-d).

Conclusions: Our results indicate that the proposed Steer-PROP sequence can be a viable alternative to SS-EPI for diffusion imaging, especially in situations where magnetic susceptibility and/or concomitant gradients are problematic. Steer-PROP offers at least a three-fold reduction in scan time when compared to conventional PROPELLER, making it possible to obtain distortion-free images in time-demanding diffusion applications, such as diffusion tensor imaging, fiber tractography, and high b-value diffusion imaging.

References: [1] Du, *et al.*, MRM, 2002, 48: 509-515. [2] Weisskoff, *et al.*, MRM, 1993, 29: 796-803. [3] Pipe, MRM, 1999, 42: 963-969. [4] Pipe, *et al.*, MRM, 2002, 47(1): 42-52. [5] Srinivasan, *et al.*, ISMRM, 2010, p. 81.

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