Steer-PROP: A GRASE-PROPELLER Sequence with Inter-Echo Steering Gradient Pulses

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Introduction k-Space sampling based on PROPELLER (periodically rotated overlapping parallel lines with enhanced reconstruction) [1] has been increasingly used for anatomic (e.g., T2 and FLAIR) and diffusion imaging due to its robustness against motion. The technique was originally implemented in a fast spin-echo (FSE) sequence [1] and later extended to echo planar imaging (EPI) [2, 3]. While FSE-PROPELLER provides excellent immunity against magnetic susceptibility artifacts, its time-efficiency requires improvement for demanding applications such as diffusion tensor imaging (DTI). EPI-based PROPELLER techniques can improve the data acquisition efficiency, but are sensitive to off-resonance effects due to the lack of refocusing RF pulses. A mediating solution may lie in the gradient and spin-echo (GRASE) [4, 5] technique, which can potentially combine the merits of both FSE and EPI. Turboprop [6] based on GRASE was proposed primarily to improve the robustness of motion correction by increasing the blade width. In this paper, we propose an alternative GRASE-PROPELLER sequence, which we call Steer-PROP, to improve the data acquisition efficiency without increasing the blade-width. The proposed technique not only reduces the scan time by a factor of at least 3 as compared to FSE-PROPELLER, but also provides an effective way to address the problems with phase errors inherent to GRASE sequences.

Methods ***Pulse Sequence:*** Unlike Turboprop [6] where multiple gradient echoes (*N*) within a spin echo are used to sample *N* parallel k-space lines within the same PROPELLER blade, Steer-PROP employs a series of blip gradient pulses to distribute the *N* gradient echoes to *N* different blades. In doing so, *N* blades are sampled within each shot. A segment of the sequence diagram is shown in Fig. 1a where three gradient echoes are produced at each spin echo. Each of the three gradient echoes is color coded and their corresponding k-space lines are shown in Fig. 1b (solid lines). The brown and black blip gradient pulses were used to steer the k-space trajectory to the desired blade. The purple gradient pulses at the end of the gradient echo train rewound the phase in order to satisfy the CPMG condition. The segment in Fig. 1a was repeated *M* times throughout the spin-echo echo train (spin echo train length = *M*), producing the remaining k-space lines (dotted lines in Fig. 1b) for each of the *N* blades. With this scheme, each excitation (or TR) acquires a total of *MN* k-space lines that are evenly distributed among the *N* blades, improving the data acquisition speed by a factor of *N* as compared to FSE-PROPELLER with the same spin echo train length. For a desired matrix size *L*, the minimum number of excitations *P* to cover k-space fully was calculated by $P = \frac{\pi}{2}.\frac{L}{MN}$.

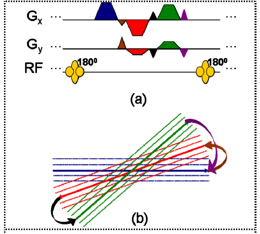

Figure 1: An inter-spin-echo segment (a) (with *N* = 3) of the sequence and the corresponding k-space traversal (b). The blade rotations are achieved by the steering blip gradient pulses.

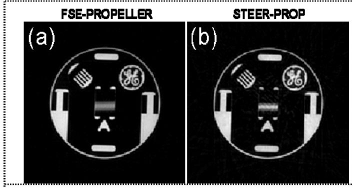

Figure 2: Diffusion-weighted images of a structured water phantom acquired using (a) FSE-PROPELLER and (b) Steer-PROP.

Data Acquisition: The Steer-PROP sequence was implemented on a 3.0T GE Signa HDx scanner (GE Healthcare, Waukesha, WI) with maximum gradient strength = 40 mT/m and slew rate = 150 T/m/s. We chose a relatively short gradient echo train (*N* = 3) to demonstrate the concept, although the sequence is also capable of longer echo trains. Gradient waveforms for the first shot were designed first to produce the targeted k-space trajectories. For each subsequent shot, a rotation matrix was used with a rotation angle increment three (i.e., *N*) times that of the corresponding FSE-PROPELLER. The sequence was initially evaluated on a water phantom and then on the brain of two healthy female volunteers to acquire T2 and diffusion-weighted images with the following parameters: TR = 4000 ms, TE = 128 ms, *M* = 8, *N* = 3, matrix size *L* = 256, FOV = 26 cm, slice thickness = 5 mm, b = 500 s/mm^2, NEX =2, and scan time = 2min 13sec. Additionally, EPI and FSE-PROPELLER images were also obtained with similar parameters for comparison.

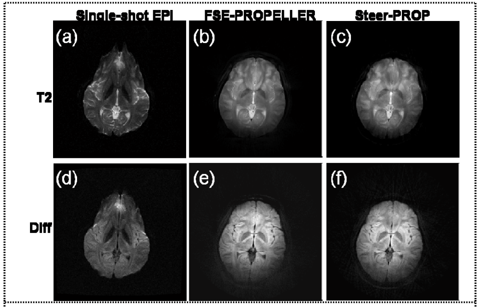

Figure 3: T2-weighted (a-c) and diffusion-weighted images (d-f) acquired using EPI (a, d), FSE-PROPELLER (b, e), and Steer-PROP (c, f).

Image Reconstruction and Post Processing: The pulse sequence was sensitive to at least three types of phase errors: inter-shot phase errors arising primarily from motion, inter-blade phase errors among the blades acquired within a shot (i.e., the phase errors among the gradient echoes), and intra-blade phase errors among the k-space lines sampled by different spin echoes in the GRASE echo train. The first two types of phase errors were corrected using the redundant data near the center of k-space, similar to PROPELLER motion correction [1]. To correct for the intra-blade phase errors, the last two spin echoes in the echo train were not phase encoded and used to perform FSE-type phase correction. All PROPELLER images were reconstructed using a customized C++ program on a Linux workstation.

Results and Discussion Figure 2 compares diffusion-weighted Steer-PROP (Fig. 2b) and FSE-PROPELLER (Fig. 2a) images of the structured water phantom. The image quality was similar even though the Steer-PROP image was acquired in 1/3 of the scan time of the image in Fig. 2a. Figure 3 shows a set of brain images (T2 and diffusion) from a volunteer comparing the performance of Steer-PROP with single-shot EPI and FSE-PROPELLER. Steer-PROP images not only eliminated the geometric distortion seen on the EPI images but also had higher SNR than EPI. The image quality of Steer-PROP was similar to that of FSE-PROPELLER, with the SNR lower by a factor of 1.5 due to the 3-fold scan time reduction as well as stronger T2* contribution to the Steer-PROP images. The increased T2* sensitivity in Steer-PROP can also explain the slight contrast difference in the T2 images (Fig. 3c vs. 3b). The shading artifacts in all PROPELLER images were caused by the dielectric effect at 3T. Other than that, no significant artifacts were seen, indicating good performance of the phase correction strategies.

Conclusions Our results indicate that the proposed Steer-PROP sequence can significantly reduce the scan time as compared to FSE-PROPELLER without substantially compromising the image quality. The Steer-PROP sequence can considerably reduce the susceptibility artifacts as compared to EPI. Equally important, the new k-space traversing strategy using the steering gradient pulses provides a robust way to remove the phase inconsistency among the gradient echoes, alleviating a thorny problem confronting GRASE sequences.

References (1) Pipe, MRM, 1999, 42: 963-969. (2) Wong, *et al.*, MRM, 2005, 54: 1232-1240. (3) Skare, *et al.*, MRM, 2006, 55: 1298-1307. (4) Oshio, *et al.*, MRM, 1991, 20: 344-349. (5) Oshio, *et al.*, Radiol., 1991, 181(2): 597-602. (6) Pipe, et al, MRM, 2006, 55: 380-385.