Benchmarking SAP-EPI and PROPELLER for Diffusion Imaging

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Introduction: "Short-Axis readout Propeller EPI" (SAP-EPI) (1) has been proposed as a new variant for EPI-based PROPELLER (2). The short-axis readout uses a faster traversal of k-space and thus minimizes artifacts from off-resonant spins and T_2^* decay. It has been shown that SAP-EPI is superior in image quality over its long-axis variant (1). Historically, DWI PROPELLER has been combined with FSE readouts because of FSE's immunity to susceptibility distortions and eddy current effects. This is the only commercially available alternative to EPI for DWI, and has demonstrated increased geometrical and motion correction properties due to the RF refocusing pulses. Clinically, this has proven a great utility for the diagnostic work-up of lesions in the posterior fossa and brain stem, as well as in patients with surgical material or with hemorrhage. However, the requirement for large flip angle FSE trains in PROPELLER-FSE to combat violations of the CPMG condition as well as quite long scan times can pose difficulties in critically ill patients, and raise problems at higher magnetic field strengths where the specific absorption rate (SAR) issues and B1 inhomogeneities increase. In these situations, with the reduced distortions and minimum SAR of SAP-EPI in concert with the great motion insensitivity of the PROPELLER trajectory, SAP-EPI might pose an attractive alternative to FSE-based PROPELLER. Determining the strengths and weaknesses of both methods and comparing them to single-shot EPI (ssEPI) is therefore of great interest. The purpose of this work was to assess DWI PROPELLER-FSE and DWI SAP-EPI with regard to performance and image quality for a typical range of scan parameters used in clinical practice.

Materials & Methods: Side-by-side comparisons of PROPELLER-FSE (T2w and DWI) provided by the vendor, ssEPI, as well as SAP-EPI accelerated by GRAPPA (R=3) (3) developed in-house were performed on a 3T whole-body MRI unit (GE Signa LX) using an eight-channel head coil and a high-performance gradient system (40mT/m, SLR=150mT/m/s). Here, PROPELLER-FSE determined the common minimum TR for a given number of slices across all three sequences under test because of the additional time for applying refocusing pulses. By using a fixed spatial resolution of 1.1×1.1×5mm, the following assessments were performed: 1) to determine the number of slices that can be interleaved for a given TR; 2) determine the minimum TE per blade width (SAP-EPI) or per echo train length (ETL) (PROPELLER-FSE); and 3) determine the SAR associated with each sequence. In addition, the level of geometric distortions in SAP-EPI was determined as a function of blade width (blade width range: 16, 32, and 64) and was compared against optimized FSE-PROPELLER (ETL range: 8, 16, and 24), as well as ssEPI. All experiments were performed in healthy young volunteers (28cm FOV, TR=4.8s) using peripherally gated DWI acquisitions to minimize confounding effects from brain pulsation artifacts. The SAP-EPI images were reconstructed with POCS (4) - since we found that preserving the phase resulted in markedly reduced artifacts compared with homodyne reconstruction used in previous work (2).

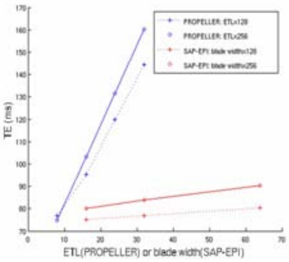

Figure 1: Echo Time vs. echo train length (ETL) for PROPELLER and blade width (SAP-EPI) for an equivalent resolution.

Results: For all parameter combinations investigated, SAP-EPI allows a smaller minimum TE, smaller minimum TR (and thus shorter scan time for a given number of slices), and lower average SAR for a given resolution (Table 1). Due to the considerable time occupied by refocusing pulses during the FSE readout and the longer readout (long axis) for each echo within a blade, the effective echo time increases substantially with increasing blade width (Fig. 1). This leads to marked increases in T2-weighting with increasing blade width (not shown). Conversely, the TE of SAP-EPI stays relatively constant with increasing blade width due to the half Fourier acquisition. Factors that determine TE in SAP-EPI are: half Fourier over-scan factor (typically 16-24), length of each readout gradient lobe, and the slew rate. Example images of T2w SE ssEPI, T2w PROPELLER FSE, SAP-EPI (T2w, DWI) images are shown in Figure 2. While there are substantial geometric distortions and T2*-related blurring in the ssEPI scans there are no apparent differences in geometric distortion between both PROPELLER methods that were acquired in the same scan time. With a minimum TR of 4.8s, the maximum number of slices achievable is 14 for PROPELLER and 36 for SAP-EPI. Although 2.5 times more slices were acquired with SAP-EPI, the average SAR is 0.67W/kg and 1.5W/kg for SAP-EPI and PROPELLER FSE, respectively. Despite the underlying EPI mechanism, a very promising aspect of SAP-EPI is its robustness against geometric distortions with increasing target resolution - affording resolutions unmatched thus far (768×768) (Fig. 3). By comparing these 768×768 SAP-EPI images with the 256×256 SAP-EPI (Fig. 2), we demonstrate that the distortions (in mm units) are kept constant.

ETL *or* blade width x 256	PROPELLER			SAP-EPI (3 shots)		
	Minimum TR (ms)	**Scan time (mins)**	**Ave SAR (W/kg)**	**Minimum TR (ms)**	**Scan time (mins)**	**Ave SAR (W/kg)**
16 x 256	5800	4:44	1.7	1900	4:45	0.49
24 x 256	7900	4:21	1.9	1960	3:08	0.45
32 x 256	10500	4:23	1.9	2000	2:24	0.42

Table 1: Comparison between various parameters for PROPELLER and SAP-EPI for 20 slices, and a given ETL (PROPELLER) or blade width (SAP-EPI) at a fixed target resolution. This assumes a minimum diffusion preparation time of 50ms (b=1000s^2/mm).

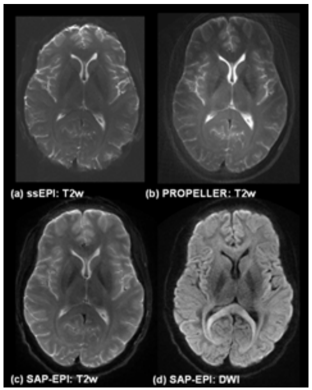

Figure 2: a) ssEPI T2w image: matrix size 256 x 256; (b-c) SAP-EPI and (d-e) PROPELLER T2w and DWI images (b=1000s^2/mm) acquired at a resolution of 1.1x1.1x5mm, TR of 4.8s (scan time 5 mins), and 3 shots. For PROPELLER the ETL = 16, NEX=2, TE_{min}=101ms. For SAP-EPI the blade width = 32, andTE_{min}=75ms.

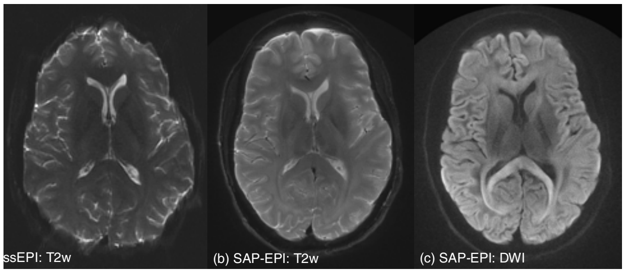

Figure 3: a) ssEPI T2w image (matrix size 256×256); b-c) 0.36mm x 0.36mm x 5mm SAP-EPI T2w and DWI images at 768×768 resolution using a blade size of 32×768, 3 shots, b=1000s/mm^2.

Discussion & Conclusion: The results of this study demonstrate that SAP-EPI is a viable alternative to ssEPI and PROPELLER-FSE. The markedly faster traversal of k-space relative to ssEPI in combination with GRAPPA generates images with negligible geometric distortions within the same imaging time as PROPELLER-FSE. The substantial speed gain of SAP-EPI over PROPELLER-FSE affords larger brain coverage or even smaller blades (and thus further distortion reduction). The absence of refocusing pulses helps to diminish SAR considerably. This is not so much of an issue at 1.5T, but certainly at 3T and higher. B1 homogeneity also deteriorates at higher field strength and thus the high flip angle regime required in PROPELLER-FSE cannot be maintained across the entire FOV.

In this work, we have used POCS reconstruction of the half-Fourier blades as this preserves the image phase of each blade prior to Fourier transforming the blade images to k-space for the final regridding. This was found to yield substantial improvements in the image quality for SAP-EPI. With complex blade data in the image domain due to the POCS reconstruction, further investigation is needed on how we can modify our earlier proposed RGPM distortion correction techniques for SAP-EPI (5), which to date has solely operated on magnitude blade image data. With this issue solved, we anticipate further increase in the effective resolution and overall better geometrical faithfulness in the basal parts of the brain. Further work is also needed for highly accurate echo centering and motion correction schemes at high image resolutions. Moreover, it remains to be shown whether the robustness of SAP-EPI holds true in patients with surgical material (aneurism clips, coils) or hemorrhage. Most likely, both methods have complimentary advantages, and increased speed can be traded for more robustness against field inhomogeneities. Recently, TurboPROP (6) has been introduced - a GRASE variant of PROPELLER-FSE. A future study should focus on a comparison with this method since it combines the benefits of EPI's fast readout and FSE's robustness against distortions. In summary, SAP-EPI and PROPELLER FSE are both extremely robust methods far superior to ssEPI. Currently, it seems that PROPELLER-FSE has slight advantages when distortion reduction is required, whilst SAP-EPI excels at higher field when SAR becomes and issue or when higher speed is required.

References:1) Skare S. Magn Reson Med 2006;55:1298-1307. **2)** Pipe JG. Magn Reson Med 1999;42(5):963-969. **3)** Andersson JL *et al.* Neuroimage 2003;20(2):870-888. **4)** Liang Z-P, Rev Magn Reson Med 1992;4:67-185. **5)** Skare S. 2006; Seattle. ISMRM. p 857. **6)** Pipe JG. Magn Reson Med 2006; 55(2):380-385. **Acknowledgements:** This work was supported in part by the NIH (1R01EB002711), the Center of Advanced MR Technology at Stanford (P41RR09784), Lucas Foundation, and Oak Foundation.