Self-Calibrated Simultaneous Multi-Slice PROPELLER

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INTRODUCTION: Simultaneous multi-slice (SMS) [1] MR imaging, sometimes in combination with regular parallel imaging in the phase encoding direction, has led to a dramatic speed up of multi-volume echo-planar imaging (EPI) [2,3] for fMRI and diffusion MRI. In multi-volume SMS imaging, the first volume can be acquired without acceleration and be used for calibration of the subsequent SMS accelerated volumes. For clinical MRI, most often only involving one volume per scan, one needs to make sure that the SMS calibration does not consume a large fraction of the total scan time. To keep the SMS calibration time short, a low resolution 2D GRE scan may be used [4]. In this work, we have developed SMS RF pulses and applied them to PROPELLER [5] imaging. As PROPELLER uses a large set of blade volumes (~10 per minute), we suggest to perform SMS and regular in-plane GRAPPA calibration on the first propeller blade volume as a part of the scan. With only one blade volume being fully sampled in both the phase encoding direction and the slice direction, and with the remaining blades fully accelerated without any ACS lines, the overall scan time could be kept very short and without needing separate GRE scans.

THEORY: For our accelerated PROPELLER sequence, GRAPPA [6] and split-slice-GRAPPA [7] was used for unfolding, and the GRAPPA kernel was rotated to calculate sets of weights the other blade volumes, similar to what was done in Ref. [8]. The kernel rotation requires interpolation of the calibration k-space; in this case we used splines. The calibration blades were acquired with a doubled field-of-view (FOV). This results in a more densely sampled k-space, which improves the interpolation. To accommodate this sample difference in k-space between the calibration blades and the remaining accelerated blades, the GRAPPA kernel was doubled in size for the estimation (see Figure 1). Using CAIPIRINHA [9], a phase ramp was applied to the calibration blades corresponding to the FOV-shifted slices. This phase ramp was rotated along with the rotating GRAPPA kernel. When combing in-plane acceleration with slice acceleration split-slice-GRAPPA is used to separate the slices and regular GRAPPA is used to unfold the images. Since the split-slice-GRAPPA kernels are trained on fully sampled data and applied on in-plane under-sampled data, the kernels were extended in the phase encoding direction to simulate under-sampling at the angle at which the kernel is rotated. The calibration blades are added and used in the succeeding PROPELLER reconstruction.

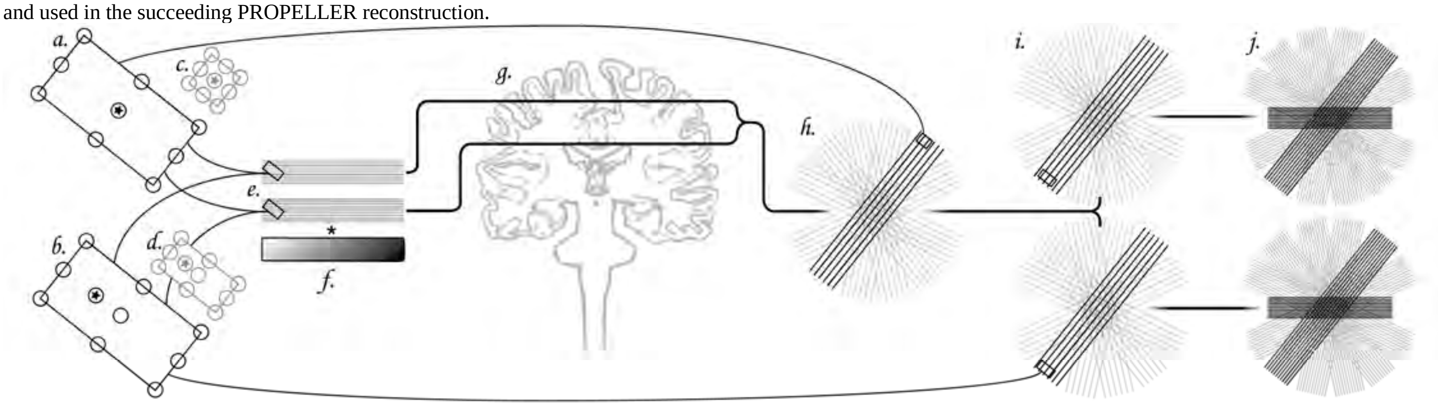

Figure 1. *Illustrating the parallel imaging section of the reconstruction process of SMS-PROPELLER.* ***a:*** *Rotated GRAPPA kernel used in the split-slice-GRAPPA algorithm to separate simultaneously excited slices.* ***b:*** *Rotated GRAPPA kernel used for unfolding in-plane under-sampling.* ***c&d:*** *The rotated GRAPPA kernels before adjustment to fit the reference data.* ***e:*** *Fully sampled PROPELLER blades used for calibration, acquired with a doubled FOV.* ***f:*** *Rotated phase ramp to simulate CAIPIRINHA FOV shift.* ***g:*** *Brain drawing showing slice positions.* ***h:*** *Slice aliased data.* ***i:*** *Separated but still in-plane under sampled data.* ***j:*** *PROPELLER blades un-folded in both directions and added calibration blades.*

METHODS: The technique was validated with our T1-W SE PROPELLER sequence. In-house generated SLR [10] RF pulses were used to create multiband pulses, which were time-shifted [11] to reduce peak power. Four scans were performed on a 3 T clinical MRI system (DVMR750, GE Healthcare, Milwaukee, WI) system using a 32-channel RF head coil (Nova Medical, MA, USA). Imaging parameters for the T1-W SE PROPELLER scans: FOV = 240×240 mm^2, N_{blades} = 25, blade matrix = 320×32, slice thickness = 4 mm, N_{slices} = 20, exc./ref. FA = 90°/160°, RBW = ±50 kHz and TE/TR = 9/500 ms. ***Scan 1****:* An SMS T1-W SE PROPELLER scan performed with slice acceleration factor = 2, CAIPIRINHA FOV/3 shift, in-plane acceleration factor = 2 and a total scan time = 1:41 min. ***Scan 2:*** A T1-W SE PROPELLER scan, acquired without slice acceleration but with an in-plane acceleration factor of 4, yielding a total scan time = 1:41 min. ***Calibration scan 1:*** A fully sampled T1-W SE PROPELLER scan with total scan time of 6:45 min. ***Calibration scan 2****:* Blade volume #1 with matrix = 320x32, FOV = 480×480 mm^2 and total scan time of 18 s, which is the case described in the theory section. ***Calibration scan 3:*** 2D GRE with matrix = 64x64, FOV = 480×480 mm^2 and total scan time of 6 s. All scans were performed within SAR safety guidelines. The calibration and unfolding of *scan 1* was performed in four ways. ***Calibration 1****:* Calibration done without rotating the kernels, on a matching fully sampled PROPELLER data from *calibration scan 1*. ***Calibration 2****:* Calibration done with the proposed method, on the blade volume from *calibration scan 2*. ***Calibration 3:*** Calibration done with the proposed method, on the low-resolution 2D GRE from *calibration scan 3*. The calibration and unfolding of *scan 2* was performed with the proposed method using the blade volume from *calibration scan 2*.

RESULTS: The results of the different calibrations are presented in Figure 2. The three calibrations all results in practically the same image quality. This can be seen when comparing images *a-c* in Figure 2. Further more the SMS accelerated images are of superior image quality when compared to the in-plane only accelerated image.

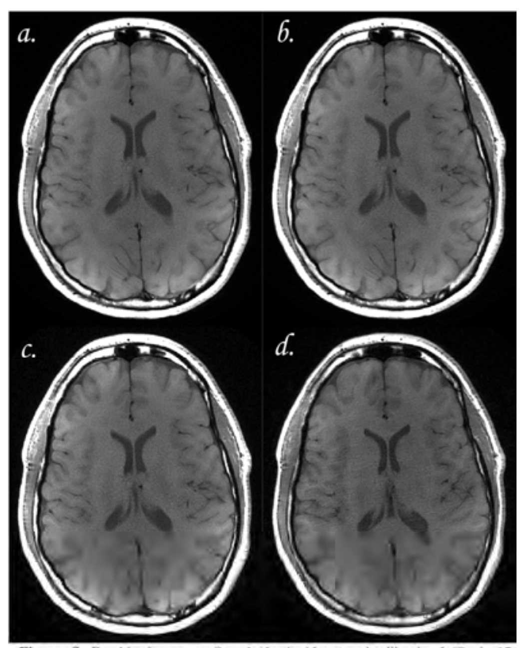

Figure 2. *Resulting images.* ***a:*** *Scan 1 (1 min 41 sec) and calibration 1 (6 min 45 sec).* ***b:*** *Scan 1 (1 min 41 sec) and calibration 2 (18 sec).* ***c:*** *Scan 1(1 min 41 sec) and calibration 3 (6 sec).* ***d:*** *Scan 2 (1 min 41 sec) and calibration 2 (18 sec).*

DISCUSSION AND CONCLUSION: Our work shows that PROPELLER scans can be accelerated with SMS in addition to in-plane acceleration, allowing almost 75 % scan time reduction. Our sequence is self-calibrating with a short calibration overhead that also has the advantage that the calibration data can be used in the reconstruction and thereby adding to the image quality. Even though our fully sampled first blade volume is not shorter than a separate 2D GRE scan, we believe a self-calibrating sequence has many workflow advantages in the clinical routine. Next, we plan to use cross-calibration for the in-plane unfolding, which means that the calibration scan can also be accelerated. The CAIPIRINHA FOV shift will spread out any potential slice-leakage in the same way that flow-artifacts are spread out in a standard PROPELLER image. This might enable even higher slice accelerations.

REFERENCES: [1] Larkman et al., JMRI 2001 [2] Moeller et al., MRM 2009 [3] Setsompop et al., MRM 2012 [4] Wang et al., ISMRM 2013 [5] Pipe, MRM 1999 [6] Griswold et al., MRM 2002 [7] Cauley et al., MRM 2013 [8] Holmes et al., 2012 [9] Breuer et al., MRM 2005 [10] Pauly et al., IEEE 1991 [11] Auerbach et al., MRM 2013