GRAPPA-accelerated short axis BLADE EPI for multi-shot diffusion weighted imaging

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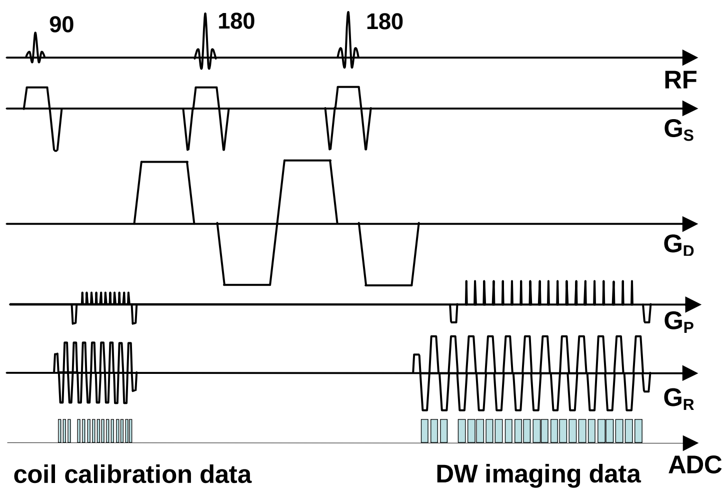
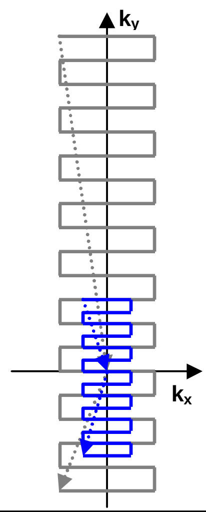
Introduction: Artifacts in diffusion weighted EPI (DW-EPI) can be significantly reduced by increasing the speed with which k-space is traversed along the phase-encoding (PE) direction. The traverse speed can be increased through parallel acquisition techniques (PAT) [1] and by shortening the time between two successive samples in the PE direction (echo spacing ES). ES can be decreased through the use of readout-mosaic-segmented EPI (RMS-EPI) [2] or short axis PROPELLER (SAP)-EPI [3]. The reasonable minimum ES is, however, limited by the slew rate of the gradient system and patient safety constraints. In this work the traverse speed of DW-SAP-EPI is further increased by PAT. In PAT-EPI the coil calibration data are usually acquired in a separate reference scan [4-6]. Sometimes this reference scan is segmented to adjust the traverse speed of the reference scan and the imaging scan and hence distortions [4, 6]. Both the separate reference scan and the segmentation prolong the measurement time and increase the sensitivity to motion and flow. In this work the coil calibration data and the imaging data for each blade are acquired after a single excitation pulse. The traverse speed during the acquisition of the sufficiently sampled calibration data is adjusted to the imaging scan by reducing the ES.

Methods: Figure 1 shows the sequence diagram. The coil calibration data are acquired by a first EPI echo train after the excitation pulse and before diffusion sensitization. Imaging data are acquired by a second EPI echo train after the double inversion diffusion sensitizing module [7]. The first echo train is sufficiently sampled; in the second echo train the distance between adjacent acquired k-space lines is increased by a factor A. The ES of the first echo train is ideally chosen A times shorter than the ES of the second echo train. The resulting k-space trajectory of the imaging echo train (grey) and the coil calibration echo train (blue) is illustrated in Fig. 2 for an acceleration factor A=2. At the beginning of each echo train three echoes are acquired without phase encoding for EPI ghost correction. The phase encoding prephasing gradient is switched parallel with the fourth readout gradient, which is not read out. This basic sequence is repeated with the direction of the blade rotated through the k-space center unless the total data set spans a circle in k-space. The data of each individual echo train are first ghost artefact corrected using the three navigator echoes and then readout regridded for ramp sampling correction. Next a blade wise GRAPPA reconstruction is performed to remove the aliasing of the DW imaging data. The GRAPPA weights are recalculated for every blade using solely the coil calibration data acquired after the same excitation pulse. The remainder of the BLADE reconstruction procedure, including 2D phase correction and optional motion correction, is unchanged. Fig. 3 shows DW-SAP volunteer images with acceleration factor A=1, 2, respectively (Matrix size 256; FOV = 230 mm; TR = 3000 ms; TE = minimum = 79/73 ms for A=1/2; slice thickness 4 mm; b=1000 s/mm^2 isotropic; readout length = 64; 16 blades per image; ETL=168/88 for A=1/2; ES = 500/250 us for imaging/coil calibration echo train). Scans were performed on a Siemens MAGNETOM Avanto 1.5 T scanner using the 12 channel head matrix coil.





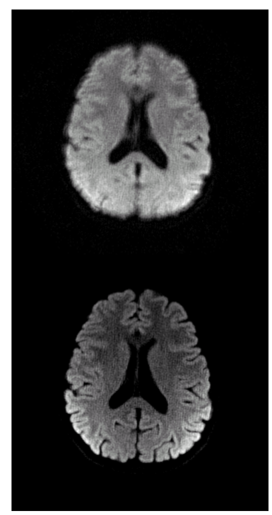


Figure1 (left): Sequence diagram. Figure 2 (center): k-space trajectories of a single blade for the imaging echo train (grey) and the coil calibration echo train (blue). Figure 3 (right): DW-SAP-EPI images acquired without (upper row) and with (bottom) parallel imaging.

Results and discussion: Distortions of individual blade images for A=1 translate in blurring after superposition of the blades. With parallel imaging distortions of the individual blade images are reduced due to the higher PE traverse speed and hence the blurring of the final image (Fig. 3).

Time effective, motion insensitive PAT acceleration of PROPELLER EPI (PAT-P-EPI) is not straightforward. In PAT-EPI the coil calibration data are usually acquired after a separate excitation pulse. In PAT-P-EPI the alignment of the data of a single reference scan to the individual blade direction prior to the parallel imaging reconstruction by means of a rotation [8] is error prone, since the rotation does not align the distorted directions and therefore might result in incomplete unaliasing or noise enhancement. Therefore the prescan method requires N_B (N_B = number of blades) additional TR intervals to acquire the coil calibration data. If a segmented reference scan is used the prescan time is further increased by a factor A. The method developed in this work, namely to acquire the coil calibration data between excitation pulse and the diffusion sensitization, does not increase the number of excitation pulses. For a given b-value the proposed method increases the time between the excitation pulse and the start of the imaging echo train by several milliseconds. However, the minimum TE of the accelerated scan is in general shorter since the greater traverse speed over- compensates the extra time needed to acquire the coil calibration data. Another novel aspect of the method is that it acquires the coil calibration data with reduced ES. Similar to segmentation this adjusts the traverse speed of the imaging and the coil calibration echo train (and hence distortions). In contrast to segmentation this does not increase the sensitivity to flow and motion. When GRAPPA is used the reduced number of samples in the readout direction is not a relevant disadvantage since the k_x-peripheral samples are usually discarded to limit the number of equation of the linear system to be solved and hence the computational weight. The time between the acquisition of the DW imaging data and the associated coil calibration data is a few tenths of ms. If a prescan is used this time interval is at least one TR interval. This makes the proposed method similarly motion insensitive as auto-calibration techniques, which cannot be used for EPI [4]. The method is therefore also of interest for PAT DW single shot EPI and PAT DW RMS-EPI.

References:

[1] Griswold et al. MRM 41:1236–1245 (1999); [2] Porter et al. ISMRM 2004, # 442; [3] Skare et al. MRM 55:1298-1307 (2006); [4] Griswold, NMR Biomed. 19:316-324 (2006); [5] Chuang et al. ISMRM 2004, # 535; [6] Holdsworth et al. ISMRM 2008, # 4, # 757; [7] Heid, ISMRM 2000, # 799; [8] Pipe, ISMRM 2003, # 66.