PERMEATE: High temporal resolution multi-echo/multi-slice dynamic susceptibility contrast perfusion imaging using GRAPPA EPI

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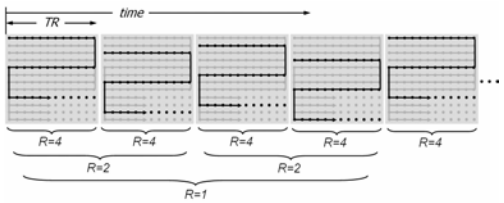

Figure 1 *– K-space acquisition pattern for the first 5 time points in a 4-shot dynamic series. Data are acquired in an interleaved fashion; the combination of 4 subsequent interleaves yields a fully sampled k-space (R=1) from which coil sensitivity maps or GRAPPA-weights can be determined. Maximum temporal resolution (Δt=TR) can be achieved with R=$n_{interleaves}$=4.*

Introduction. Dynamic susceptibility contrast (DSC)-based PWI is of great utility to determine "tissue-at-risk" in acute stroke patients. Together with DWI it can help triage patients who can potentially benefit from IV tPA treatment or mechanical thrombectomy. However, the DSC-based determination of hemodynamic parameters is often frustrated by the poor image quality that results from the use of single-shot EPI. Besides the geometric distortions and poor resolution associated with EPI scans, there can be profound problems in determining an arterial input function (AIF) accurately; however, the latter is mandatory to obtain the tissue residue function by deconvolution[1] and consequently affects the veracity of the hemodynamic parameters. Image quality issues arise mainly due to (i) strong T2*-induced blurring, (ii) susceptibility gradients emanating from the sinuses and the auditory canals adjacent to the brain, and (iii) the high concentration of contrast material in the vessels during bolus passage that causes clipping of the bolus maximum for typical echo times. Both multi-shot acquisitions and parallel imaging, such as GRAPPA[2] and SENSE[3], have been demonstrated to be extremely powerful methods to reduce geometric distortions and image blurring in echo planar imaging (EPI). Previous attempts at using multi-shot EPI with DSC have met with limited success due to the need for high temporal localization in the k-space acquisition, which is overcome here with a novel approach using parallel imaging for temporal localization. This study minimizes the problems associated with single-shot EPI in DSC-PWI by using multi-shot parallel imaging in combination with a multi-slice multi-echo acquisition[4,5,6] dubbed PERMEATE (PERfusion with Multi-Echo and Accelerated Temporal Enhancement) EPI that allows perfusion and pure T2* mapping at a very high temporal resolution.

Materials and Methods. A multi-slice DSC-PWI pulse sequence was developed with interleaved multi-shot multi-echo echo-planar readouts. Each interleaf was reconstructed separately using a GRAPPA based algorithm[7]. Here, GRAPPA weights were determined by combining all interleaves to a fully sampled *k*-space (Fig. 1). Each shot was then reconstructed separately using the determined GRAPPA weights, forming a quasi-single shot dataset for each TR, with effective distortions and blurring of an multi-shot acquisition. The minimum temporal resolution of the dynamic acquisition is determined by *TR*. During each *TR*, *n* echoes per slice are obtained, allowing calculation of T2* on a per pixel basis by means of a magnitude weighted non-linear fit. The total number of slices acquired per *TR* is determined by *n* and *TR*. In three volunteers and nine patients that presented with stroke-like symptoms the new sequence and reconstruction were tested after informed consent was obtained using a 1.5T scanner (GE Signa LX, 12.0) with high performance gradients (40 mT/m, *SR*=150) using either a dedicated 8-channel head or neurovascular array coil (both MRI Devices: *FOV*=24cm; *slice/gap*=5/1mm; *slices*=15; *TR*=1.125ms; matrix 96x96; α=70°; NEX=1; timepoints=120. Comparative evaluations were performed between *n*=3 and 4 interleaved scans (= reduction factor *R* of 3 and 4). For the *R*=3 case 3 echoes (TE_1…TE_3=13.8, 31.6, 49.4ms) were measured, while 4 echoes (TE_1…TE_4=12.4, 27.3, 42.2, 57.1ms) could be acquired in the *R*=4 case due to the shortened EPI readout. After 5 baseline scans, 20ml Magnevist (Berlex, Princeton, NJ) was injected at a rate of 4ml/s followed by a 20ml saline flush using a dual-piston power injector (Spectris, Medrad, Indianola, PA).

Results. Fig. 2 shows a side-by-side comparison of DSC-PWI PERMEATE scans performed with R=3 and 4; the image quality is remarkably better when compared with conventional single-echo/single-shot EPI. With the parameters chosen for this study 15 slices per TR could be acquired that allowed satisfying brain coverage. According to an increasing g-factor, R=4 scans were slightly noisier than R=3 but no residual aliasing artifacts were noticeable for both series. Fig. 3 shows 1st, 2nd, and 4th echo for the baseline phase and during bolus passage using an R=4 PERMEATE scan. When compared to conventional single-shot EPI, the PERMEATE approach allowed a significant reduction of distortions from off-resonant spins. Specifically, the regions adjacent to sinuses and the auditory canals were well preserved. The major intracranial vessels can be clearly delineated and the typical T2*-"vessel blooming" effect during bolus passage can be avoided. Due to the higher bandwidth per pixel, the displacement of voxels containing large amounts of contrast material is not noticeable. Since PERMEATE acquires multiple echoes that allow T2* measurements, confounding T1 relaxation effects from leaky vessels or the very high temporal resolution can be avoided and thus improves the mapping of hemodynamic parameters (Fig. 4).

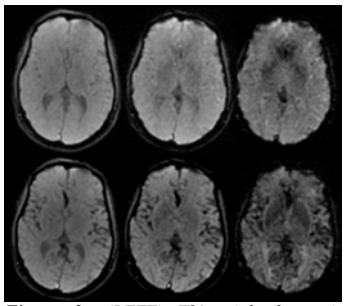

Figure 3 *– (LEFT) T2*-weighted quasi-single-shot EPI with R=4. The top row shows the first, second and fourth echo (TE_1, TE_2, TE_4=12, 27, 57ms) whereas the bottom row shows three echo images during the peak of the bolus passage.*

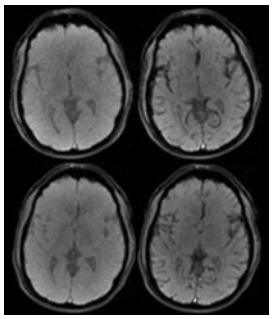

Figure 2 *– (LEFT): T2*-weighted quasi-single-shot EPI with R=4 (top row, TE_1=12.4ms) and R=3 (bottom row, TE_1=13.8ms). The first column shows one out of 5 baseline scans. (RIGHT) The maximum contrast change during the bolus passage. The GRAPPA calibration information is obtained from 3 or 4 interleaves. Due to the higher acceleration factor the individual R=4 are slightly noisier but the shorter readout afford an extra echo. Despite the high acceleration both data sets are of high quality without noticeable reconstruction artifacts.*

Conclusion. An interleaved multi-echo approach for DSC-PWI combined with k-space based reconstruction of individual interleaves provides major advantages and obvious quality improvements over conventional T2*-weighted single-shot EPI. Further, prior studies[4-6] used only two echoes from which it is difficult to obtain T2*, especially in highly saturated vessels. Parallel imaging was used for distortion reduction together with the multi-echo quantitative T2* approach, giving an effective temporal resolution of only 1s, which allows much better assessment of hemodynamical changes. The auto-calibration approach also reduced the motion sensitivity of the sequence, which can be otherwise problematic in stroke patients. Despite the SNR reduction introduced by parallel imaging, the overall SNR of the quantification was not excessively compromised because quasi-continuous measurements were taken over 3-4 echoes (SNR ~ $t_{acq\_total}^{0.5}$) for each time point and each slice.

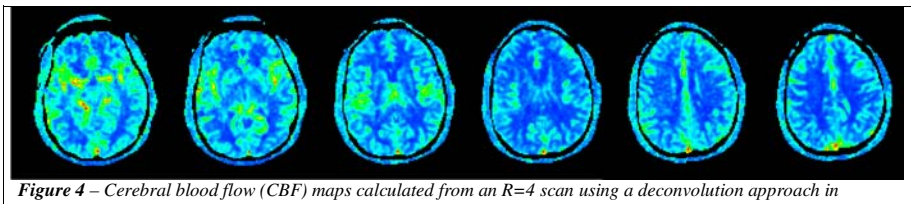

Figure 4 *– Cerebral blood flow (CBF) maps calculated from an R=4 scan using a deconvolution approach in combination with automatic AIF detection. Significantly less vessel blooming is apparent and gray/white matter can be very well delineated.*

References. [1]Ostergaard L, *et al*. MRM 36: 715-25, 1996. [2]Griswold M, *et al*. MRM 47: 1202-10, 2002; [3]Pruessmann K, *et al*. MRM 42: 952-62, 1999. [4]Vonken EJ, *et al*. JMRI 10:109-117, 1999. [5]Reishofer G, *et al*. 10th ISMRM, 2002; [6]Bammer R, *et al* 12th ISMRM, 2004, p. 362. [7]Skare S, *et al* 13th ISMRM, 2005, p. 2422. **Acknowledgements.** This work was supported in part by the NIH (1R01EB002771), the Center of Advanced MR Technology at Stanford (P41RR09784), Lucas Foundation, and Oak Foundation.