Interleaved Dual-Echo Spiral-Out-Spiral-In DSC Imaging With Generalized SENSE

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Introduction: T2*-driven dynamic susceptibility contrast (DSC)-based PWI is most often performed using single-shot EPI readout. However, the determination of hemodynamic parameters, such as cerebral blood flow, is challenged by technical difficulties: Besides the strong geometric distortions and poor resolution of EPI scans, there are considerable problems in determining accurately an arterial input function (AIF), which is mandatory for deconvolving the tissue response signal[1]. Using single-shot EPI, large feeding vessels, such as the internal carotid arteries (ICA) or branches of the major cerebral arteries, are frequently difficult to depict and can be contaminated by tissue partial volume averaging. This is mainly due to (i) strong T2*-induced blurring, (ii) susceptibility gradients emanating from the sinuses and (iii) the auditory canals adjacent to the brain, and the high concentration of contrast material during bolus passage that causes clipping of the bolus maximum due to the lack of dynamic range and low SNR. We have minimized these problems by using a dual-echo acquisition in combination with a multi-shot sensitivity-encoded variable-density interleaved spiral imaging approach.

Methods: A multi-slice DSC-PWI pulse sequence was implemented with interleaved variable-density spiral readout gradients[2] where the center of k-space was sampled with sufficient density for estimation of the coil sensitivities and for phase-navigation (Fig 1). For high scan efficiency, a spiral-out/in trajectory was used (Fig 2). To avoid hysteresis effects, the spiral-out trajectory (early echo) was the time-reversed version of the spiral-in waveform. This design gives a minimum TE for the early echo (TE_1=6ms) (spiral-out) while producing enough T2*-effect in the feeding arteries without severe geometric distortions or saturation effects[3]. The spiral-in trajectory guarantees that the image formation is finished at the late echo time (TE_2=55ms), providing the most effective readout while still sufficiently sensitive to detect the subtle contrast passage in deep white matter. Calculating ΔR2* from the two echoes helps to avoid T1-effects.

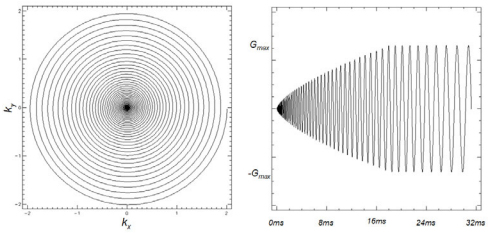

Figure 1 – Variable-density spiral design. *(left) One interleave of a 4 interleaf VD spiral scan. The k-space coverage at the origin is considerable higher than at the outer portion of k-space. (right) Corresponding gradient-waveform that is played out on the x-gradient coil. At the beginning, the gradient-waveform starts in the slew-rate limited mode. After it reaches the maximum amplitude (determined by the FOV and the maximum available sampling rate) it changes to the gradient-amplitude limited regime.*

All MR scans were performed on a 1.5T MRI scanner (Signa CV/i, GE Medical Systems, Waukesha, WI) fitted with high performance gradients (40 mT/m, t_{rise} = 268μs) and a four-element phased array coil. All procedures were approved by the institutional review board of our institution. The dual-echo spiral sequence was implemented using the following parameters: FOV=22cm, 5mm/1mm section thickness/gap, 20 slices, $TR/TE_1/TE_2/\alpha$ = 500ms/6ms/55ms/45°, reconstruction matrix 128 x 128, bandwidth ±100 kHz, four interleaves, dynamic scan resolution = 2 s, and 80 time points. To reduce geometric distortions from off-resonant spins, a SENSE reduction factor of 2.0 was introduced along the radial dimension of the trajectory. An iterative generalized SENSE (GSENSE) algorithm[4] was used to reconstruct the undersampled spiral trajectories. Coil sensitivity information was retrieved from the center portion of each interleave.

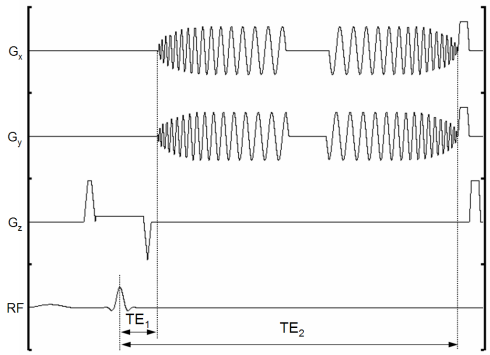

Figure 2 (left) – Interleaved dual-echo spiral-out-spiral-in imaging pulse sequence. *An interleaved spiral-out scan guarantees an early echo to improve the measurement of AIF in ICA, MCA, or ACA. The spiral-in part enables the most compact acquisition since the image formation is finished when the second echo is acquired. For each spiral, a SENSE reduction factor of 2.0 is used along the radial dimension.*

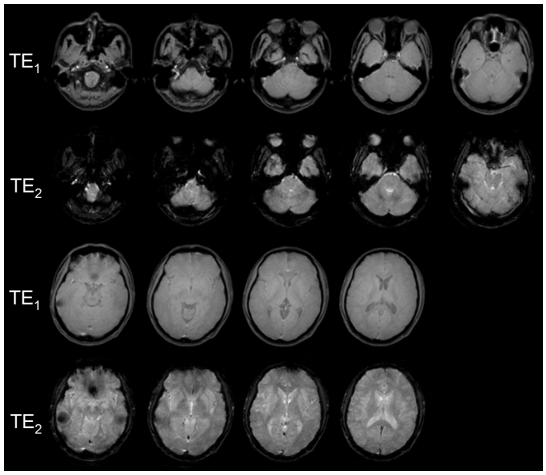

Figure 3 (right) – Interleaved dual-echo spiral-out-spiral-In scan in a healthy volunteer. *The pulse sequence was applied at lower levels of the brain to demonstrate its great potential for AIF measurements without significant distortions. At the early echo image all major vessels could be clearly delineated and show less contamination from partial volume effects due to reduced blurring and smaller voxel size. The late echo provides sufficient T2*-sensitivity to detect signal changes in the parenchymal microvasculature during bolus passage. Overall, the interleaved regime significantly reduced geometric distortions around areas with large susceptibility gradients.*

Results: Spiral MRI uses the available gradient power effectively by distributing the load to at least two gradient channels. The variable density approach uses increased sampling near to the k-space origin, which enables phase navigation and auto-calibration (GSENSE) capabilities; this minimizes motion sensitivity of the sequence and the SENSE reconstruction process. Figure 3 shows a series of images that were acquired using the new dual-echo spiral sequence. The lower portion of the head was scanned to demonstrate the robustness against susceptibility distortions. When compared to conventional single-shot EPI, the interleaved spiral approach combined with GSENSE allowed a significant reduction of distortions from off-resonant spins. Specifically, the regions adjacent to sinuses and the auditory canals were well preserved. The large feeding vessels can be clearly delineated and the typical T2*-"blooming" effect during bolus passage can be avoided. In contrast to single-shot EPI, where pixel shifts (of voxels containing large amounts of Gd) along the phase-encode direction due to the low bandwidth per pixel can be quite significant and may lead to perturbed AIF shapes, the interleaved spiral approach is much more immune against such distortions. Due to the short readouts and the fact that the acquisition is finished almost immediately after the second echo (Fig. 2), the sequence is very efficient and allows full brain coverage.

Conclusion: The interleaved dual-echo spiral-out-spiral-in approach combined with GSENSE provides significantly improved image quality, better spatial resolution, and, hence, better vessel conspicuity. These improvements allow one to perform more reliable measurements of the AIF, while still being sufficiently sensitive to small T2*-changes in white matter. In addition, quantitative ΔR2*-maps, calculated from the two echoes, account for T1-effects, which is important especially at shorter TRs and for time points after the initial bolus passage. Future work will explore the benefits in PWI analyses from additionally using the critically sampled center portion of k-space to provide dynamic series with higher temporal resolution (500ms) at the cost of spatial definition.

References: [1]Ostergaard L, *et al*. MRM 36: 715-25, 1996. [2]Kim DH, *et al*. MRM 50: 214-9. [3]Vonken EJ, *et al*. JMRI 10:109-117, 1999. [4]Pruessmann KP, *et al*. MRM 46: 638-51.

Acknowledgements: This work was supported in part by the NIH (1R01EB002771, 1R01NS35959, 1R01NS39325), the Center of Advanced MR Technology at Stanford (P41RR09784), and the Lucas Foundation.