High Resolution Dynamic Susceptibility Contrast Perfusion Imaging Using Multi-Echo Spirals and Temporal Compressed Sensing-Based Reconstruction

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Introduction: Dynamic susceptibility contrast (DSC) perfusion weighted MRI (PWI) is a widely used approach for measuring haemodynamic perfusion parameters, such as cerebral blood volume/flow (CBV/CBF) and mean transit time (MTT). These quantitative maps reveal clinically relevant information for treatment of stroke and brain tumor patients that may not be obtained with regular MRI exams. The perfusion parameters are derived from changes in signal-time course of injected contrast agent, with most important information obtained over a span of 10-20 sec [1], necessitating very rapid time-resolved imaging, which requires tradeoffs with spatial resolution (typically,128x128 in-plane). While more accurate models for parameter estimation have been developed, the available imaging techniques often are unable to provide sufficient input to models (e.g., limited resolution reduces accuracy of arterial input function (AIF) calculation). Traditionally used single shot echo-planar imaging (EPI) decreases spatial resolution further due to T_2^* signal decay during long readout accompanied by significant geometric distortions. Segmented acquisition at multiple echo times and subsequent R_2^* mapping for quantification [1] can minimize some EPI artifacts and provide insensitivity to T_1 effects at the expense of further reduction of temporal and spatial resolution. In this work, we present a novel approach to high resolution DSC PWI, which utilizes a combination of compressed sensing (CS)-type reconstruction with efficient multi-echo spiral acquisition.

Methods: The rationale for trajectory and data reconstruction design as dictated by the need for rapid acquisition of accelerated data (for high spatial/temporal resolution) at multiple echo times is explained in detail below. *Reconstruction Approach:* Source image reconstruction from highly undersampled data cannot be achieved by standard approaches alone, e.g., parallel imaging (pMRI), which suffers from residual aliasing artifacts and resolution/SNR loss at high accelerations *R*. Typically, regularization is done by adding a penalty term on the size of signal itself or its transform as measured by either noise-optimizing l_2 norm or sparsity promoting, CS-type l_1 norm ($\|x\|_{l_p} = (\sum|x_n|^p)^{1/p}$). Single image regularization can provide only limited improvement, while exploiting inter-image dependencies in a time series increases acceleration capabilities. We note that, for each pixel, time course of contrast propagation is described by a smoothly varying (differentiable) curve. As demonstrated previously in the context of contrast-enhanced angiography [2] and T_1 relaxometry [3], such image series can be efficiently sparsified by second derivative operator in temporal dimension (Δ_t^2). The time series of images is therefore reconstructed by the Δ_t^2-CS technique [3] solving $f = \arg\min_f\left(\|Ef - b\|_2^2 + \lambda\|\Delta_t^2 f\|_{l_1}\right)$, where f is the underlying signal vector, E is encoding matrix for all time frames, b is the measured *k*-space data, and λ is regularization parameter. *Data Sampling:* We designed a multi-echo, interleaved spiral acquisition with bit-reversed scheduling in both echo time and temporal dimensions (Fig. 1). Such acquisition provides efficient k-space coverage with high degree of incoherency enabling separate application of the Δ_t^2-CS approach to individual echo-time image series. *In-vivo Studies:* Following informed consent according to the IRB at our institution, human subjects with relapsing-remitting multiple sclerosis disease were scanned on a 3.0T scanner (Discovery ™ MR750, GE Healthcare, Waukesha, WI) with an 8-channel head coil. A double-dose bolus injection (0.2 mM/kg of gadodiamide, Omniscan, GE Healthcare) was performed at a rate of 4 ml/s 30 s into the scan. The segmented eight-interleaf, four-echo time spiral sequence (TR=1.35 s, TE=3.2, 15.22, 27.24, 39.26 ms) was acquired for 20 consecutive 5 mm slices with in-plane resolution 1.375x1.375 mm^2. Additionally, EPI images were acquired (ASSET factor 2, 0.1 mM/kg of Gd-DTPA, 128x128, TE/TR=0.045/1.5 s, 20 (5 mm) slices). *Data Processing:* Temporal image series were reconstructed separately for each TE with prior phase correction of each spiral interleaf based on self-navigation feature of multi-shot spiral imaging [5]. For each time point, R_2^* maps were obtained by nonlinear fit of all four TE images to the model. The obtained source images were processed with Jim software package (Xinapse Systems Ltd, Aldwincle, UK) to determine AIF and yield haemodynamic perfusion parameters following the method of [5].

Figure 1. Acquisition order of each of the four enumerated TEs (shown in different colors for the first 3 out of 8 excitations). Unacquired spiral interleaves shown with dotted lines.

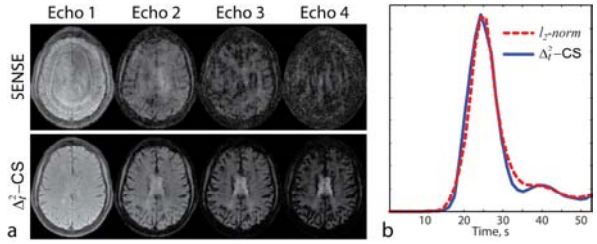

Figure 2. The proposed method performance compared to peer techniques. a) Comparison of source images obtained with SENSE and our method at peak arterial frame. b) AIF obtained with L1 and L2 norm regularization.

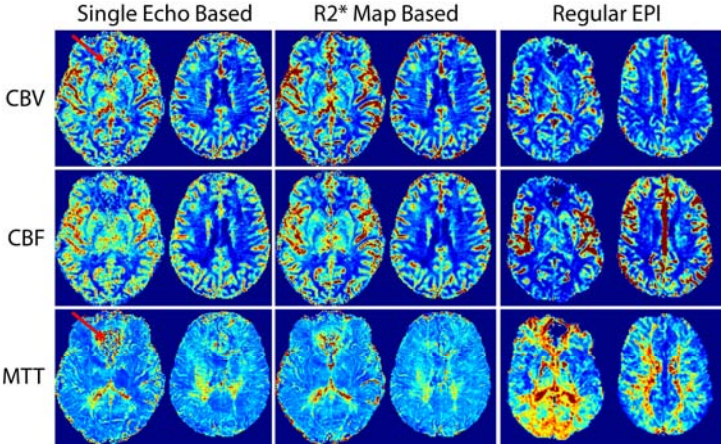

Figure 3. Comparison of PWI maps obtained from single echo images, R2* maps, and EPI.

Results: Reconstruction results from all four TEs clearly illustrate (Fig. 2a) that pMRI [6] alone cannot support the target acceleration (R=8) with a given number of coil receivers, while Δ_t^2-CS efficiently suppresses aliasing artifacts/provides high SNR for all TEs. AIF from l_1-norm based Δ_t^2-CS has a sharper shape and well-defined recirculation, which are misrepresented with standard quadratic (l_2-norm) regularization. Figure 3 compares PWI maps obtained from individual echo images and R_2^* maps, and EPI images from similar anatomical locations. Both single echo time and R_2^*-based PWI maps show clear advantage over EPI both in terms of resolution and geometric distortions and signal drop. Note the improved gray-white distinction and ability to resolve deep medullary veins provided by the CS-based method compared to EPI. Also, note improved SNR and reduced artifacts with R_2^* based PWI compared to single echo estimation (red arrows).

Discussion and Conclusions: High resolution DSC PWI is highly desired clinically for improved diagnosis and treatment. However, inherent limitations of the existing imaging methodology restrict the attainable temporal and spatial resolutions. In this work, we proposed a combination of novel multi-echo spiral acquisition with advanced CS-type constrained reconstruction, which demonstrated significant improvement in image quality and resolution, namely, a nominal 2.7 times decrease of pixel size and whole head coverage compared to current state-of-art DSC-PWI [1] without compromising temporal resolution. The actual resolution may be higher due to minimized signal blurring due to shorter readout than in standard EPI. Our technique also features R_2^* mapping for PWI quantification, which was shown to avoid T_1-related signal bias in vessels and less sensitive to T_2^* saturation at peak arterial frame [1,7]. Four echo times provide sufficient dynamic range to detect concentration changes in different tissue types.

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