Accelerated Spiral Chemical Shift Imaging with Compressed Sensing

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Introduction: Volumetric phase-encoded (PE) chemical shift imaging (CSI), suffers from intrinsically long acquisition times. To combat this limitation, approaches such as parallel imaging and efficient encoding with echo-planar [1] or spiral trajectories [2] have successfully been deployed for spectroscopic imaging with much higher voxel count than is feasible with conventional phase encoding. Recently, compressed sensing (CS) [3] has gained much attention in MRI and has been extensively used to accelerate acquisitions for many different applications, including CSI [4].

The goal of this work is to further improve the encoding efficiency of CSI with spiral readouts by the incorporation of CS. General undersampling patterns with incoherent aliasing can impose constraints on the k-space trajectory design (in terms of maximum gradient's amplitude and slew rate), and require non-uniform Fourier transform implementations. In this work we demonstrate a sub-class of undersampling in spiral CSI with non-uniform k_f axis sampling, by sampling along spiral k-space trajectories of variable duration during the long acquisition window. For a given voxel size and spectral bandwidth (BW), the combined spiral-CS CSI provided acceptable spectral quality, and a reduction in acquisition times by a factor of 3 when compared to the original spiral CSI encoding. The feasibility of the methods was demonstrated *in vivo*.

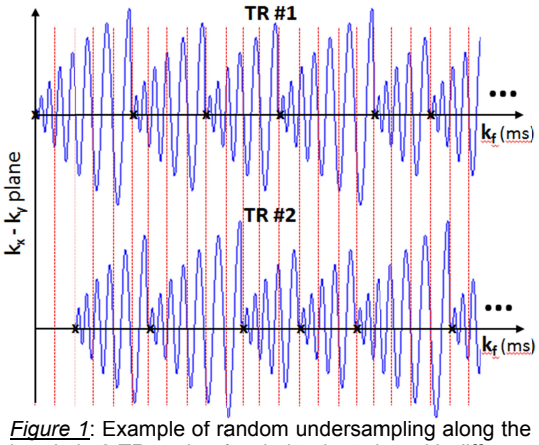

Figure 1: Example of random undersampling along the k_f axis in 2 TRs using 3 spiral trajectories with different voxel sizes (i.e. different durations). The spacing between the vertical red dotted lines is Δt = 1/(spectral BW), while the black crosses ('**x**') depict the sampled k_f points (12/24 in the time window shown).

Methods: All experiments were performed on a 3T Tim Trio Siemens scanner (Siemens Healthcare, Erlangen, Germany), using a 32-ch receive array. PRESS-box excitation was placed entirely within the brain (8x9x1cm^3, TE = 144ms, TR = 2s), 6 OVS pulses were used to suppress subcutaneous lipids, and CHESS was used for water suppression. The combined spiral-CS CSI acquisitions were compared to 0.5cc, single-slice conventional spiral CSI readouts (2 angular interleaves, 6 temporal interleaves, N_{avg}=18, t_{acq}=7.2min, FOV_{xy}=20cm, and spectral BW=1.2KHz). For the spiral-CS CSI acquisitions, three different spiral trajectories with voxel sizes of 0.92cc, 0.68cc and 0.5cc were designed, with durations of 2.5ms, 3.33ms and 4.17ms, respectively. Since these durations are integer multiple of 1/(spectral BW), the randomized undersampling along the k_f axis was achieved by consequently playing each of the three trajectories chosen at random, one after the other. Since the mean length of the three spiral trajectories was 3.33ms = 4/(spectral BW), roughly 1/4 of the k_f samples were sampled. For more robust reconstruction, data were collected during an additional TR period, this time randomly selecting which of the three trajectories to play at the remaining non-sampled k_f samples. Fig 1 depicts a representative sampling of the (k_x,k_y,k_f) space. Therefore, in terms of total scan times, *the spiral-CS CSI readouts achieved a reduction factor of 3 in acquisition time (t_{acq_cs} = 2.4min)* compared to the original 0.5cc spiral CSI readout by reducing the number of temporal interleaves from 6 to 2.

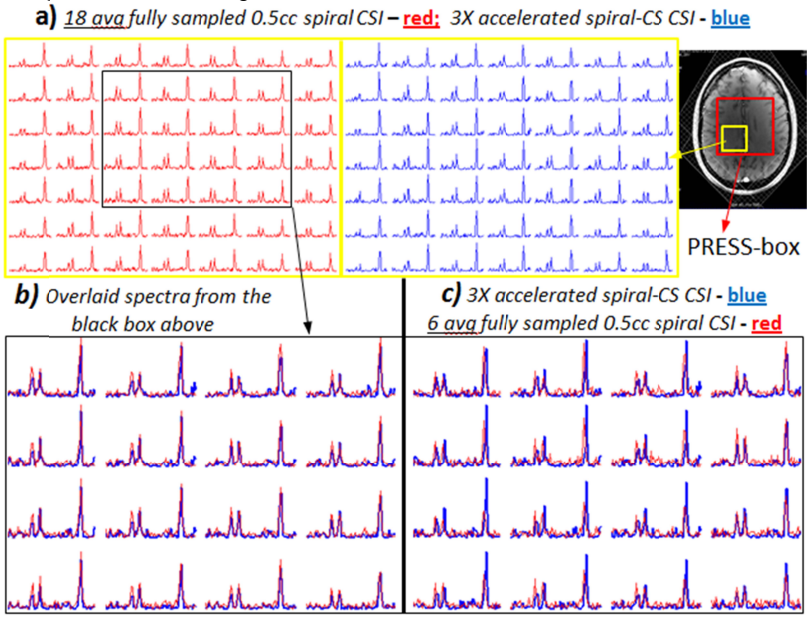

Fig 2: Side-by-side (a) and overlaid (b) plot comparisons between the 0.5cc fully sampled spiral CSI and 3X accelerated spiral-CS CSI acquisitions; The overlaid plots in (c) compare the latter spectra but now with time-matched fully sampled 0.5cc spiral CSI, where the hit in SNR is apparent.

The spirally CSI data were 2X-gridded onto a Cartesian grid using a Kaiser-Bessel window, with matrix size (k_x,k_y,k_f) = (32,32,384). Compared to the data acquired with the conventional 0.5cc spiral CSI scan, the spiral-CS CSI data sampled 39% of $(k_x,k_y.k_f)$ (reduction factor of R = 2.56), out of which ~48% were along the k_f axis (188 out of 384 time points were randomly sampled), and ~52% were in k_x-k_y space (the higher frequency k-space points of 0.92cc and 0.68cc spiral lobes). The undersampled data were reconstructed using $\ell 1$ norm penalty on the spatial gradients of the CSI image in all three dimensions (x,y,f) via the FOCUSS algorithm [5].

Results and Discussion: The feasibility of the proposed 3X accelerated spiral-CS CSI acquisitions was tested *in vivo*. Fig 2a shows side-by-side comparisons of spectra from the fully sampled, single-slice 0.5cc spiral CSI scan (N_{avg}=18, t_{acq}=7.2min) shown in red, and the accelerated spiral-CS CSI acquisition (t_{acq}=2.4min) shown in blue. Fig 2b presents overlays of 4x4 grid of spectra from Fig 2a, to demonstrate the similarity of the two data sets. Further, in Fig. 2c, the red color spectra derive from a fully sampled 0.5cc spiral CSI scan, but with a reduced acquisition time (and therefore reduced SNR) to match the proposed spiral-CS CSI imaging time (N_{avg}=6, t_{acq}=2.4min).

Conclusion: We have combined the time-efficient spiral CSI algorithm with compress sensing (CS) in order to further increase the encoding efficiency in CSI, with acceptable *in vivo* spectral quality.

Support: NIH: R01EB007942, R01EB006847, NCRR P41RR14075; Siemens Healthcare, Erlangen; Siemens Medical Solutions USA; Siemens-MIT Alliance. **References:** [1] Posse et al., MRM(37), p.858-65,1997; [2] Adalsteinsson et al., MRM(42), p.314-23,1999; [3] Lustig et al., MRM(58), p.1182-1195, 2007; [4] Hu et al, JMR(192), p.258-264, 2008; [5] Gorodnitsky et al, IEEE T.Sig.Proc,1997