# Investigating the quantitative fidelity of prospectively undersampled chemical shift imaging with compressed sensing and parallel imaging reconstruction

Kieren G Hollingsworth[1] and David M Higgins[2]

[1]*Institute of Cellular Medicine, Newcastle University, Newcastle upon Tyne, Tyne and Wear, United Kingdom,* [2]*Philips Healthcare, Guildford, Surrey, United Kingdom*

**Target audience** Physicists interested in accelerated acquisition techniques and clinicians interested in water-fat separation.

**Purpose** Since the first articles applying compressed sensing to MR imaging [1,2], there has been much interest in the use of undersampled acquisition of MR data with constrained non-linear reconstruction to produce the image. Such acquisitions have the potential to save expensive scanner time and improve patient compliance, and would be particularly useful for speeding up lengthy acquisitions of $T_1$, $T_2$ and the measurement fat fractions derived from chemical shift imaging. This last measure is particularly useful in assessing longitudinal change in fatty liver and in muscular dystrophy. A number of abstracts have shown qualitatively promising reconstructions combining compressed sensing and parallel imaging [3,4], but there have been few quantitative analyses. This study optimizes and assesses the quality of reconstruction of chemical shift separated images from prospectively undersampled 3D data using a custom pulse sequence compared to fully sampled data in a volunteer to determine any systematic or random error in the fat fraction introduced by the undersampling.

**Methods** Fully-sampled and prospectively undersampled data were acquired on a 3T Philips Achieva using a custom 3D gradient echo pulse program with Poisson disk undersampling [5] with a central fully-sampled region of 20 x 13 for coil calibration: three prospective undersamplings were acquired, with net data reductions of 3.5x, 4.9x and 6.2x respectively (Figure 1a). A 6 channel cardiac coil (Philips, Best) was used for signal reception and raw data was acquired separately for each coil element. The matrix size used was 128x128x48 yielding a voxel resolution of 2.5 x 1.48 x 5mm, and three gradient echoes were acquired for IDEAL reconstruction TR/TE/FA = 10ms/4.40,5.18,5.96ms/3°. The fully sampled acquisition time was 184s and the undersampled acquisition times were 53s, 38s and 30s respectively. A healthy subject was recruited under local ethical approval and informed consent. The imaging block was centred over the mid-calf and acquired data for both legs with the read direction left-right. The data were reconstructed taking advantage of both parallel imaging and compressed sensing using the CS-SPIRiT approach as advocated in [2]. In this work the well-established Daubechie 4,4 wavelet was used as the sparsifying transform. The SPIRiT algorithm and the sparsifying transform were applied to recover the images using,

$$\min_x \|Dx - y\|^2 + \lambda_1 \|(G - I)x\|^2 + \lambda_2 \|\Psi\{IFFT(x)\}\|_1,$$

where y contains the acquired undersampled k-space (for each coil), x is the reconstructed k-space, G is the SPIRiT operator for the coil calibration kernels [2], I is the identity matrix, D maps the sampled k-space locations only in x to the acquired data, and $\Psi$ is the sparsifying transform (Daubechie 4 wavelets). 60 iterations were used with $\lambda_1$ = 0.01 and $\lambda_2$ = {0.05, 0.025, 0.01, 0.01, 0.0075, 0.0050, 0.0010, 0.0005}. A 5x5 SPIRiT kernel was used. The optimal regularization constants were determined by establishing the mean error per pixel in the magnitude and phase of the reconstructed undersampled images compared to the fully sampled image, subject to an intensity threshold mask on the fully-sampled image to exclude areas of low signal and of noise. *Chemical shift separation:* The chemical shift separation was performed using the graphcut algorithm of Hernando [6] in the water-fat separation toolbox [7]. A 6-component fixed spectrum model was used to represent fat resonances with frequencies {-3.80,-3.40,-2.60,-1.94,-0.39,0.60 ppm} and amplitudes {0.087,0.693,0.128,0.004,0.039,0.048} with respect to water. *Regions of interest*: Using ImageJ (NIH), regions of interest were drawn on 10 axial sections at mid-calf on the left leg: the areas delineated at these levels were the tibialis anterior, soleus, medial and lateral gastrocnemius and the bone marrow of the tibia. The mean fat fraction was evaluated and averaged for each anatomical area on the fully sampled reconstruction and on the undersampled reconstruction. In addition, all 50 pairs of data were evaluated to derive Bland-Altman parameters of bias and reproducibility.

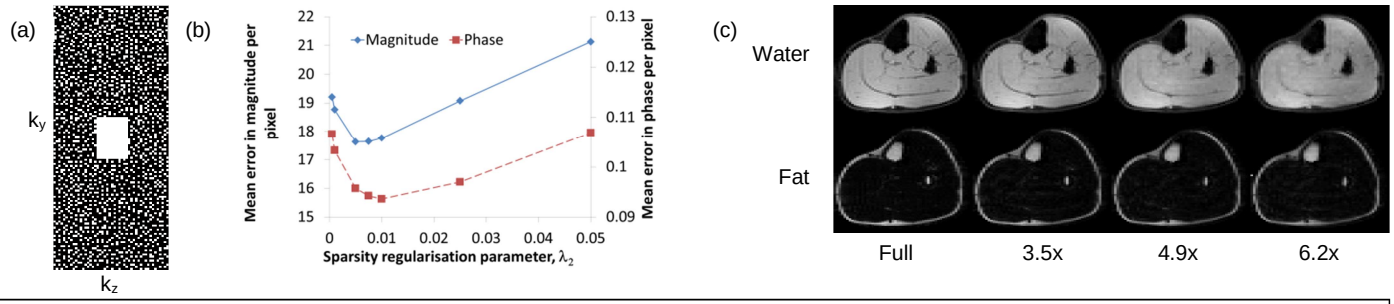


**Figure 1** : (a) Poisson disk 3.5x undersampling pattern, (b) the sparsity regularization parameter, $\lambda_2$, plotted against the mean error per pixel in the magnitude and phase of the 3.5x undersampled reconstruction compared to the full reconstruction, (c) comparison of the reconstructed separated water and fat images from full, 3.5x, 4.9x and 6.2x showing good preservation of anatomical features.

**Results** Figure 1b shows the result for the optimal regularization parameter that minimizes the error in the 3.5x data reconstruction is slightly different for magnitude and phase errors: $\lambda_2$ = 0.0075, 0.025 and 0.025 are the compromise values for 3.5x, 4.9x and 6.2x undersampling respectively between the optima for magnitude and phase error which give the best balance between oversmoothing and noise breakthrough. Figure 1c shows the reconstructed water and fat images. Table 1 summarises the comparison of the fully sampled and undersampled results for the regions of interest. Taken as a whole, the Bland-Altman analysis shows no net bias between the two fat measurements: the mean difference (bias) between the two measures is 0.06%, 0.13% and 0.20% for the 3.5x, 4.9x and 6.2x undersampling respectively (95% CI: [-1.20%,1.32%],[-1.20%,1.49%] and [-1.47%,1.87%] which are not clinically significant and a reproducibility of 1.26%, 1.33% and 1.67% between the undersampled and fully sampled reconstructions. However, paired t-testing within the individual ROIs reveals there are no systematic differences in fat fraction measured within the ROIs. Figure 1c shows that anatomical detail is well preserved with undersampling, with some loss of detail at 6.2x undersampling.

**Table 1 :** Mean fat fraction recorded from leg regions of interest

| Anatomical area | Full | 3.5x CS-PI | 4.9x CS-PI | 6.2x CS-PI |
|---|---|---|---|---|
| Tibialis anterior | 2.8 ± 0.1 | 2.8 ± 0.4 | 2.9 ± 0.3 | 3.0 ± 0.6 |
| Soleus | 4.1 ± 0.2 | 3.8 ± 0.2 | 4.2 ± 0.5 | 4.3 ± 0.4 |
| Medial gastrocnemius | 3.5 ± 0.3 | 3.6 ± 0.4 | 3.9 ± 0.4 | 3.4 ± 0.7 |
| Lateral gastrocnemius | 3.8 ± 0.2 | 3.9 ± 0.9 | 4.1 ± 0.7 | 4.1 ± 0.7 |
| Bone marrow | 97.6 ± 0.9 | 98.0 ± 1.5 | 97.3 ± 1.3 | 97.9 ± 1.0 |

**Discussion/Conclusions** The fidelity of quantitative chemical shift separation using Poisson Disk undersampling and reconstruction combining parallel imaging and compressed sensing is very good, and likely to prove acceptable for clinical studies. Further assessments in pathological cases and phantom objects are now underway. In principle, given the arrangement of coil elements, the most efficient direction in which to omit phase encodes for parallel imaging is to have the phase-slice encoding plane in axial orientation, with the read direction in the foot head direction, though the number of phase encodes then required left-right to produce an anatomically acceptable image increases the acquisition time by a factor 2-3 if the undersampling cannot be increased proportionately. The relative efficiency of the two arrangements is the subject of further work.

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**References :** [1] Lustig *Magn. Res. Med.* 2007; 58:1182, [2] Lustig *Magn. Res. Med.* 2010; 64: 457, [3] Sharma *Magn. Res. Med.* 2012 [Epub], [4] Wiens *Proc. ISMRM* 2012;20:7, [5] Cook *ACM Trans Graph* 1986;5:51, [6] Hernando *Magn. Res. Med.* 2010; 63: 79, [7] Hu *Magn. Res. Med.* 2012; 68:378.