Optimal Spread Spectrum for Enhanced Multi-Receive Compressed Sensing MRI

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INTRODUCTION: Compressed Sensing-MRI (CS-MRI) has proven to be effective in reducing data acquisition time and preserving image quality of MRI [1]. The reconstruction quality of CS is highly dependent on the level of signal (image) sparsity as well as the level of incoherent measurements [1]. In conventional MRI, Fourier encoding concentrates the energy of MR signal in the center of k-space, this limits the incoherent sampling and hence hinders the performance of CS reconstruction. Therefore, non-Fourier encoding methods have recently been investigated to spread the energy of MR signal and hence enhance the performance of CS-MRI. However, most of these methods use impractically long RF pulses or require non-trivial implementation. In this work, we propose a practical encoding scheme based on the spread spectrum analysis of Chirp modulated Fourier sensing matrix, to enhance the incoherent sampling of multi-receive MRI. The proposed method outperforms Fourier encoding in preserving image quality at high acceleration factors.

METHOD: Our objective is to design an encoding scheme that optimally spreads the energy of the image signal in the sensing domain "k-space" and can practically be implemented conventionally using pulse sequence design. The Restricted Isometry Property (RIP) of a sensing matrix is a measure of the energy spread of the signal in the k-space and determines the performance of CS reconstruction [2, 3]. The RIP condition of the sensing matrix Θ when measuring a sparse signal x_k is given by:

$$(1-\delta_k)\|x_k\|_{l_2}^2 \le \|\Theta x_k\|_{l_2}^2 \le (1+\delta_k)\|x_k\|_{l_2}^2 .$$

The smaller the RIP constant δ_k of the sensing matrix, the fewer the measurements required to faithfully reconstruct the signal. Based on this, the proposed method optimally selects the sensing matrix by empirically assessing the RIP constant [3] of the modulated Fourier matrices [2] resulting from Chirp modulation of different bandwidths ΔC in (3). The proposed method also exploits the multiple channels acquisition to maximize the level of energy spread of MR signal and hence further enhances the RIP CS-MRI performance [4]. Fig.1 shows the empirical RIP analysis used to assess the performance of the modulated Fourier versus the conventional Fourier sensing matrices at multi-receive system. The optimally selected sensing matrix is implemented using RF pulses that will optimally spread the energy in k-space along the "phase encoding" direction. "SpinEcho" pulse sequence is modified to implement the proposed encoding. Fig.2 shows the sequence design for the *ith* phase encoding excitation. The Chirp modulated RF pulses "Chirp[i]" are calculated by Fourier transform of the excitation profile and scaled up to achieve 90^o flip angle [5]. The fully acquired data is then uniformly randomly under-sampled and then used to reconstruct the image by the multiple-receive CS reconstruction algorithm given in (1), where Ψ is the wavelet sparsifying transform matrix, $\hat{x}$ is the reconstructed image, TV is total variation operator, λ_1, λ_2 are the regularization parameters for the sparsity and the TV of the reconstructed image respectively [3]. For N receive MRI, the sensing matrix Θ consists of N stacked modulated Fourier matrices as in (2).

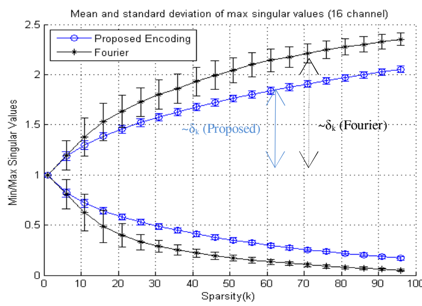

Fig.1 Empirical RIP assessment of the optimal chirp modulated Fourier matrix (blue) and the conventional Fourier matrix (black) in a 16 receive system.

$$\min_{\hat{x}} \|Y - \Theta\hat{x}\|_{l_2}^2 + \lambda_1\|\Psi\hat{x}\|_{l_1} + \lambda_2\|TV(\hat{x})\|_{l_1} . \qquad (1)$$

$$Where,\ \Theta = \begin{bmatrix} diag[F\varphi]*diag[s_{1,r}]_{r=1,2,..R^2} \\ \vdots \\ diag[F\varphi]*diag[s_{N,r}]_{r=1,2,..R^2} \end{bmatrix} \qquad (2)$$

$$\varphi = diag[e^{-i(\Delta C l^2 + \Delta C)}]\Big|_{l=1,2,...,L} \qquad (3)$$

F is Fourier transform, $s_{n,r}$ is the sensitivity of the n^{th} receive channel at the r^{th} location.

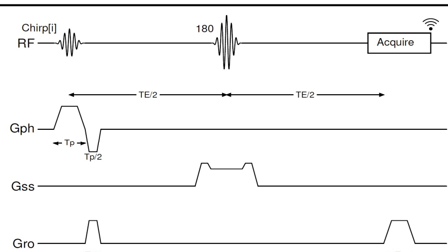

Fig.2 Pulse sequence diagram for the implementation of Chirp modulated Fourier encoding.

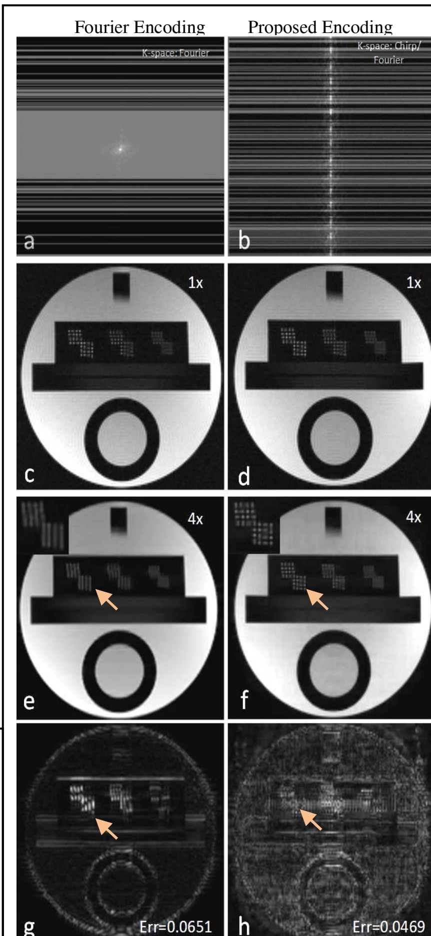

Fig.3 Experimental results: (a-b) k-space and the under-sampling pattern, c-d fully sampled images, (e-f) CS reconstructed images with 4x acceleration factor, (g,h) relative error.

RESULTS: The experimental results were compared with those of Fourier encoding in multi-receive CS framework. We used the variable density under-sampling pattern suggested in [1] for Fourier encoding and a uniformly random under-sampling pattern for the proposed method (Fig.2 a,b). The proposed method achieves better resolution at high acceleration factor (e.g. 4x). Fig.3 shows scans of a phantom at 3T Skyra (Siemens HealthCare, Erlangen, Germany) using 32 channels head coil. Left is the results of conventional Fourier encoding using "SpinEcho" sequence and Right is the results of the proposed pulse sequence (Fig.2). Both scans were taken with the same parameters (TE/TR: 25/750 ms; 256×256; RF duration 2.56ms; FOV: 200mm and Flip angle: 90°). From the zoomed portion of the image and the relative error comparison, the proposed encoding scheme improves the performance of multi-receive CS-MRI.

CONCLUSION: We have proposed an optimal and conventionally implementable encoding scheme for multi-receive CS-MRI based on the spread spectrum and the empirical RIP analysis. Experimental results show that the proposed technique outperforms Fourier in improving the performance of multi-channel CS reconstructions at high acceleration factors.

References: [1] Lustig, et al. MRM 2007. [2] Xiaobo Qu, et al, arXiv 2013. [3] K.Pawar, et al, arXiv 2014 [4] R.Otazo, et al, ISMRM 2009. [5] Pauly, et al, JMR 1989