Three-Dimensional Hybrid-Encoding for Compressed Sensing MRI

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INTRODUCTION

Although CS has been demonstrated to accelerate the speed of Fourier encoded MRI in several imaging applications [1,2], Fourier encoding is known to have limitations and may not be optimal for CS MRI [3,4]. A few works have investigated use of non-Fourier encoding for CS MRI [5-7]. However, none of these existing non-Fourier methods have demonstrated significant improvement over Fourier encoding in practical experiments. In this work, we propose a hybrid encoding scheme for 3-D imaging. Specifically, based on the conventional 3-D Fourier imaging, we replace the Fourier encoding along the phase encoding direction by a circulant random encoding. The encoding scheme excites the object along the phase encoding direction randomly. This excitation profile is repeated but shifted by a single pixel spatially during each excitation. With the proposed hybrid encoding scheme, the benefits of both Fourier encoding and random encoding can be obtained simultaneously. The low frequency signal can still be densely sampled in the Fourier encoding direction for high SNR. At the same time, the signal energy is more spread out in the circulant encoding direction such that high frequency information is adequately sampled. Using both simulation and real experiments, we demonstrate that hybrid encoding is superior to Fourier encoding in preserving resolutions when the same reduction factor is used.

THEORY AND METHOD

Our objective is to design a novel encoding scheme for 3-D imaging that is superior to the conventional Fourier encoding in the CS framework. We have demonstrated the feasibility of circulant random encoding in MRI using 2-D imaging experiments in our previous work [8]. In this work, we integrate circulant random encoding with conventional Fourier encoding in 3-D imaging to achieve 2-D accelerations. The proposed method exploits random encoding with a circulant structure along the "phase encoding" direction, while keeping conventional Fourier encoding along the readout and slice encoding directions. Figure 1 illustrates the 3-D imaging technique. Without loss of generality, x is assumed to be the readout, y the circulant encoding, and z the slice encoding. The undersampling is done in the k_y-k_z plane of *k*-space, where a variable density random sampling is used along the k_z direction (Fourier encoding), and a uniform random sampling is along the k_y direction (circulant encoding). A pulse sequence is designed to implement the circulant encoding, shown in Fig. 2. A random RF pulse with uniform magnitude and random phase is used for random excitation. Under small tip angles, the random excitation profile can be calculated by the Fourier transform of the pulse [9]. The image is reconstructed in the y-z plane for each x. If assuming the image vector to be reconstructed in the y-z plane as **f**, the encoding matrix **H** can be written as the Kronecker product of a circulant random matrix and a 1-D Fourier transform matrix. The matrix **H** has a block circulant structure with each block being a Fourier transform matrix. The original image vector **f** can be reconstructed from the undersampled data **b** by solving

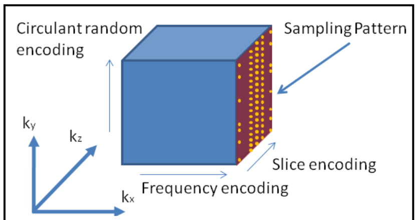


Fig.1 Illustration of the proposed hybrid encoding method in 3-D acquisition.

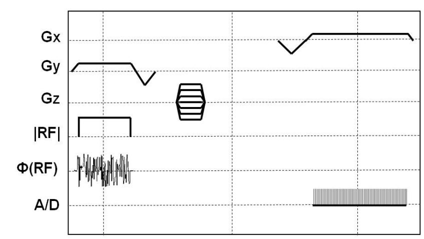


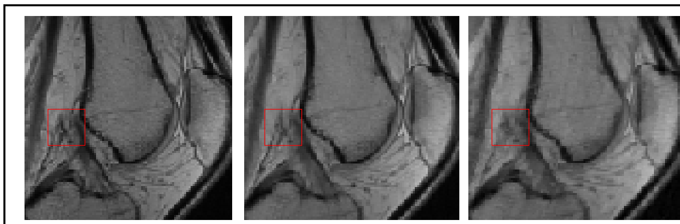
Fig.2 Timing diagram of the pulse sequence for the proposed 3-D hybrid encoding scheme.

$$\arg\min_{\mathbf{f}}\{\|\mathbf{b}-\mathbf{H}_u\mathbf{f}\|_2^2+\lambda_1\|\mathbf{W}\mathbf{f}\|_1+\lambda_2\,\mathrm{TV}(\mathbf{f})\} \quad (1)$$

where **W** and TV represent wavelet and total variation.

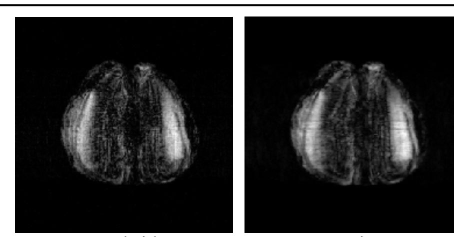
RESULTS AND DISCUSSION

We conducted both simulations and experiments to demonstrate the performance of the proposed hybrid encoding method. The results were compared with those of the conventional Fourier encoding in the context of CS. For Fourier encoding, we followed the sampling scheme used in [1], where a 2-D variable density random undersampling was used to sample the high spatial frequency region densely. Non-linear conjugate gradient was used to reconstruct the image based on Eq (1). In simulation, a set of 3-D knee data (256 × 256 × 16) was used to simulate the proposed hybrid encoding with a reduction factor of 3.4. Figure 3 compares the reconstructed images in x-y plane. The hybrid encoding method is seen to preserve better resolution than Fourier encoding (indicated by red boxes). A pummelo (see Fig. 4) was scanned on a 3T commercial MRI scanner (GE Healthcare, Waukesha, WI) with a single-channel head coil using both the proposed sequence in Fig. 2 (RF pulse 6.144 ms) and the conventional 3-D gradient echo pulse sequence with the same parameters (TE/TR: 15/40 ms; rBW: 5.96 kHz; 256×256×32; FOV: 16 cm^2; Flip angle: 7°). The proposed hybrid encoding method is able to improve the resolution and remove the aliasing artifacts in Fourier encoding.



Original Hybrid Fourier

Fig. 3 Simulation results with 3.4× reduction.



Hybrid Fourier

Fig. 4 Experimental results with 2.0× reduction.

CONCLUSION

We propose a novel 3-D hybrid encoding method for compressed sensing. Simulations and experimental results demonstrate that the proposed hybrid encoding method brings together the benefits of both Fourier and random encoding and improves the resolution of CS reconstructions over the conventional Fourier encoding.

REFERENCES

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