CIRcular Cartesian UnderSampling (CIRCUS): A Variable Density 3D Cartesian Undersampling Strategy for Compressed Sensing and Parallel Imaging

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INTRODUCTION

Compressed sensing (CS) and parallel imaging (PI) have been exploited to reduce scan time by undersampling k-space data. This is highly desirable for 3D applications that have unreasonably long scan times. To recover images from undersampled data, random sampling is desired [1-2]. Poisson- disk sampling (PDS) provides even but random distribution of samples, which is suited for CS&PI. Variable-density PDS (vPDS) can further improve image reconstruction [3]. However, the computational cost for generating PDS or vPDS is high and it is impractical for interleaved or real-time applications. Non-Cartesian trajectories (such as radial and spiral) have been used for undersampling k-space giving flexibility in interleaving as well as controlling the undersampling factor. Similarly Cartesian radial- or spiral-like sampling patterns have also been explored [4-6]. This study proposes a novel method for generating undersampling patterns for 3D Cartesian acquisition that provides easy implementation, flexible sampling patterns, and high accuracy of image reconstruction with CS&PI.

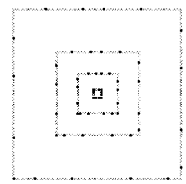

Fig. 1 k_y-k_z plane circular under-sampling. Solid dots are selected based on a golden ratio profile.

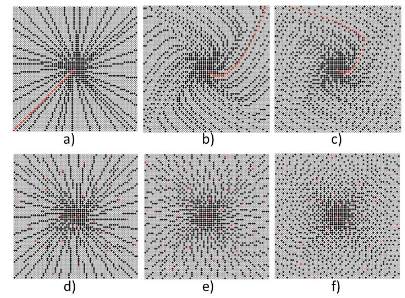

Fig. 2 k_y-k_z plane circular undersampling at each square a) starts from the same position (left bottom corner), b-f) starts with specific shifts according to the size of the square.

MATERIALS AND METHODS

Our proposed CIRcular Cartesian UnderSampling (CIRCUS) method generates variable-density sampling patterns in the k_y-k_z plane of 3D Cartesian acquisitions. Given a N×N sampling matrix on the k_y-k_z plane composed of N/2 squares of different sizes, ranging from 2×2 to N×N (four representative squares are shown in Fig.1), CIRCUS selects sampling points circularly along the edges of the squares, by skipping a certain number of points based on a uniform or golden ratio profile (Fig.1) [7]. By introducing shifts to the starting sampling points of the squares, we can flexibly design the sampling patterns to be radial, spiral, or random with certain degree of randomization (examples are shown in Fig. 2). In Fig.2 the starting points of the circular sampling at each square are plotted in red. Thus by sampling one point at each square sequentially and then sampling the next selected point and so on, we can achieve k-space interleaving appropriate for time-resolved or real-time imaging applications. Thus CIRCUS has flexibility for adjusting both the sampling pattern and the sampling ordering.

We compared our CIRCUS patterns with undersampling patterns (Fig.3 1-3, uniform random, PDS, vPDS), that have previously been demonstrated to be suited for CS&PI. Fig.3 4-7, shows CIRCUS patterns for uniform radial, golden-ratio radial, randomized uniform and golden-ratio radial. The randomized patterns were generated with high degree of randomization. All 7 patterns contain a fully sampled center and were retrospectively applied to fully sampled data sets, including Shepp-Logan simulation phantom, experimental phantoms (3T GE scanner), human neck (3T Siemens scanner), and brain (Lustig [2]) images. CS and SPIRIT were applied for image reconstruction [1-3]. Random sampling (Fig.3 1-3) was repeated 10 times each.

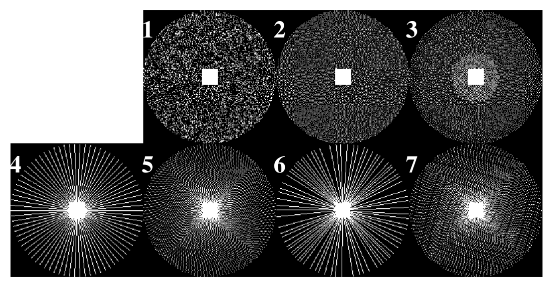

Fig. 3 k_y-k_z undersampling (R=6): 1) uniform random, 2) Poisson-Disk random, 3) variable-density Poisson-Disk random, 4) uniform radial, 5) golden-ratio radial, 6) randomized uniform radial, 7) randomized golden-ratio radial.

RESULTS & DISCUSSION

Normalized root-mean-square errors (NRMSE) were measured from images obtained with the 7 sampling patterns versus full data reference images (Fig.4.) As demonstrated by other researchers, variable-density random sampling outperforms uniform random sampling. Randomized CIRCUS patterns (patterns 5&7 in Fig.4,) have very reliable performance, similar (with SPIRIT) or perhaps even better (with CS) than those with vPDS (pattern 3 in Fig.4). Fig.5 demonstrates that images obtained with randomized CIRCUS sampling are comparable to the reference images for CS and SPIRIT.

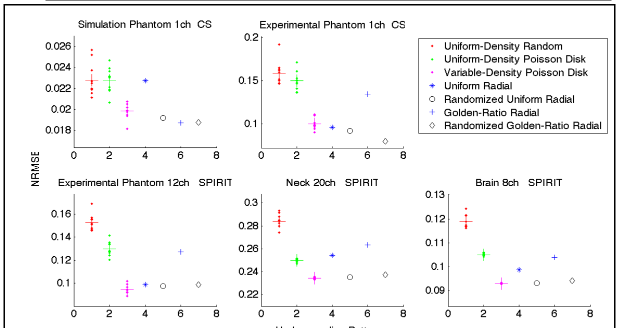

Fig. 4 Normalized root-mean-square errors were measured for five studies with the sampling patterns in Fig. 3 (R=6).

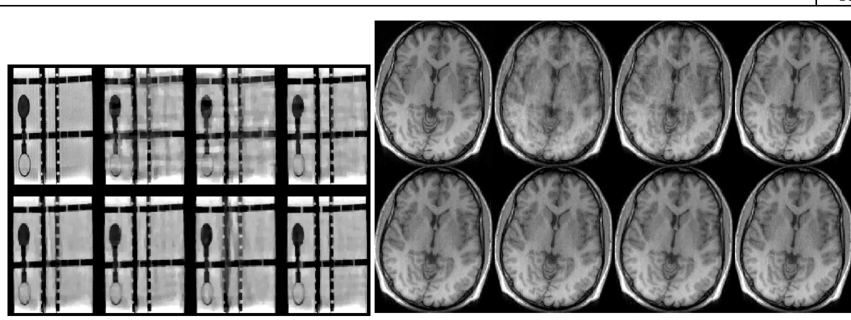

Fig. 5 Experiment phantom (left, CS, Fig.4b) and brain (right, SPIRIT, Fig.4e) images with sampling patterns in Fig.3 (R=6). The first sub-images are the reference.

CONCLUSIONS

A novel method to generate efficient undersampling patterns for 3D Cartesian imaging with compressed sensing and parallel imaging was proposed. Reliable image reconstructions with proposed randomized CIRCUS patterns have been demonstrated.

REFERENCES 1. Lustig M, et al, MRM 2007;58, p1182. **2**. Lustig M, et al, MRM 2010;64, p457. **3**. Vasanawal SS, et al, IEEE BMI 2011; p1039. **4**. Haider CR, MRM 2008;60, p749. **5**. Du J MRM 2009;61, p918. **6**. Doneva M, et al, ISMRM 2011; p641. **7.** Winkelmann S, IEEE-TMI;26, p68.