# Free-breathing dynamic contrast-enhanced MRI of the liver with radial golden-angle sampling scheme and advanced compressed-sensing reconstruction.

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**Introduction:** Assessment of multi-phase (arterial and venous) post-contrast acquisition is essential for liver lesion detection and characterization (1). Dynamic post-contrast liver MR examinations are usually performed using a T1-weighted fat-saturated 3D volumetric interpolated pulse sequence (VIBE) with Cartesian k-space sampling in a breath-hold (BH). However, this method is sensitive to respiratory motion and results in non-diagnostic images in patients who cannot adequately breath-hold. Free-breathing radial k-space sampling with a stack-of-star acquisition scheme (Cartesian sampling in the z-direction and radial sampling in the xy-plane) can generate images which are of comparable image quality to the conventional BHVIBE but at the expense of longer acquisition time (2). This long acquisition is a limitation for dynamic liver imaging. View-sharing techniques such as k-space-weighted image contrast (KWIC), which permits manipulation of the image contrast by temporal filtering of the acquired views, have been applied to reconstruct undersampled data (3), but acceleration is limited by temporal blurring. An alternative approach for accelerated imaging is compressed sensing (CS), where temporal correlations in the dynamic imaging data are exploited to reduce number of required radial spokes (4). Radial sampling is well suited for CS due to the inherent presence of incoherent aliasing artifacts. Using the golden-angle scheme helps to further increase this incoherence (5).Because higher accelerations can be achieved by combining CS and parallel imaging (6), we have recently developed a new reconstruction method that combines compressed sensing and parallel imaging for radial trajectories (k-t RASPS: RAdial SParse-Sense).

**Purpose:** To compare image quality of (1) interleaved 'angle-bisection' radial sampling with KWIC reconstruction, (2) interleaved 'angle-bisection' radial sampling with k-t RASPS reconstruction and (3) golden-angle radial sampling with k-t RASPS reconstruction to the reference conventional BHVIBE in healthy subjects with normal breath-holding capacity.

**Materials and Methods:** In this prospective HIPAA compliant IRB approved study, 6 healthy male subjects (age range: 24-41 years) were imaged at 3T (MAGNETOM Verio, Siemens AG, Erlangen, Germany). Each subject underwent 3 separate contrast-enhanced MRI examinations after injection of 10 cc of gadolinium contrast at a rate of 2cc/second. Acquisition schemes were: (1) conventional BHVIBE in arterial and portal venous phases of enhancement (timing calculated from a test bolus) with acquisition time of 14 seconds for each phase, (2) free-breathing radial acquisition with the interleaved angle-bisection scheme. 400 radial spokes were acquired in 4 rotations (100 spokes/rotation) in 60 seconds with acquisition initiated at the scan delay of time to peak (calculated from a test bolus), and (3) continuous GA radial acquisition with 600 spokes in 90 seconds with imaging initiated at the time of contrast injection. Matching sequence parameters are as follows: slice thickness 3 mm, flip angle $12^{o}$, voxel size 1.6 x 1.6 x 3 mm, TR/TE 3.56-3.62 ms/1.51-1.55 ms, 80 slices, BW 590-610 Hz/pix.

**Image reconstruction:** Interleaved radial data with 100 spokes per rotation were reconstructed using both KWIC and k-t RASPS. GA data were also reconstructed for 100 spokes each using k-t RASPS by minimizing the functional $||R\bullet E\bullet x-y||_2+\lambda||T\bullet x||_1$, where y is the undersampled k-space data, x is the image to be reconstructed, T is the sparsifying transformation, and E is an operator that incorporates multiplication with the coil sensitivities, Fourier transformation, and a projection to the sampling locations in k-space. Further, R is a gridding operator that interpolates the Fourier data onto spokes to ensure data consistency in radial k-space. KWIC reconstruction was performed online using a software package provided by the vendor and k-t RASPS reconstruction was performed in a customer developed software in MATLAB (MathWorks, MA) using a nonlinear conjugate gradient algorithm and temporal total variation as the sparsifying transform. Coil sensitivity maps were calculated using the adaptive coil combination method (7) with the temporal average of the gridded images as coil calibration reference.

**Image Analysis:** Appropriate phases of arterial and venous enhancement for all the different acquisition and reconstruction schemes were presented in a random order and in a blinded fashion to 2 readers (board-certified radiologists with 4 and 6 years of experience). For each data set, each reader independently scored if the enhancement pattern was arterial or venous, and subsequently quality of enhancement (QE) and overall image quality (IQ) were scored using a scale of 1–5; with the highest score indicating the most desirable exam. The GA- k-t RASPS (GA-CS), interleaved KWIC (I-KWIC) and interleaved- k-t RASPS (I-CS), and Cartesian BH VIBE (BH) were compared with mixed model analysis of variance (ANOVA) in terms of each measure of image quality.

| Arterial Phase (Table1) (corrected for 2 readers) | BH | I-KWIC | I-CS | GA-CS |
|---|---|---|---|---|
| QE | 4.9 ±0.1 | 3.8 ±0.1 | 3.4 ±0.1 | 4.6 ±0.1 |
| IQ | 4.8 ±0.1 | 2.8 ±0.2 | 3.0 ±0.2 | 4.0 ±0.2 |
| **Venous Phase (Table 2) (corrected for 2 readers)** | **BH** | **I-KWIC** | **I-CS** | **GA-CS** |
| QE | 5.0 ±0.2 | 3.8 ±0.2 | 4.0 ±0.2 | 4.5 ±0.2 |
| IQ | 4.8 ±0.1 | 3.3 ±0.1 | 3.4 ±0.1 | 4.3 ±0.1 |

**Results:**

**Arterial phase (Table1):** BH exam had significantly higher IQ score compared to all other reconstructions ($p<0.05$). GA-CS had the second-highest IQ score and this was significantly higher compared to I-KWIC and I-CS ($p<0.05$). More importantly, both readers scored GA-CS arterial acquisitions as having IQ score of good or excellent (≥4) in all subjects except in one subject, where it was scored as 3 (acceptable) by one reader. There was no difference in QE score between BH and GA-CS acquisition ($p=0.80$), whereas I-CS and I-KWIC reconstructions had significantly lower QE score compared to BH and GA-CS ($p<0.5$).

**Venous phase (Table2):** There were no significant differences in IQ ($p= 0.1939$) or QE ($p= 0.3151$) between the BH and GA-CS acquisition. In comparison, I-KWIC and I-CS had significantly lower IQ score compared to BH ($p<0.05$) and GA-CS ($p<0.05$) and lower QE score compared to BH ($p<0.05$). Both readers scored GA-CS venous acquisitions as having IQ score of good or excellent (≥4) in all subjects.

**Conclusion:** In this study we have shown the utility of a 3D radial golden-angle acquisition scheme with joint reconstruction combining CS and PI for free-breathing dynamic contrast-enhanced liver MRI with image quality comparable to a breath-hold exam and significantly better than other radial acquisition and reconstruction schemes.

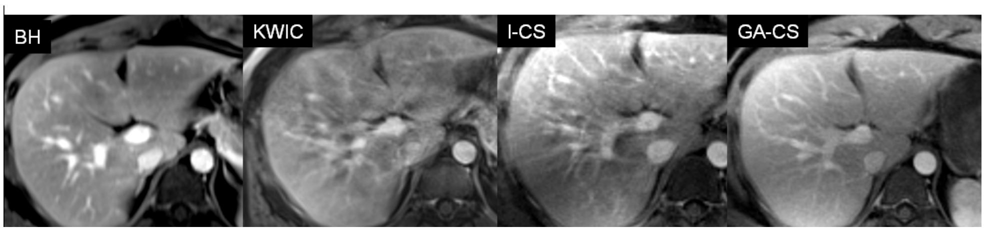


**Figure:** Venous phase acquisitions in a 24 year old

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