3D hybrid radial acquisition with compressed sensing for LGE imaging of left atrium: A simulation study

G. Adluru[1], S. Vijayakumar[1], N. Burgon[2], E. Kholmovski[1], N. Marrouche[2], and E. DiBella[1]
[1]Radiology, University of Utah, Salt Lake City, UT, United States, [2]Cardiology, University of Utah, Salt Lake City, UT, United States

Introduction: Atrial fibrillation currently affects over 7 million people in the U.S. and Europe. Late Gadolinium Enhancement (LGE) imaging offers a means to assess ablation of the left atrium and the pulmonary vein ostia [1, 2]. In order to quantify the extent of scar, images with high resolution in-plane as well as through-plane are required. The standard approach is to acquire LGE images using a 3D Cartesian k-space inversion recovery sequence with ECG and respiratory gating [1, 2]. While the method can differentiate signal enhancement in the left atrium before and after ablation, more accurate assessment is desirable in order to better track the treatment progress as well as to be able to screen patients and possibly predict the success of the ablation procedure [3]. Better visualization of the thin left atrial wall may be possible with a different k-space sampling and compressed sensing or constrained reconstruction methods [4-6]. Radial imaging offers a promising way to obtain high resolution images while being robust to motion and k-space undersampling [7]. Here we use simulation experiments and patient data to explore a 3D hybrid radial acquisition scheme (stack of stars) for obtaining improved quality images from fewer data samples.

Methods: A realistic simulated phantom was generated from an LGE Cartesian acquisition of a post-ablation patient acquired on a Siemens Verio 3T scanner. 19 different structures across 40 slices were manually segmented and assigned T_1 and M_0 values to create a 3D phantom (Table 1). Signal from a gradient echo inversion recovery sequence was computed as in [8]. The time between the inversion pulse and the first α pulse, TI, was chosen to null the myocardium when the center of 3D k-space was sampled (280msec). The time between the last α pulse and the next inversion pulse was 500msec, α was chosen as 22^0, and TR was set to 6.5 msec.

Structure	Tissue	Blood	Wall	Fat/Torso	Liver	Lung
T_1value (msec)	400	300	270	250	350	500
M_0 value	20	20	20	10	20	1

Table 1: Tissue = left ventricle, right ventricle, left atrium, right atrium; Blood = descending aorta (DA), ascending aorta (AA), pulmonary artery (PA), superior vena cava (SVC); Wall = Aorta, DA, AA, PA, SVC.

Images for all slices at each of 40 α pulse instances were generated. Corresponding Cartesian k-space data was generated by taking 3D Fast Fourier Transform. Two hybrid schemes were used to generate the final 3D k-space data, ***(i)*** kx-ky-first: Radial lines for all angles were acquired first in kx-ky plane and then kz is incremented. ***(ii)*** kz-first: Radial lines for a fixed angle in kx-ky plane were acquired for all kz-encodings before incrementing the projection angle. Similar schemes have been studied for MR angiography [7]. Lines in-plane for kx-ky-first scheme were interleaved in subsets of four in order to reduce data inconsistency artifacts [9]. A center-out acquisition [10] was used for kz encoding in kz-first scheme. For both schemes a total of 40 radial lines in kx-ky for each kz were sampled and were approximated using nearest neighbor Cartesian points. It was assumed that 40 α pulses were applied in each heartbeat. With just 40 rays per slice, the images had significant streak artifacts which were removed using compressed sensing/constrained reconstruction total variation approach [4-6] by iteratively minimizing the cost function $C = \left\|Em-d\right\|_2^2 + \beta\left\|\sqrt{\nabla_x^2+\nabla_y^2+\varepsilon}\right\|_1$ where E is the encoding matrix that maps the image estimate m to sampled k-space data, d. β is the weighting factor for the L1 norm constraint term and ∇x , ∇y represent spatial gradients in x,y respectively. No z gradient in the constraint was used because data was fully sampled along kz. 3D data was inverse Fourier transformed in the slice dimension and each slice was processed separately for the piecewise constant phantom. For comparison, undersampled Cartesian data was also generated with 40 phase encoding lines in kx-ky sampled in Variable Density (VD) random fashion [5] with 21 lines in the center of each plane. In-vivo data acquired from the 3T scanner was also used to compare radial and Cartesian schemes. Fully sampled 3D Cartesian data was undersampled by a factor of three (R=3) in Cartesian and radial VD patterns. Constrained reconstruction in-vivo was performed using a 3D total variation constraint, $\left\|\sqrt{\nabla_x^2+\nabla_y^2+\nabla_z^2+\varepsilon}\right\|_1$ where ∇z is the gradient along the slice dimension.

Results: The simulated phantom image reconstructed from the kz-first scheme is significantly better than that from the kx-ky-first scheme and matches well with the true image with slight blurring of edges. While the Cartesian image is better than that from the kx-ky-first scheme, it is significantly blurred compared to the image from the kz-first scheme. It took thrice the number of phase encoding lines for the Cartesian image quality to be comparable to that from the kz-first scheme. In-vivo results with simulated radial sampling also illustrates that for the same scan time, radial acquisition offers significantly better image quality (bottom row of figure).

Discussion and Conclusion: In the kz-first scheme, signal modulation due to recovery of the longitudinal magnetization is encoded across slices leading to inconsistent data in the kz-direction. This gives a point spread function that causes blurring of edges across all slices while image contrast is preserved since the kx-ky plane corresponding to kz=0 has consistent data for the nulled myocardium. In the kx-ky-first scheme there is no inconsistency in the kz dimension but the rapid changing of signal from negative to positive (depending on T_1 and TI) within each slice leads to significant inconsistencies which results in poor quality. The 3D hybrid radial stack of stars with kz-first encoding and constrained reconstruction is a promising alternative for better visualization of the left atrium with reduced scan times.

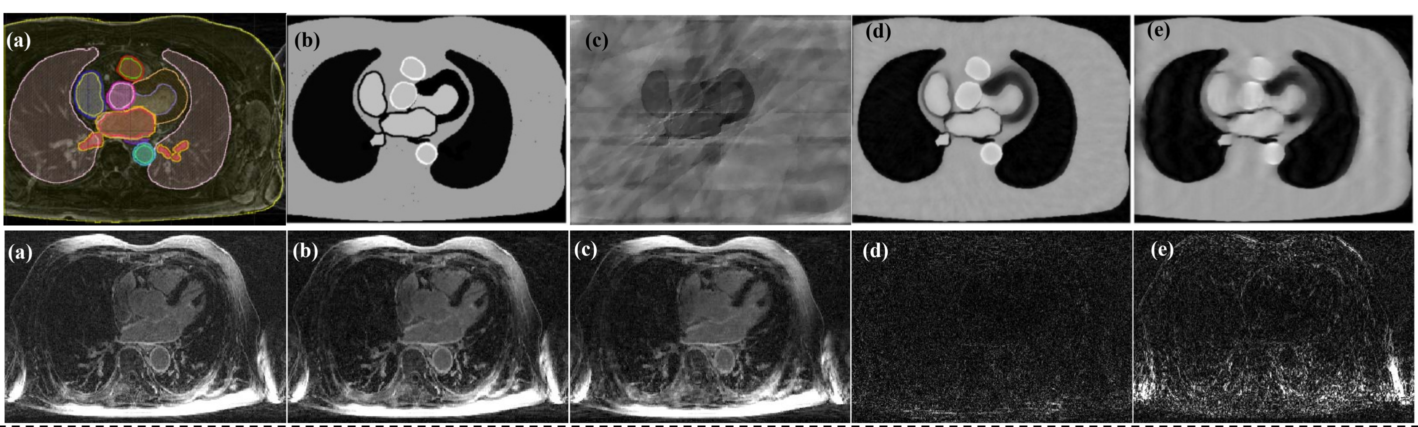

Figure: *Top row corresponds to phantom images.* **(a)** Manually segmented regions in an in-vivo image shown with color coding. **(b)** Image at the time when the myocardium is nulled. **(c,d,e)** Images obtained from kx-ky-first, kz-first and Cartesian schemes respectively. Constrained reconstruction was used.
Bottom row corresponds to in-vivo results. **(a)** Inverse Fourier transform reconstruction of fully sampled data **(b,c)** R=3 constrained reconstructions with radial and Cartesian sampling schemes respectively. **(d,e)** Absolute difference images between (a)-(b) and (a)-(c) respectively.

References: [1] Peters DC. et al. Radiology 243:690-695,2007 [2] McGann CJ et al. JACC; 52(15):1263-1271, 2008. [3] Oakes RS et al. Circ; 119(13): 1758-1767,2009. [4] Block KT et al, MRM, 57:1086-1098, 2007. [5] Lustig M et al, MRM,58:1182-1195, 2007 [6] Adluru G et al, JMRI 29(2):466-73, 2009. [7] Peters DC et al. MRM,43: 91-101, 2000 [8] Larsson HBW et al. MRM 46: 272-281, 2001. [9] Peters DC et al. MRM 55: 1150-1156, 2006. [10] Maki JH et al, JMRI,6: 642-651, 1996.