Fast reconstruction of 3D LGE images of the left atrium in a compressed sensing framework using Split Bregman

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Introduction: Over 7 million people in Europe and the US suffer from atrial fibrillation. A new and valuable method for assessing the degree of fibrosis in the left atrium either before or after ablation treatment is to acquire Late Gadolinium Enhancement (LGE) images of the left atrium (LA). The current method of acquiring high resolution 3D Cartesian inversion recovery data with ECG gating and respiratory navigator gating is time consuming. Parallel imaging techniques like GRAPPA have been used to reduce the scan time, though acceleration factors are less than R=2 [1]. Two groups have looked at higher accelerations, using 3D stack of stars and total variation (TV) [2], or using properties of similarity patches learned from the image as constraints [4,5]. Both methods are very computationally intensive, especially the process of learning from patches. We propose to use the Split Bregman approach [3] to reconstruct LGE images of the LA with 3D TV as constraints for high quality rapid reconstructions with high acceleration factors.

Method: The cost functional to be minimized is given by, $C = \mu\|Em - d\|_2^2 + \left\|\sqrt{D_x^2 + D_y^2 + D_z^2}\right\|_1$

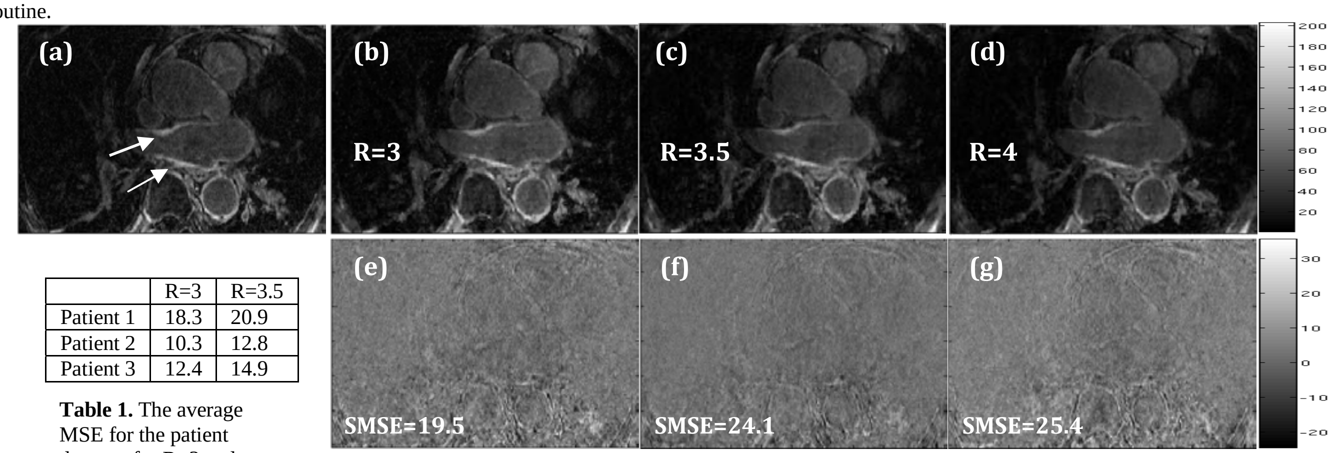
where D_x, D_y and D_z represent the spatial gradients in x, y and z respectively and E is the encoding matrix. m represents the estimated image and d the measured k-space data. μ is the weighting factor that is used to balance the data fidelity term and the total variation constraint. Traditional minimization schemes like gradient descent have a slow rate of convergence. Using the Split Bregman formulation, fast convergence for L1 regularized problems like those used in compressed sensing has been shown [3]. Using the Split Bregman formulation, the above cost functional becomes

$$\min_{m,dx,dy,dz} \left\|\sqrt{(dx)^2 + (dy)^2 + (dz)^2}\right\|_1 + \mu\|Em - d\|_2^2 + \alpha\|dx - \nabla_x m - bx\|_2^2 + \alpha\|dy - \nabla_y m - by\|_2^2 + \alpha\|dz - \nabla_z m - bz\|_2^2$$

where dx, dy and dz are auxiliary/dummy variables added using Split Bregman technique. bx, by and bz come from optimizing the Bregman distance of the regularization term. A minimum solution for m is found by alternatively minimizing m and dx, dy and dz. The unconstrained version of the problem is implemented here and by using the Bregman update rule, $d^{k+1} = d^k + d - Em^{k+1}$. This is equivalent to the "adding the noise back" iterative scheme [6]. Here we have applied Split Bregman to the 3D TV based L1 formulation because the non linearity and poor conditioning of the L1 minimization problem makes it slow to solve otherwise. The weights were empirically chosen to be α=0.9 and μ=0.5 and we found that the reconstruction scheme was robust to small changes in weights. Fully sampled 3D datasets were acquired on a Siemens 3T Verio scanner from three atrial fibrillation patients using TR=3.8ms, TE=2.1ms, TI=300-400ms, 44 slice encodings, a slice thickness of 2.5mm and flip angle=14 degrees. To simulate undersampling, a variable density sampling pattern was used, fully sampled along kx, while directions ky, kz were undersampled. Sparsification factors of R= 3, 3.5 and 4 were used and reconstructions were compared with IFT of the fully sampled Cartesian k-space data. Mean squared error, difference images and visual inspection were used to evaluate the reconstructed images.

Both the Split Bregman and gradient descent schemes were implemented in MATLAB. Parallel toolbox as well as Jacket [7] was used to run the reconstruction on GPU's. Two CPU and two GPU cores were used for the reconstruction. We found that good quality images using the Split Bregman scheme could be reconstructed in about 7 seconds.

Results: Comparisons with the IFT of the fully sampled data showed that good quality reconstructions could be achieved for sparsification factors of R=3.5. Some smoothing could be seen at R=4, though the enhancement in the LA wall in this post-ablation patient was still visible. Mean squared errors (MSE) and difference images (Fig. 1) between reconstructed image and "truth" showed that the enhancement in LA was well visualized. Table 1 shows the average MSE of all the slices in a dataset combined. The Split Bregman scheme reduces the reconstruction time to 7 sec, which is much less than a gradient descent minimization scheme which takes about 3 minutes to reconstruct the images. Such fast reconstructions could enable the use of this compressed sensing based reconstruction scheme in daily clinical routine.



	R=3	R=3.5
Patient 1	18.3	20.9
Patient 2	10.3	12.8
Patient 3	12.4	14.9

Table 1. The average MSE for the patient datasets for R=3 and R=3.5.

Fig 1. (a) A slice from a fully sampled image, the arrows show the enhancement in the LA wall. **(b), (c)** and **(d)** Reconstruction using the proposed method for R=3, R=3.5 and R=4 respectively. **(e), (f) and (g)** Difference image between the truth and the images reconstructed in (b), (c) and (d) respectively. The slice MSE is reported along with the difference images.

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