MOTION-COMPENSATED ITERATIVE SELF-CONSISTENT PARALLEL IMAGING (SPIRIT) AND ANALYTICAL Q-BALL IMAGING RECONSTRUCTION FOR HIGH SPATIAL AND ANGULAR RESOLUTION DIFFUSION IMAGING WITH MULTI-SHOT MULTI-CHANNEL NON-CARTESIAN DATA

Congyu Liao[1], Hongjian He[1], Song Chen[1], Merry Mani[2], Mathews Jacob[2], Vincent Magnotta[2], and Jianhui Zhong[1]

[1]*Center for Brain Imaging Science and Technology, Zhejiang University, Hangzhou, Zhejiang, China,* [2]*University of Iowa, Iowa, United States*

PURPOSE: For high spatial resolution diffusion imaging, multi-shot diffusion MRI is used to reduce blurring and distortions caused by T_2^* decay. However, shot-to-shot phase inconsistency can cause considerable motion artifacts, and the scan time is usually prolonged to cover enough diffusion directions for higher angular resolution in q-space. As for motion compensation, multi-shot multi-channel non-Cartesian diffusion imaging[1] with CS-SENSE[2] and AS-SPIRiT[3] reconstruction methods, which combine parallel imaging and compressed sensing, has been employed to accelerate imaging. The SENSE-based method would result in inaccurate sensitivity map, and may limit the quality of reconstruction. Whereas AS-SPIRiT has only been used for DTI model without high angular resolution so far. Such a model could be not appropriate for crossing fibers. In this study, we proposed a motion-compensated SPIRiT acceleration scheme with analytical Q-Ball imaging (QBI) based reconstruction[4] to obtain orientation distribution function (ODF) with high spatial and angular resolution. This metric demonstrated improved quality with reduced noise and motion artifacts compensated with the method.

METHODS: The reconstruction algorithm was based on SPIRiT[5] which does not need sensitivity maps for parallel imaging. For multi-shot non-Cartesian diffusion imaging, the variable phase error matrix P was estimated using the k-space data at the center of the self-navigated variable density spiral (VDS) trajectory of each shot. Suppose N shots and M diffusion directions were acquired using L coils, the original SPIRiT formulation was converted to an optimization problem given by:

$$\arg\min_{x}\sum_{q=1}^{M}\left(\left\|\sum_{n=1}^{N}\left(D_n\sum_{l=1}^{L}x_{n,l}P_{n,l}-y(k_{q,n})\right)\right\|_2+\lambda\left\|\sum_{n=1}^{N}(G_n-I)x_n\right\|_2\right),$$

where $x_{n,l}$ is the reconstructed image of n^{th} shot from l^{th} coil, $y(k_{q,n})$ is the under- sampled k-space data of the n^{th} shot in q^{th} diffusion direction from all coils, P is the shot-to-shot phase variation matrix, which is applied as multiplication in image domain and can be removed after several iterations, D is the non-uniform FFT operator, G is the SPIRiT calibration kernel, I is the identity matrix, and λ is the regularized coefficient for balancing the sampling and calibration weights. The optimization problem was solved by LSQR algorithm. The flow chart of the proposed scheme in one diffusion orientation was shown in Fig. 1.

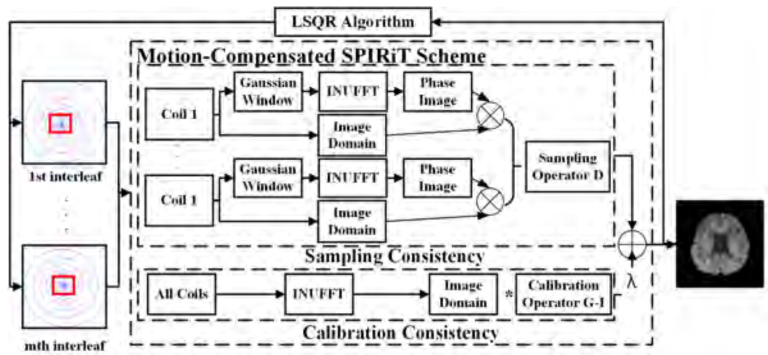

Figure 1. Flow chart of motion-compensated SPIRiT acceleration scheme in a DW image of one particular diffusion direction.

The high spatial resolution images from all diffusion directions were reconstructed using a fast regularized analytical QBI method. The data sampled in the sphere of q-space was approximated with spherical harmonic. With the definition of spherical harmonic basis matrix B, coefficient matrix C and Legendre polynomial matrix M, the signals of different diffusion directions S were used to reconstruct the ODF by:

$$ODF = MC = M(B^TB+\lambda L)^{-1}B^TS,$$

where L is Laplace–Beltrami matrix, λ=0.006 is the regularized parameter which can be evaluated with L-curve method.

The *in vivo* human brain diffusion data was acquired using a Siemens 3T scanner with 12-channel head coil. The dataset included 1 b0 image and 64 diffusion-orientation images which were uniformly sampled on a sphere surface at b=1200 s/mm^2. The VDS sampling trajectory had 22 spatial interleaves and the readout duration was 18.6 ms, TE/TR = 61/2500 ms. The in-plane spatial resolution of 1.04*1.04 mm^2 was achieved from an FOV of 200*200 mm^2 and matrix size of 192*192. Totally 10 slices were acquired with slice thickness=2.5 mm. We retrospectively under-sampled the data with acceleration factor R=2 and compared the result reconstructed from the new motion-compensated SPIRiT method with that from conventional CG-SENSE method. The reconstruction parameters included calibration size=16*16, and SPIRiT kernel size=7*7. Both algorithms were implemented in the same environment using MATLAB.

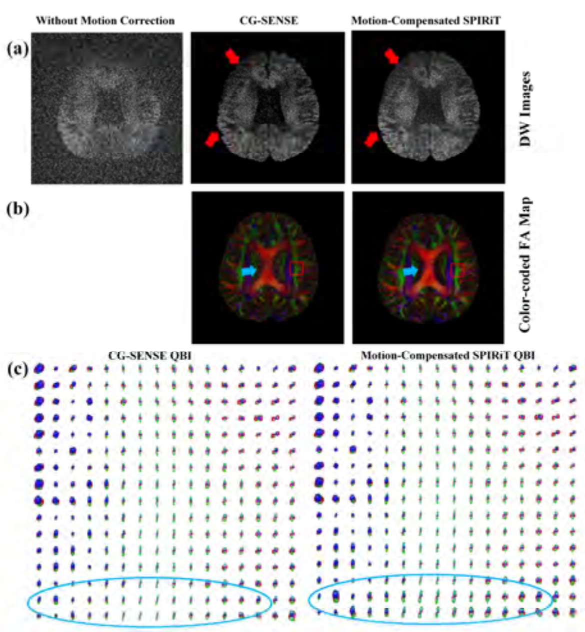

Figure 2. (a) The diffusion images reconstructed without motion correction from CG-SENSE and from motion-compensated SPIRiT method for one diffusion orientation of the same slice. Acceleration factor R=2 for both. **(b)** The color-coded FA map using DTI model and **(c)** the QBI reconstructed ODF using both methods for the ROI marked by red box region in Fig. 2(b)).

RESULTS & DISCUSSION: Fig. 2 displays images of a selected diffusion orientation and slice reconstructed without motion correction, and motion- compensated with CG-SENSE and SPIRiT method respectively. As it is shown, motion artifacts were effectively removed by both the correction methods. Specifically, SPIRiT-based method provided images with improved contrast and less noise (indicated by a red arrow in DW images) and further reduced artifacts (marked by a blue arrow in FA map). Fig. 2(c) displays the regularized analytical QBI-based ODF reconstruction in a ROI of 16*16 (red box region in Fig. 2(b)), where the existed crossing fiber cannot be distinguished with the DTI model. To compare SENSE and motion-compensated SPIRiT methods, we investigated the precisions of ODF, which can be assessed by the normalized sum-of-squares error (NSSE) that was calculated as:

$$NSSE = \sum_{ROI}\left\|ODF_{ref}-ODF_{recon}\right\|_2^2 / \sum_{ROI}\left\|ODF_{ref}\right\|_2^2,$$

where ODF_{ref} was calculated from fully sampled data and ODF_{recon} was calculated from under-sampled data with CG-SENSE or motion-compensated SPIRiT reconstruction. The results showed that in the ROI of 16*16 region near the blue arrow region in Fig. 2(b), $NSSE_{SPIRiT}$ (0.0135) was lower than $NSSE_{SENSE}$ (0.0234), which indicated SPIRiT provided more precise ODF than SENSE. The current result was consistent with that from SENSE reconstruction, whereas our new method provided ODF with more structural details and was robust for crossing fiber (i.e. blue circle in Fig. 2(c)).

CONCLUSIONS: The motion-compensated SPIRiT acceleration scheme with regularized analytical QBI was a fast and robust method which provided more accurate reconstruction of structural details for high spatial and angular resolution diffusion imaging applications.

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