High Resolution Multi-Shot SENSE DTI Using Self-Navigated Interleaved Spirals (SNAILS)

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INTRODUCTION: High resolution diffusion-weighted images are commonly acquired with multi-shot sequences such as PROPELLER (1) and self-navigated interleaved spirals (SNAILS) (2). These multi-shot sequences usually have to deal with shot-to-shot phase variation and longer data acquisition time. Another approach for high resolution diffusion-weighted imaging (DWI) combines single-shot EPI with sensitivity encoding (SENSE) (3). Using coil sensitivity information, SENSE enables reduction of phase encoding steps. In this work, we combine SENSE with multi-shot DWI to speed up data acquisition. One difficulty for multi-shot SENSE DWI is to perform phase correction on data modulated by complex-valued coil sensitivity of each receiver coil element. We have developed a technique that simultaneously performs SENSE reconstruction and phase correction. Using this technique, SNAILS with multiple receiver coils are implemented to acquire high resolution diffusion tensor imaging (DTI) data. We show that SNAILS offers great property for multi-shot SENSE DWI. High resolution diffusion-weighted images and FA maps are obtained with SENSE reduction factor up to four.

METHOD: Under the weak voxel condition, SENSE data acquired in **k**-space can be expressed in a matrix and vector format as (4),

$$\mathbf{d} = \mathbf{E}\,\mathbf{m} \quad [1]$$

Here, **d** is **k**-space data stored in a column vector; **m** is image space data stored in the same fashion; and **E** is the encoding matrix of size $N_c N_k$ x N^2. N_c is the number of receiver coils, N_k is the number of k-space sampling points, and N is the image size. For the γ-th coil, the entries of matrix **E** are

$$\mathbf{E}_{(\gamma,k),\rho} = \exp(-i\,\mathbf{k}_k \mathbf{r}_\rho) s_\gamma(\mathbf{r}_\rho) \quad [2]$$

where $\mathbf{k}_k$ is the k-th sampling point in **k**-space, $\mathbf{r}_\rho$ is the ρ-th pixel of an image, and $s_\gamma(\mathbf{r}_\rho)$ is the complex spatial sensitivity of the γ-th coil.

A diffusion-weighted image is usually corrupted by an extra phase term. This phase originates from subject motion during diffusion encoding periods and varies from shot to shot. When an array of coils is used to receive MR signal, this phase error needs to incorporate into the SENSE formulation. By including this phase, the encoding matrix can be modified as,

$$\mathbf{E}_{(\gamma,k,n),\rho} = \exp(-i\,\mathbf{k}_{k,n}\,\mathbf{r}_\rho)\; s_\gamma(\mathbf{r}_\rho)\; p_n(\mathbf{r}_\rho) \quad [3]$$

Here, $\mathbf{k}_{k,n}$ is the k-th sampling point of the n-th interleaf, and $p_n(\mathbf{r}_\rho)$ is the motion-induced phase. Comparing to Eq. [2], we observe that $s_\gamma(\mathbf{r}_\rho)p_n(\mathbf{r}_\rho)$ is a composite sensitivity profile of the γ-th coil during the n-th interleaf. Under this treatment, image reconstruction for multi-shot SENSE DWI is equivalent to traditional SENSE reconstruction.

In vivo DTI data were acquired with SNAILS on a GE Signa 1.5T whole-body system using an 8-channel head coil. The sequence parameters were: number of interleaf = 20, FOV = 22cm, matrix size = 256x256, TR = 2.5s, TE = 67ms, b = 800s/mm^2, and NEX = 2. Six diffusion encoding directions were applied to measure the diffusion tensor. To reconstruct an image, composite sensitivity maps were first estimated for each interleaf and each coil using fully sampled center **k**-space data. The conjugate gradient method was then applied compute the image iteratively. Reduction factors up to four were obtained by skipping a number of interleaves; and for each reduction factor diffusion tensors were calculated.

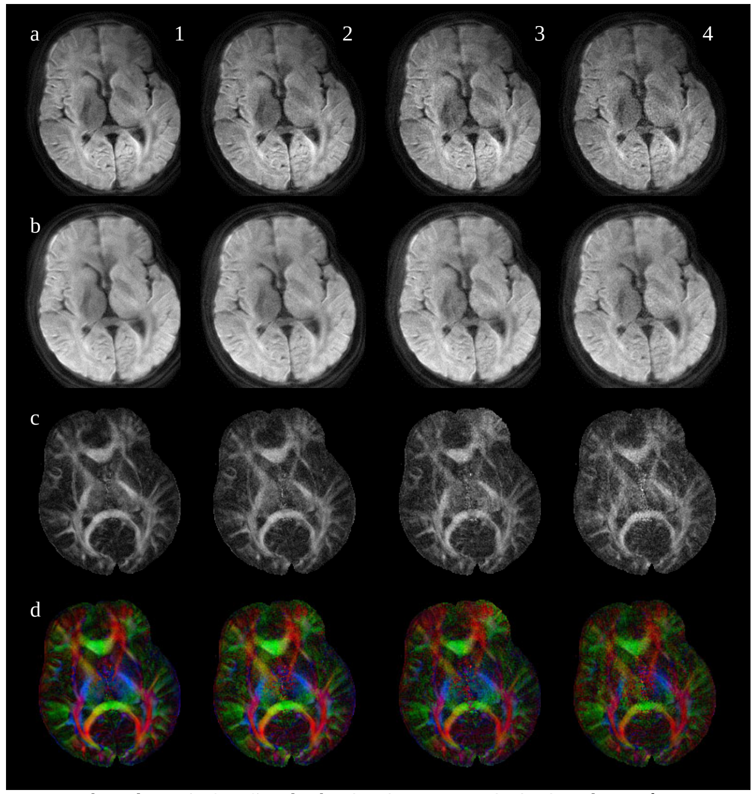

Fig 1 – High resolution (256x256) multi-shot SENSE DTI using SNAILS. Reduction factor ranges from 1 to 4. (a) initial images; (b) corrected final images; (c) FA maps; (d) color-coded FA maps.

RESULTS: Figure 1 shows a representative set of diffusion-weighed images and corresponding FA maps with reduction factors ranging from one to four. The diffusion encoding direction is [1 0 1]. Row (a) shows the initial estimation of the image. Row (b) shows corresponding images reconstructed with the conjugate gradient method. Compared to the initial images, signal intensity is greatly improved in the final images. Row (c) shows FA maps. Row (d) shows corresponding color-coded FA maps. The color coding is: red (A/P), green (R/L), and blue (S/I).

DISCUSSION: We have shown that phase errors from multi-shot DWI can be incorporated very easily into the SENSE formulation. We have also successfully performed multi-shot SENSE DWI with SNAILS. By oversampling the center of **k**-space, SNAILS provides the capability of both sensitivity self-calibration and motion navigation. With SENSE SNAILS, high resolution DTI data can be acquired at a faster speed. The readout time of each interleaf can be shortened, thus reducing image blurring caused by off-resonance.

In multi-shot SENSE DWI, reliable sensitivity information is important for accurate image reconstruction. For single-shot acquisitions, the motion-induced phase error $p(\mathbf{r}_\rho)$ is a common factor for all coils, thus can be absorbed into vector **m** and neglected in image reconstruction. For multi-shot acquisitions, however, the phase error varies from shot to shot and can not be separated from the encoding matrix. Therefore it is crucial to dynamically update the composite sensitivity maps. This estimation can be readily achieved by using SNAILS. With SNAILS, each interleaf of variable-density spirals oversamples the center of **k**-space. For each interleaf, a low-resolution composite sensitivity map can be directly measured using the center portion of k-space data.

With an accurate knowledge of the composite sensitivity map, images can be calculated iteratively using the conjugate gradients method. In the original SENSE algorithm, the matrix-vector product of $(\mathbf{E}^H\mathbf{E})\mathbf{m}$ is computed using a sequential forward and backward gridding. For multi-shot SENSE DWI, these two gridding procedures have to be performed for each interleaf and each coil separately during each CG iteration. With a large number of interleaves, gridding can be very time consuming. However, $(\mathbf{E}^H\mathbf{E})\mathbf{m}$ can be computed much faster using the transfer function approach, in which it is computed in **k**-space by multiplying the image with a transfer function.

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