Multi-Shot Imaging with Conjugate-Gradient Motion Correction

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Highlights:

- Description of multi-shot MR signal equation in matrix form in the presence of motion
- Application of conjugate gradient optimization to multi-shot MR image reconstruction in the presence of motion
- Effect of rotational motion on k-space sampling consistency
- Effect of motion correction on directional encoding schemes
- Application of non-linear conjugate gradient on multi-shot diffusion tensor imaging

Introduction

Most commonly used anatomical imaging sequences such as T1-weighted SPGR, time-of-flight MRA, T2-weighted fast spin echo T1-weighted spin-echo, etc. use multiple interleaves to acquire a single imaging volume. As compared to fast acquisition strategies that acquire multiple volumes, such as diffusion tensor imaging, perfusion imaging and fMRI, correction of motion during a multi-interleave (a.k.a multi-shot, segmented) imaging sequence is challenging for multiple reasons:

- Multi-volume imaging sequences that rely on fast EPI acquisitions (DTI, fMRI, perfusion) can employ methods such as volume-to-volume ((1)) or slice-to-volume registration ((2,3)) since each acquired slice will be artifact-free. However, motion during multi-shot sequences results in aliasing artifacts within the same imaging volume or slice. Thus, independent methods, such as self-navigated trajectories (4), navigator echoes (5) or external tracking (6) are needed to determine motion.
- After retrospective correction, rotational motion during a multi-shot acquisition results in gaps in k-space. This violates the Nyquist sampling theorem in certain regions of k-space and results in aliasing artifacts (7,8).
- In sequences where directional encoding is used, such as phase-contrast MRA and diffusion tensor imaging, motion alters the effective directional encoding (9) .

In this talk, matrix form of the MR signal equation will be introduced, and the effects of motion will be described using this form (8,10). Next, Nyquist undersampling caused rotational motion will be described and a conjugate-gradient based formulation to correct for this undersampling will be introduced. Finally, the effect of motion on sequences that use directional encoding will be presented, and a non-linear conjugate gradient-based optimization to correct for directional encoding in diffusion tensor imaging will be described.

Theoretical Background

MR signal equation can be written as follows:

$$S_{\kappa,\gamma} = \sum_{\rho=1}^{N_\rho} s_\rho c_{\rho,\gamma} e^{-\frac{j2\pi}{N}\mathbf{k}_\kappa \cdot \mathbf{r}_\rho} \qquad [1]$$

where $S_{\kappa,\gamma}$ is the acquired k-space data, s_ρ is the image, $c_{\rho,\gamma}$ is the coil sensitivity profile, $\mathbf{k}$ is the k-space location, $\mathbf{r}$ is the image space location, κ is the k-space location index, ρ is the image space location index and γ is the coil index. Using matrix formalism, equation [1] can be written as:

$$\mathbf{S} = \mathbf{FCs} \qquad [2]$$

where $\mathbf{S}$ is the acquired k-space data $\left(N_\kappa N_\gamma \times 1\right)$, $\mathbf{s}$ is the image $\left(N_\rho \times 1\right)$, $\mathbf{C}$ is the coil sensitivity profile matrix $\left(N_\rho N_\gamma \times N_\rho\right)$ and $\mathbf{F}$ is the Fourier transformation matrix $\left(N_\kappa N_\gamma \times N_\rho N_\gamma\right)$.

In the presence of motion, Eq. [2] becomes:

$$\mathbf{S}_i = \mathbf{F}_i \mathbf{C} \mathbf{U}_i \mathbf{s} \qquad [3]$$

where *i* represents the shot number and $\mathbf{U}_i$ is the deformation matrix that represents motion for shot i. By augmenting all matrices with the number of shots, one obtains:

$$\mathbf{S}^{aug} = \mathbf{F}^{aug}\mathbf{C}^{aug}\mathbf{U}\mathbf{s} \qquad [4]$$

Here, $\mathbf{S}^{aug}$ is $\left(N_\kappa N_\gamma \times 1\right)$, $\mathbf{F}^{aug}$ is $\left(N_\kappa N_\gamma \times N_\rho N_\gamma N_i\right)$, $\mathbf{C}^{aug}$ is $\left(N_\rho N_\gamma N_i \times N_\rho N_i\right)$ and $\mathbf{U}$ is $\left(N_\rho N_i \times N_\rho\right)$. Eq [4] can be solved for $\mathbf{s}$ using linear least-squares optimization:

$$\mathbf{s} = \arg\min_{\mathbf{s}'} \left\| \mathbf{S}^{aug} - \mathbf{F}^{aug}\mathbf{C}^{aug}\mathbf{U}\mathbf{s}' \right\| \qquad [5]$$

Dues to the high-dimensionality of the inverse problem, Eq. [5] can be solved using a linear conjugate gradient method. Although Eq. [5] is the way to formulate the inverse reconstruction problem, the operations are never carried out using matrix multiplications due to the high memory requirements. For example, the matrix $\mathbf{F}^{aug}$ requires 64TB of memory for a 2D 256x256 image acquired using 8 coils and 32 interleaves. Instead, all operations in Eq. [5] are accomplished using FFT (Fast Fourier Transform), gridding, point-by-point image multiplications and interpolations.

One advantage of iterative solution using Eq. [5] is that, rotational motion results in gaps in k-space and violation of Nyquist condition. In this case, the complementary encoding information obtained from coil sensitivity profiles $\mathbf{C}$ and the use of iterative optimization can eliminate artifacts resulting from the violation of Nyquist condition.

The situation becomes more complicated in the presence of directional encoding. Two such examples are determination of velocity direction and magnitude in phase-contrast MRA and the determination of diffusion tensors in diffusion tensor imaging (DTI). In this case, diffusion tensor or velocity becomes part of Eq. [5]. Particularly for DTI, the MR signal equation must be written in the following form:

$$S(\mathbf{k}) = \sum_{\mathbf{r}} s\left(\mathbf{Rr} + \Delta\mathbf{r}\right) e^{-\sum\left(\mathbf{R}^T\mathbf{bR}\right)\bullet\mathbf{D}\left(\mathbf{Rr}+\Delta\mathbf{r}\right)} e^{-j\mathbf{k}\bullet\left(\mathbf{Rr}+\Delta\mathbf{r}\right)} \qquad [6]$$

Here, due to the appearance of the diffusion tensor **D** in the exponent, the linear form in Eq. [5] and a linear-least squares solution based on conjugate gradient cannot be used anymore. It will be shown that this equation can be solved using a non-linear conjugate gradient approach.

References

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