Accelerated multi-shot diffusion imaging

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Target Audience: Researchers interested in using diffusion imaging to probe brain structures.

Purpose: MR diffusion-weighted imaging (DWI) has evolved into an immensely useful tool. However, motion sensitivity remains a serious problem in DWI. To protect against motion-induced phase variations, single-shot 2D echo-planar imaging (EPI) is typically employed to generate 'snapshot' images, and the error-prone phase information is dismissed. Alternately, one can use navigator echoes to detect and account for phase variations, thus enabling multi-shot DWI. Multi-shot imaging can be useful, for example, to alleviate the geometrical distortion problems that tend to plague single-shot imaging (e.g., see Fig. 1). But multi-shot imaging can lead to prohibitively-long scan times, and for this reason, the method proposed here was designed to very much speed-up multi-shot DWI acquisitions. As compared to a single-shot EPI sequence as typically used in DWI, the proposed approach improves image quality, especially in terms of geometric distortion, at potentially no cost in scan time.

The present method is based on the observation that DWI data tend to be very sparse when represented in the x-y-k_b-k_d space, where k_b and k_d are the conjugate variables associated with b and d, the b-factor and diffusion direction, respectively. The accelerated multi-shot DWI technique presented here was designed to fully utilize the available navigator information, both magnitude and phase, for motion compensation and regularization purposes. Results were obtained where sizeable acceleration rates were achieved, in a manner that proves readily compatible with additional acceleration methods such as parallel imaging, or partial-Fourier imaging. Modern acceleration schemes often combine a number of different individual strategies for added effect, and the present approach might well prove a worthwhile contributor to the mix.

Method: The present work is based on the observation that the imaged object, $\boldsymbol{o}$, tends to be very sparse in the x-y-k_b-k_d space. The expression for the encoding matrix, **E**, as shown below, is similar in form to that obtained in the phase-corrected multi-coil navigated method from Atkinson *et al* (1):

$$\mathbf{E}_j = \sum_i (\mathbf{F}_d \times \mathbf{F}_b \times \mathbf{F}_y^H \times \mathbf{W}_i \times \mathbf{D}_i \times \mathbf{F}_y \times \mathbf{c}_j \times \mathbf{p}_i \times \mathbf{F}_d^H \times \mathbf{F}_b^H); \quad \mathbf{E} = [\mathbf{E}_1 \ldots \mathbf{E}_{Nc}]^T; \quad \hat{\boldsymbol{o}} = (\mathbf{E}^H \times \boldsymbol{\Psi}^{-1} \times \mathbf{E} + \lambda^2 \mathbf{L})^{-1} \times \mathbf{E}^H \times \boldsymbol{\Psi}^{-1} \times \boldsymbol{s}, \qquad [1]$$

where $\mathbf{F}_y$, $\mathbf{F}_d$ and $\mathbf{F}_b$ perform Fourier transforms along y, b and d, respectively, $\mathbf{p}_i$ is a motion-related phase correction (from navigator data), $\mathbf{D}_i$ subsamples k-space, $\mathbf{c}_j$ is the sensitivity map for coil j (out of N_c coil elements), $\mathbf{W}_i$ can be used to suppress unreliable data, the summation is made over interleaved segments, $\hat{\boldsymbol{o}}$ is the reconstructed image, $\boldsymbol{s}$ is the acquired signal, $\mathbf{E}^H \times \boldsymbol{\Psi}^{-1}$ is a preconditioning term and $\lambda^2\mathbf{L}$ is a damped least-squares regularization term. Equation 1 differs from Ref (1) as it operates on a 3-D space (k_y-b-d) rather than a 1-D space (k_y), and because of its different sampling scheme, $\mathbf{D}_i$, and regularization, $\lambda^2\mathbf{L}$. The most desirable sampling scheme would lead to a $\mathbf{D}_i$ matrix that minimizes the condition number of the resulting **E** matrix, for a given acceleration factor, R. The selected sampling scheme in k_y-b-d space is depicted in Fig. 2. For regularization purposes, the magnitude of the navigator signal in y-k_b-k_d space was used to evaluate the regularization matrix **L**, in a manner consistent with work in (2).

Our navigated multi-shot EPI sequence is depicted Fig. 3. Imaging was performed on a 3.0 T MR system (GE Signa CVi, 40 mT/m, 150 T/m/s, axial slices, thickness=4mm, spacing=4mm, TR=3s, echo train length=32, bandwidth=±250kHz, N_d=6). Figure 4 gives a schematic representation of the reconstruction algorithm. Because it has no directional dependence, the b ≈ 0 data could be fully sampled at little cost in scan time, and this is why these data are treated differently from the b > 0 data in Fig. 4. A total of five human volunteers were imaged, following informed consent with an IRB-approved protocol.

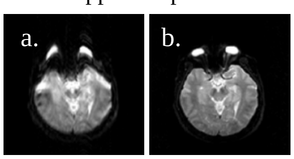

Fig. 1: *Compared to single-shot EPI (a), a 4-shot scan reduces distortion (b).*

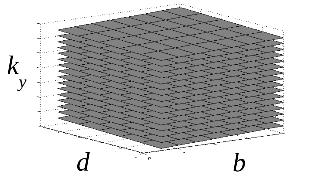

Fig. 2: *For example, 16 tilted planes separated by 8 k_y lines would lead to 128 y locations, with R=8.*

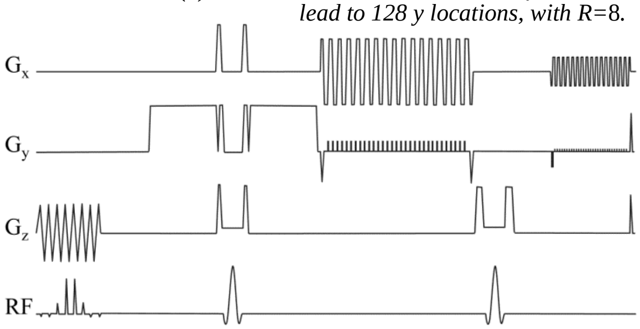

Fig. 3: *Navigated multi-shot EPI sequence used here.*

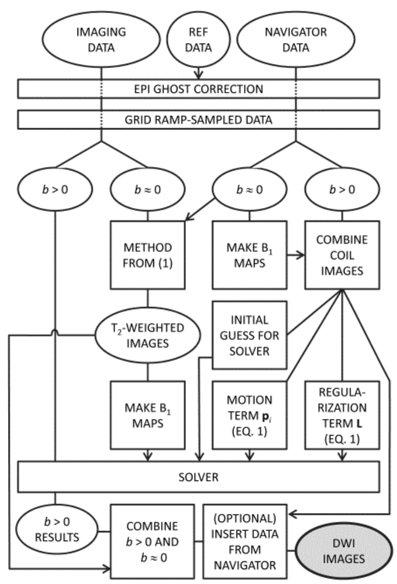

Fig. 4: *Reconstruction algorithm.*

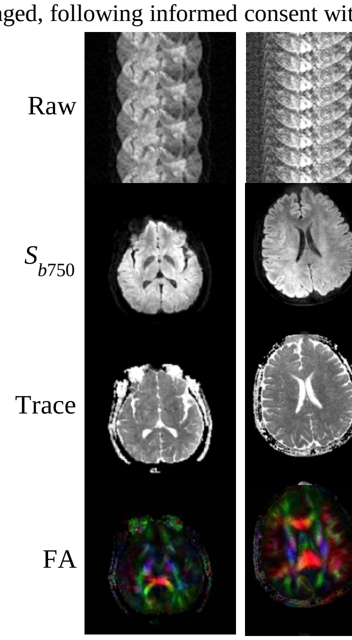

Fig. 5: *Examples of results*

Results: The DWI results displayed here are quite representative, in terms of overall quality, of the collection of images we obtained. Figure 5 shows raw (aliased) acquired images and tensor-processing results (S_{b750}, trace and fractional anisotropy), for an R=4, 128×128, 25.6×25.6 cm^2, N_b=4 dataset acquired with a single-channel quadrature coil (left), and an R=8, 192×256, 17.0×22.7 cm^2, N_b=8 dataset acquired with an 8-channel coil (right).

Conclusion: As compared to non-accelerated single-shot methods, the present approach allows a reduction in the length of the echo train and, accordingly, a reduction in geometrical distortions. A key characteristic of the proposed method is how thoroughly the navigator signal gets utilized.

References: [1] Atkinson et al. MRM 2006;56:1135. [2] Tsao et al. MRM 2003;50:1031.

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