Pushing the Resolution of 3D Spin Echo Diffusion Acquisition

J. L. Holtrop[1], A. T. Van[2], and B. P. Sutton[1,3]

[1]*Bioengineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States,* [2]*Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States,* [3]*Beckman Institute, University of Illinois at Urbana-Champaign, Urbana, IL, United States*

Introduction: High resolution diffusion weighted imaging (DWI) is desired to examine structural properties of small white matter structures in the brain, such as the hippocampus. Higher resolution in DWI has the potential to explore new structures previously unaccessible at lower resolutions and will also reduce partial volume effects when looking at diffusion properties of specific structures. Achieving enough SNR in reasonable scan times has been one of the main limitations to achieving higher resolution diffusion weighted images. In this work, we employ a multi-shot multi-slab approach to DWI [1] that has increased SNR efficiency compared with standard DWI methods. By combing a multi-slab approach with recent advances in motion correction for 3D diffusion imaging, along with parallel imaging and field correction techniques, we have developed an approach capable of producing full brain 1mm isotropic diffusion weighted images with reasonable SNR at 3T.

Methods

Multi-slab Imaging: For a spin-echo sequence there is a trade off that can be made to optimize the TR of the sequence, if a sequence has a long TR, more signal recovery happens between excitations, however if the TR is reduced, more averages (or more encodings) of the same excited volume can be made. The averaging and signal recovery trade-off can be seen in Figure 1 using T1 and T2 relaxation times of brain tissue. 2D DWI acquisitions with full brain coverage have long TRs (~10 seconds for 2mm thick slices). If using 2D imaging these TRs cannot be made shorter due to the fixed number of excitations needed. However, if instead of exciting 2D slices the imaging volume is divided into 3D slabs that are composed of several slices, the TR of the sequence can be decreased and optimized for SNR efficiency. This approach enables increased data acquisition time for an excited volume without increasing the total acquisition time of the sequence. Because SNR is proportional to the square root of acquisition time for each slab/slice, SNR efficiency increases.

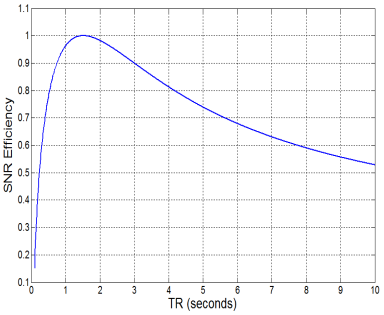

Figure 1: SNR efficiency based on TR for a tissue with a T1=1084ms and T2= 69ms.

Multi-shot spiral: Single shot imaging is commonly used in diffusion imaging due to its robustness to motion artifacts. However, when increasing resolution, the readout duration increases. When the readout duration is increased, T2* decay causes blurring to the point spread function and signal loss [2]. To avoid this issue, techniques such as multi-shot or parallel imaging are commonly used to shorten readout durations. Shorter readout durations come at a cost: parallel imaging comes at a loss of SNR while multi-shot increases the number of excitations required to image a volume. Due to the high resolution targeted and the multi-slab approach, a multi-shot acquisition was used to enable a large imaging volume to be encoded without a loss in SNR. A spiral readout trajectory was used due to its efficient coverage of k-space and ability to sample the echo at the beginning of the readout, keeping echo times short. A target readout duration of 60-70 ms was desired because of the ability to correct for field inhomogeneity at this length. Using a 240x240 matrix size, a 24x24 cm^2 field of view requires a 4-shot fully sampled constant density spiral in order to keep the spiral duration to 70 ms. Fewer shots using parallel imaging are possible if less SNR is acceptable..

Motion correction: Due to the multi-shot acquisition, a motion-induced phase correction technique was used that was able to account for motion in 3D diffusion imaging and prevent signal loss due to phase cancellation between the shots. The technique by Van et al. [3] was used to robustly eliminate rigid-body induced phase errors, combined with cardiac gating of the sequence to reduce non-rigid pulsation motions. This technique requires a 3D navigator which was acquired as a stack of spirals after an additional 180 refocusing pulse following the imaging readout.

Imaging Acquisition: In order to achieve a high SNR efficiency, a TR of 2 R-R intervals was used with 4 slabs, with 2 slabs being excited in each R-R interval. This multi-slab approach resulted in the use of 4 3D slabs to cover the imaging volume of the whole brain. Slabs were made 32 mm thick with 25% overlap between slabs to account for aliased energy due to imperfections in the slab excitation profile. This resulted in slabs 24 mm thick and a FOV of 240x240x96mm^3 at a 1 mm isotropic resolution. Data was acquired on a Siemens 3 T Trio with a 12 channel head coil. A PGSE sequence was used for diffusion weighting with a b–value of 1000 s/mm^2. The acquisition used a stack of spirals for 3D encoding with 32 phase encoding steps and 4 shot spirals for each phase encode, resulting in a 128 shot acquisition per volume. A TE of 70ms was used for image data and a TE of 188ms for navigator data with a 15x15x10 matrix size. Field maps and sensitivity maps were acquired from a separate sequence.

Image Reconstruction with GPU: The strategies employed to reach 1 mm isotropic resolution resulted in a computationally challenging image reconstruction problem. To reconstruct a 240x240x32 matrix image, using SENSE, field-inhomogeneity corrections, and non Cartesian k-space trajectories, requires a significant amount of computational power, taking 10 days to reconstruct a data set with 1 b-value and 6 diffusion encoding directions on a dual core workstation. Although the acquisition used was a stack-of-spirals, motion induced phase results in random shifts of the trajectories, resulting in a truly 3D k-space trajectory. In order to reconstruct images in a reasonable time, the computing power of GPUs was used in combination with the iterative methods of the IMPATIENT MRI code [4].

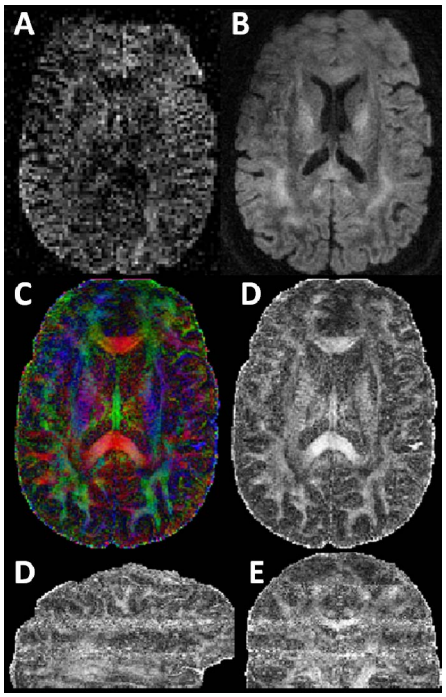

Figure 2: DWI from a 2mm EPI sequence (A) and a 1mm 3D approach (B). FA maps from 6 directions of diffusion encoding for the 3D 1mm sequence (C-E)

Results: Measurements of SNR, using the difference method [5], on a phantom indicated that the proposed method for 1x1x1mm^3 had 10 times the SNR of a 2D 2x2x2mm^3 EPI sequence for one image, with the ability to acquire multiple averages of the 2D acquisition in the same amount of scan time, the proposed method still shows twice the SNR of the 2D method. A 1 mm isotropic diffusion image using the proposed technique is shown in Figure 2, along with FA and color-coded FA maps showing good detail and separation of white and gray matter. The reconstruction time was brought down from 10 days to a more reasonable 4 hours for a complete DTI data set by using GPUs.

Discussion: We have presented an SNR efficient approach to DWI that enables the acquisition of 1 mm isotropic diffusion weighted images. Resulting DWI show high levels of detail and contain significant SNR compared with commonly acquired 2mm resolution images.. The SNR improvement from this approach may enable parallel imaging to speed up the acquisition of DTI data and may enable the use of more diffusion encoding directions for accurate estimate of a diffusion tensor.

References: [1] A. T. Van, et al. ISMRM 2010, p.1618 [2] F. Farzaneh, et al. *Magnetic Resonance in Medicine,* vol. 14, pp. 123, 1990. [3] A. T. Van, et al. *IEEE Transactions on,* vol. 30, pp. 1933-1940, 2011. [4] Xiao-Long Wu, et al. *2011 IEEE International Symposium ,* 2011, pp. 69-72. [5] S. B. Reeder, et al. *Magnetic Resonance in Medicine,* vol. 54, pp. 748-754, 2005.

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