Diffusion-Weighted Matched-phase Adiabatic Spin Echo (DW-MASE) Sequence for Ultrahigh Field Brain Diffusion-Weighted Imaging

Hadrien Dyvorne[1], Rafael O'Halloran[1], and Priti Balchandani[1]
[1]*Radiology, Icahn School of Medicine at Mount Sinai, New York, NY, United States*

Target audience: Physicists and radiologists with an interest in performing diffusion-weighted imaging at high fields such as 7 Tesla.

Introduction: Diffusion-weighted imaging (DWI) can benefit greatly from the increased signal-to-noise ratio (SNR) achievable at ultrahigh magnetic fields such as 7 Tesla (7T). Unfortunately, inhomogeneity in the applied radiofrequency (RF) or B_1 field leads to spatially heterogeneous loss in image SNR and contrast, especially when large-flip-angle RF pulses are used, as is the case in DWI. We designed and implemented a DWI sequence which utilizes a Matched-phase Adiabatic Spin Echo (DW-MASE) to provide greater immunity to B_1-inhomogeneity. The hypothesis is that the matched-phase semi-adiabatic RF pulse-pairs in DW-MASE will lead to increased diffusion signal uniformity and more accurate computation of DWI-based parameters when compared to a conventional DWI sequence which uses standard non-adiabatic pulses. This was tested in a spherical phantom and a healthy volunteer at 7T.

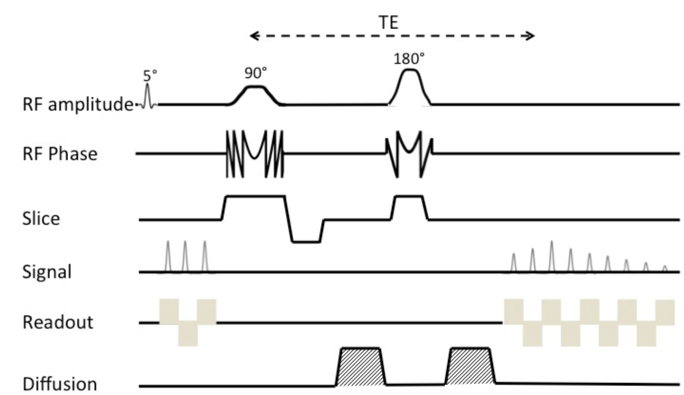

Figure 1*: Pulse sequence diagram for DW-MASE.*

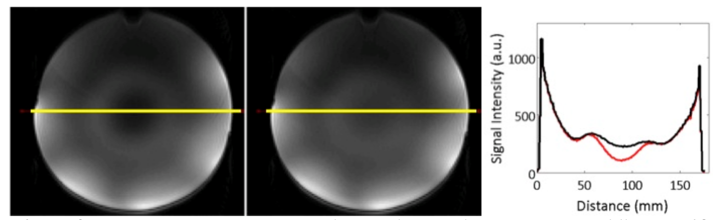

Figure 2*: comparison of conventional DWI (left) and DW-MASE (middle) in a 180 mm-diameter spherical phantom. Right: signal intensity profile.*

Methods: An adiabatic refocusing pulse was designed using the adiabatic Shinnar-Le Roux (SLR) algorithm [1], with a 4 ms pulse duration, 1.32 kHz spectral bandwidth and 12.4 µT peak RF amplitude at adiabatic threshold. A matched-phase 90° excitation pulse (8 ms duration) was derived from the beta squared polynomial of the adiabatic 180° [2] in order to correct for the nonlinear phase induced by the adiabatic refocusing pulse. Both RF pulses were inserted in a Stejskal-Tanner DWI sequence with a single shot echo planar imaging readout to produce the DW-MASE sequence (Figure 1). We compared the performance of DW-MASE to that of conventional DWI using linear phase SLR pulses of similar durations and slice profile. MR acquisitions were performed on a spherical phantom as well as in a healthy volunteer, using a Magnetom 7T scanner (Siemens Healthcare, Erlangen, Germany) equipped with 70 mT/m gradient sets. Informed consent was obtained prior to volunteer scans. Imaging parameters were: 40 slices (axial orientation), spatial resolution 1.4 x 1.4 x 2 mm^3, parallel imaging R=3 (GRAPPA), TE/TR of 55/8800 ms (for conventional DWI) and 57/12300 ms for (for DW-MASE), 68 directions acquired with b = 1000 s/mm^2. Diffusion volumes were registered to anatomical MPRAGE images and eddy current-induced distortions were corrected using FSL [2]. Tract Density Imaging (TDI) and white matter tractography were performed using MRTRIX [3].

Results: The signal intensity of the image acquired with DW-MASE was higher than that of the image acquired with conventional DWI in the center of the spherical phantom (Figure 2) and in mid-brain areas of the healthy volunteer (yellow arrow) (Figure 3A). The increased signal in these areas led to higher tract density in the thalamus (an area heavily affected by the B_1-inhomogeneity) for TDI calculated from the DW-MASE data (yellow arrow) when compared to TDI derived from conventional DWI (Figure 3B). Figure 3C shows a group of tracts in the stria terminalis area (yellow arrow), which were only observable with DW-MASE and not with conventional DWI, despite being seeding with the same anatomical ROI. A negative consequence of using adiabatic pulses is that there is a 40% increase in specific absorption rate (SAR), thus requiring a longer scan. However, total scan duration remains clinically feasible (7:46 min for DW-MASE vs. 5:53 min for conventional DWI) for a full set of 68 diffusion directions.

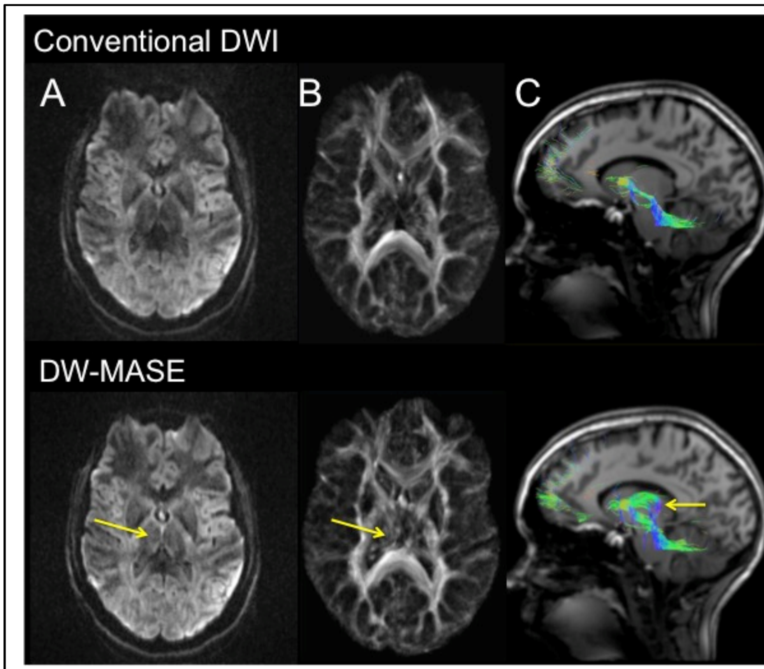

Figure 3*: White matter tractography of a 68-direction DWI acquisition on a healthy volunteer. Top row: conventional DWI, bottom row: DWI-MASE. A: magnitude image for a single diffusion direction at b = 1000 s/mm^2. B: tract density images. C: tract visualization between left mid-brain and left anterior limb of the internal capsule.*

Discussion and Conclusion: A semi-adiabatic matched-phase pulse pair was developed for DWI at 7T and integrated into a DW-MASE sequence, resulting in improved diffusion data quality and better signal homogeneity for whole brain DWI. While previous studies have used adiabatic pulses for twice-refocused DWI [5], this work is the first to implement an adiabatic refocusing pulse in a single-refocused DWI acquisition, thereby allowing shorter echo time, higher SNR and reduced SAR compared to a twice-refocused approach. The primary limitation is that adiabatic pulses lead to 40% higher SAR and scan time increase, however the SNR gain in crucial regions of the brain may allow for reduced signal averaging. We found that the improved signal inhomogeneity with DW-MASE led to more accurate representation of the anatomy and improved accuracy of diffusion metrics such as tract density. Increased accuracy is especially important when applying DWI to measure structural connectivity for surgical planning for which missing fiber tracts could result in a potentially disastrous outcome.

References:

[1] Balchandani et al, MRM 64:843–851 (2010);
[2] Balchandani et al, MRM 67:1077–1085 (2012);
[3] Jenkinson et al, Neuroimage 62:782-90, 2012;
[4] Tournier et al, Neuroimage 2007; 35 (4): 1459-1472;
[5] Balchandani et al, MRI 32 (2014) 804–812.

Acknowledgements: NIH-NINDS R00 NS070821, Icahn School of Medicine Capital Campaign, Translational and Molecular Imaging Institute and Department of Radiology, Siemens Healthcare.