Quantitative Magnetization Transfer Imaging of Human Cervical Spinal Cord at 7 Tesla

Richard D. Dortch[1,2], Adrienne N. Dula[1,2], Ke Li[1,2], Jane A. Hirtle[2], Catherine E. Frame[2,3], Pooja Gaur[2,4], John C. Gore[1,2], and Seth A. Smith[1,2]

[1]*Radiology and Radiological Sciences, Vanderbilt University, Nashville, TN, United States,* [2]*Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States,* [3]*Radiation Oncology, Vanderbilt University, Nashville, TN, United States,* [4]*Chemical and Physical Biology, Vanderbilt University, Nashville, TN, United States*

Introduction: Magnetization transfer (MT) imaging has been used to assess macromolecular content in the human brain; yet, similar studies in the spinal cord have been limited. The difficulties associated with spinal cord imaging include high-resolution demands (cord diameter ≈ 1.5 cm) and the presence of motion due to CSF pulsation and respiration. Despite these difficulties, MT has been characterized in the spinal cord via the MT ratio normalized to the CSF (MTCSF), a measure that has been shown to be sensitive to changes in myelination [1,2]. Unfortunately, MTCSF is also sensitive to changes in tissue relaxation times and flow effects in CSF. As a result, more rigorous quantitative MT (qMT) approaches have been pursued at 1.5 and 3 T [3,4]. Given the resolution demands of imaging the spinal cord, qMT studies of the spinal cord may benefit from the increased SNR available at 7 T. Therefore, we have developed a protocol for high-resolution qMT imaging of the cervical spinal cord at 7 T and here we report data acquired in healthy subjects.

Methods: Pulse Sequence: A selective inversion recovery (SIR) qMT imaging sequence with a turbo field echo (SIR-TFE) readout (Fig. 1)—applied previously in the human brain at 7 T [5]—was used here to collect qMT data of the cervical spinal cord. A composite inversion pulse [5] was employed to uniformly invert the free pool magnetization in the presence of large ΔB_0 and B_1^+ variations. Data Acquisition: Four healthy volunteers (20–33 y.o.) were imaged using a 7 T Philips MR scanner. A surface quadrature coil and a 16-channel spine array (Nova Medical) were used for RF transmission and reception. SIR-TFE data were acquired in an axial volume from C2 to C4 using: t_i =6–8000 ms (14 values), t_d = 2.5 s, echo spacing/TE/α = 5.7 ms/3.6 ms/15°, echoes per shot = 180, resolution = 1×1×5 mm^3, field-of-view = 180×80×50 mm^3. Flow-compensation was employed to minimize artifacts from CSF pulsation. B_1^+ was measured in the same volume using the actual flip angle imaging method [6]. Data Analysis: All SIR-TFE volumes were co-registered to the volume acquired at t_i = 8000 ms using a 3D affine registration based upon normalized mutual information [7]. Regions-of-interest (ROIs) were conservatively defined in the dorsal (*dc*) and lateral columns (*lc*) and in gray matter (*gm*) to minimize partial-voluming (Fig. 2). Data from each ROI were fit to a biexponential model derived from a two-pool model of the MT effect [8]. This yielded the macromolecular to free proton pool size ratio (*PSR)*, the MT rate (k_{mf}), and the R_1 of the free pool (R_{1f}). An estimate of macromolecular pool saturation due to the inversion pulse was required for these fits. This was obtained via numerical simulation of the inversion pulse using the mean B_1^+ in the cord [8].

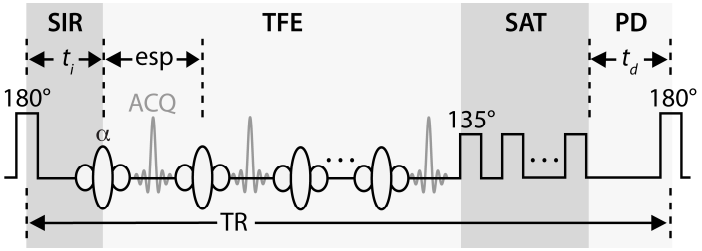

Fig. 1. SIR-TFE pulse sequence. The TFE readout is followed by a train of RF pulses designed to saturate (SAT) both pools and a predelay (PD) period to allow for partial *z*-magnetization recovery. Legend: t_i = inversion time, t_d = predelay, esp = echo spacing, ACQ = acquisition.

Results and Discussion: Sample SIR-TFE images as a function of t_i are given in Fig. 2. Note the contrast between white and grey matter and the absence of flow-related artifacts. Sample experimental data and model fits are given in Fig. 3. SIR-TFE data had an SNR of 110 ± 40 across all ROIs [defined as M_0 divided by the standard deviation (SD) of the residuals]. Previous Monte Carlo simulations [8] indicate that this is sufficient to robustly fit the parameters reported herein. Mean qMT parameters were tabulated across the middle six slices for all volunteers (Table I). *PSR* values were slightly higher in white matter relative to grey matter. This is in agreement with previously reported *PSR* values from the human cervical spinal cord at lower field strengths [3,4], although the relative difference between white matter and gray matter *PSR* values was smaller herein, perhaps due to blurring from the TFE readout. MT rates (k_{mf}) were also similar between white and grey matter, but should be interpreted with caution due to the large variability of this parameter. Consistent with previous T_1 measurements in the cervical spinal cord at 3 T [9], R_{1f} values were higher in white matter relative to gray matter. These preliminary results suggest that qMT imaging can be performed in the human cervical spinal cord at ultra-high field. Future work will include modifying the blurring effect of the TFE readout and applying this method in multiple sclerosis patients.

Table I. Mean ± SD qMT parameters.

ROI	*PSR* (%)	k_{mf} (s^{-1})	R_{1f}(s^{-1})
dc	12.1 ± 3.2	18 ± 12	0.63 ± 0.04
lc	11.5 ± 2.8	20 ± 15	0.64 ± 0.04
gm	10.7 ± 2.8	15 ± 8	0.58 ± 0.03

References: [1] Smith. MRM 2005(54):201. [2] Zackoswski. Brain 2009(132):1200. [3] Smith. MRM 2009(61):22. [4] Dortch. ISMRM 2010. [5] Dortch. ISMRM 2011. [6] Yarnykh. MRM 2007(57): 192. [7] Studholme. Pat Recog 1994 (31):633. [8] Li. MRM 2010 (64):491. [9] Smith. MRM 2008(60):213.

Acknowledgments: NIH/NIBIB K01 EB009120 and R01 EB000461.

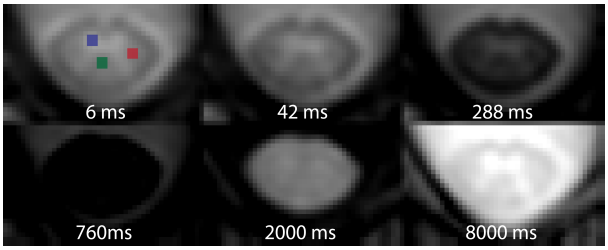

Fig. 2. SIR-TFE images (six of 14 t_is) from a slice at C3; and ROIs for the *dc* (green), the *lc* (red), and *gm* (blue).

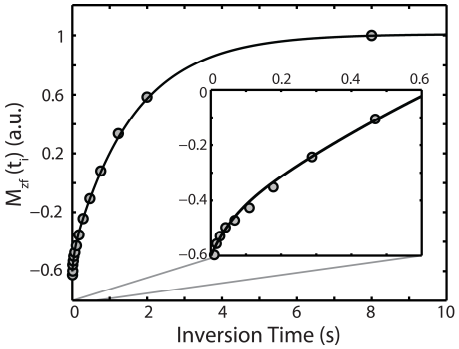

Fig. 3. Representative SIR data from the *dc*. Note the agreement between the SIR data (circles) and the biexponential model (solid line) and the deviation from a monoexpoential model (see zoomed inset).