Simultaneous Whole-Brain T_1 and Flip Angle Mapping with MP3RAGE

James A. Rioux[1], Manojkumar Saranathan[1], and Brian K. Rutt[1]
[1]*Radiology, Stanford University, Stanford, CA, United States*

Target Audience: Researchers and clinicians interested in fast, high-resolution quantitative imaging and parameter mapping of the brain.

Purpose: Measurement of T_1 values in the brain enables many promising applications, such as visualization of deep gray matter structures or automatic segmentation and classification of tissues.[1] However, clinical implementation of high-resolution, whole-brain T_1 mapping has been limited by the absence of a robust protocol that offers high accuracy, insensitivity to B_1 effects and short acquisition times. Recent developments have enabled faster T_1 imaging; for example, MP2RAGE allows the collection of two MPRAGE images within a single acquisition, which are sufficient to perform a lookup of T_1 based on the signal equations. Depending on parameters, B_1 inhomogeneity may bias the T_1 lookup, although this can be corrected with a separately acquired flip angle map.[3]

In this work we present refinements to MP2RAGE that can improve its performance. The timing of MP2RAGE acquisitions often allows a third image to be collected with no increase in scan time. This addition, dubbed MP3RAGE[4], was first proposed by Hung *et al*, who used the third image to correct for imperfect inversion pulses. We instead demonstrate its use in reducing B_1 sensitivity and allowing calculation of a flip angle (FA) map concurrently with the T_1 map.

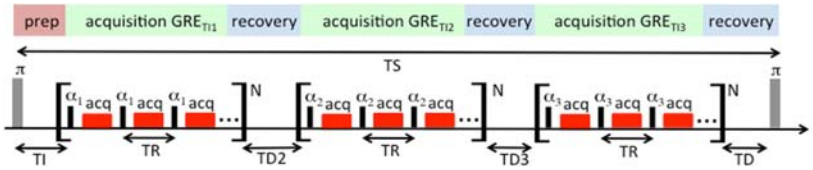

Figure 1. MP3RAGE sequence schematic. k-space is acquired in segments of N pulses of flip angle α following inversion. Segments are acquired starting at effective inversion times TI, TI2=TI+N*TR+TD2, TI3=TI2+N*TR+TD3, with total segment time TS.

Methods: The MP3RAGE sequence is illustrated in Figure 1; three images with different T_1 contrasts are obtained per inversion. Using the same formula[2] proposed for MP2RAGE lookup, three different combinations of these images are possible:

$$C_{12} = \frac{GRE_{TI1}\, GRE_{TI2}}{GRE_{TI1}^2 + GRE_{TI2}^2} \qquad C_{13} = \frac{GRE_{TI1}\, GRE_{TI3}}{GRE_{TI1}^2 + GRE_{TI3}^2} \qquad C_{23} = \frac{GRE_{TI2}\, GRE_{TI3}}{GRE_{TI2}^2 + GRE_{TI3}^2}$$

As shown in Figure 2a, an appropriate choice of parameters (selected with Matlab simulations of the signal equations) yields a C_{13} that varies monotonically with T_1 and has virtually no B_1 sensitivity. This allows creation of T_1 maps such as that shown in Figure 3a by a simple lookup. In contrast, the C_{23} signal (Figure 2b) has much higher B_1 sensitivity. Once a T_1 map is available, the flip angle can also be obtained via lookup, as shown in Figure 4. For these examples, the inversion pulse efficiency was set to -0.85, which has been empirically determined to provide accurate maps for the inversion pulse used in our implementation.

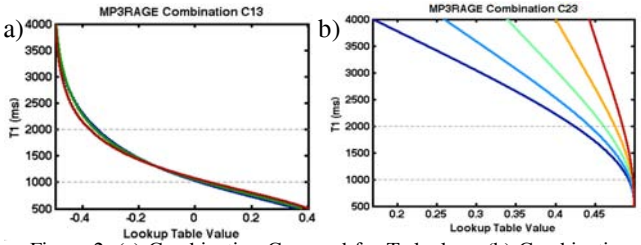

Figure 2. (a) Combination C_{13}, used for T_1 lookup. (b) Combination C_{23}, used for subsequent flip angle lookup. In both, green=nominal B_1, red= +50% nominal, blue= -50% nominal.

All images were obtained at 7T using a GE Discovery MR950 scanner (GE Healthcare, Waukesha WI) with a Nova 2chTx / 32chRx head coil (Nova Medical, Wilmington, MA). Two healthy volunteers (F, age 32 +/- 1 years) were scanned in accordance with IRB guidelines. 3D MP3RAGE images were obtained at 1mm isotropic resolution with TS=7500ms, TI=700ms, TI2=2200ms, TI3=4000ms, FA=4/5/5, N=200, TR=7.4ms. Using a 2x1 ARC acceleration factor, acquisition time was 10 minutes. A single-slice IR-FSE reference T_1 map was acquired with ETL=8, TR=6000ms, and five inversion times, TI=50,200,600,1500,4000ms. Reference FA maps were acquired with a spiral Bloch-Siegert B_1 mapping sequence[5] (18 5mm slices, TR/TE=3000/10.7ms, FA=30, 4 interleaves of 2048 readout points, 30s scan time).

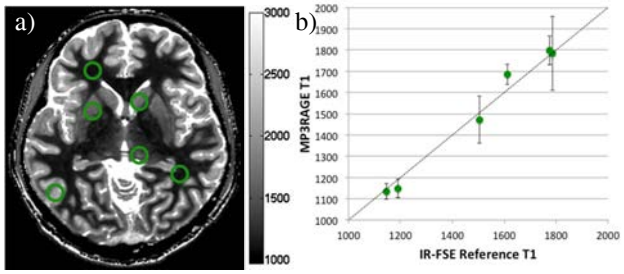

Figure 3. (a) MP3RAGE T_1 map obtained from one slice of a 3D image. (b) Comparison of T_1 values in several ROIs (green circles in Figure 3a) with T_1 in the same ROIs in IR-FSE reference map.

Results and Discussion: The slice of the MP3RAGE T_1 map corresponding to the single-slice IR-FSE reference demonstrates strong agreement with the reference over a range of T_1 values corresponding to white and gray matter at 7T. The absolute percent error of all ROIs is 2.3 +/- 1.7 (mean +/- st.dev). The T_1-to-Noise-Ratio (T_1NR), calculated as the average of (ROI mean / ROI st.dev), is slightly less than that of the reference map (24 vs. 30), but MP3RAGE covers the entire brain instead of one slice and is acquired in a similar time. The agreement between the MP3RAGE flip angle map and the reference FA map (Figure 4b) is also good (~ 8% error along the typical profile illustrated in Figure 4).

Further acceleration of MP3RAGE is possible with reduced segment time TS and additional ARC undersampling; this allows acquisition of T_1 maps at higher resolution or in less time with the standard SNR penalty. Parameter optimization may allow additional gains in T_1 and FA map quality. Finally, the C_{12} combination is currently unused, but in the future it may allow for calculation of inversion efficiency in addition to T_1 and FA.

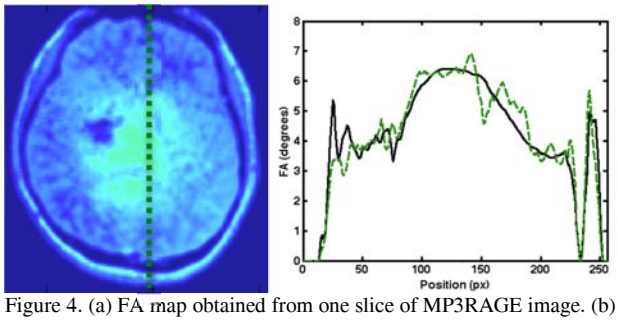

Figure 4. (a) FA map obtained from one slice of MP3RAGE image. (b) FA profile (green) compared with profile from reference map (black).

Conclusions: The parameters and image combinations outlined in this work allow for accurate T_1 mapping suitable for whole-brain coverage at high resolution, with scan times of 10 minutes or less. B_1 sensitivity is minimal – a critical requirement and advantage of the MP3RAGE method for high field imaging – and simultaneous FA mapping is also possible.

References: [1] Geyer et.al. *Front Hum Neurosci* 5 (2011). [2] Marques et.al. *NeuroImage* 49 (2010). [3] Marques and Gruetter, *PLoS ONE* 8:7 (2013). [4] Hung et.al. Proc. ISMRM #2353 (2013). [5] Saranathan et.al. *MRM* doi:10.1002/mrm.24959 (2013).

Acknowledgement: Research support from NIH (P41 EB015891, 1U54 A151459, 1P50 A114747), GE Healthcare, and the Richard M. Lucas Foundation.