Methods for quantitative magnetization transfer imaging

Ives R Levesque[1], Nikola Stikov[2], and G Bruce Pike[2]
[1]Electrical Engineering, Stanford University, Stanford, CA, United States, [2]Montreal Neurological Institute, McGill University, Montreal, QC, Canada

Purpose: Magnetization transfer (MT) contrast [1] is distinct from T_2 and T_1 contrast, and is informative in various tissues. Quantitative MT imaging (QMTI), also referred to as cross-relaxation mapping, is the estimation and mapping of MT model parameters. We will review basic concepts of MT, and the main methods of QMTI. More specifically, we will review data acquisition and analysis for techniques that employ off-resonance saturation, selective inversion recovery (SIR), and steady-state free-precession (SSFP). We discuss the assumptions, advantages, and limitations of each method, discuss field strength and optimization, and provide practical information for implementation and use.

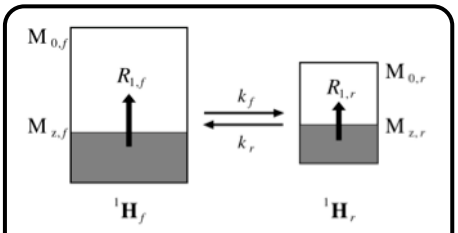

Fig. 1. Two-pool model of MT.

Outline of Content:

Background: The MT effect can be described with a two-pool model (Fig. 1), with a free water compartment (T_{2f} > 10 ms) and a more restricted macromolecular compartment (T_{2r} ~ 10 μs) [1,2]. Sequences create MT contrast by selective saturation of the restricted pool using off-resonance RF, or by selective excitation of the water pool. The behaviour of the magnetization vector **M** is described by the coupled Bloch-McConnell equations (Eq. 1):

Eq 1:
$$\dot{\mathbf{M}}(t) = \left[\mathbf{R}_1 + \mathbf{R}_2 + \mathbf{K} + \Delta(\delta) + \Omega_1(t,\delta)\right]\mathbf{M}(t) + \mathbf{R}_1\mathbf{M}_0 ,$$

where $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{K}$, Δ and $\mathbf{\Omega}(t,\delta)$ are matrix terms for relaxation, exchange, off-resonance, and RF pulses respectively. Each QMTI method combines an MT-sensitive acquisition with a manageable – preferably analytical – solution to Eq. 1. Depending on the method, MT model parameters are obtained by direct computation or non-linear estimation, sometimes requiring a separate T_1 measurement.

Off-resonance methods: These work with continuous wave (CW) or pulsed saturation, and exploit RF frequency selectivity. The CW technique is often considered the reference, and it has a simple analytical solution [3], but is impractical for in vivo applications. A number of variants exist for pulsed saturation [4,5,6], all based on spoiled gradient-echo sequences with a shaped saturation pulse (Fig. 2), which differ primarily by assumptions in the signal description and performance [7,8]. Pulsed off-resonance QMTI offers near-complete characterization of the two-pool model but has issues with SAR and SNR efficiency.

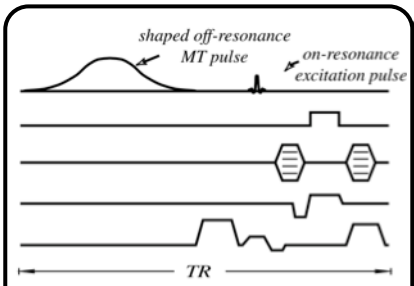

Fig. 2. Spoiled GRE sequence with saturation pulse for MT weighting.

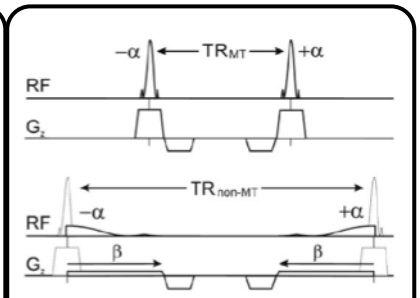

Fig. 3. Modulating the MT effect with balanced SSFP [11].

Steady-state free-precession: SSFP sequences with short RF pulses have been shown to include MT contrast [9], which can be controlled by modulation of the TR and/or RF pulse duration (Fig. 3). SSFP-QMTI is described by a solution to Eq. 1 with the same form as the Freeman-Hill equation [10,11], with assumptions about T_{2r} and restricted pool RF saturation. SSFP-QMTI has advantages mainly for fast, volumetric mapping thanks to high SNR efficiency. A non-balanced variant has been reported for mapping near significant B_0 variation [12].

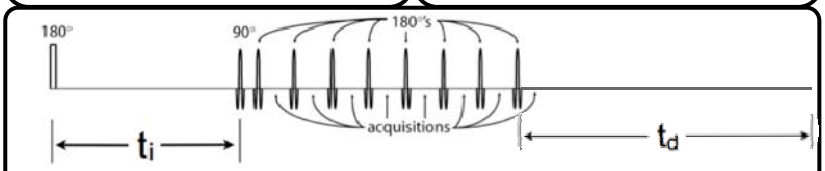

Fig. 4. SIR sequence with FSE readout [14]. t_i = inversion time, td = delay time

Selective inversion recovery (SIR): SIR-QMTI [13] inverts the water pool with a short inversion pulse, separating the initial free and restricted pool magnetizations. Recovery is observed at various TIs (Fig. 4), and is described by a simple solution to Eq. 1 with assumptions about T_{2r} and restricted pool RF saturation. This method primarily uses FSE readouts [14] and produces lower SAR, but requires long scan times.

Summary: We will review the major methods for QMTI and summarize their advantages and limitations. We will include general findings of each technique, notably in neurological (Fig. 5) and muskuloskeletal imaging, for human and animal applications.

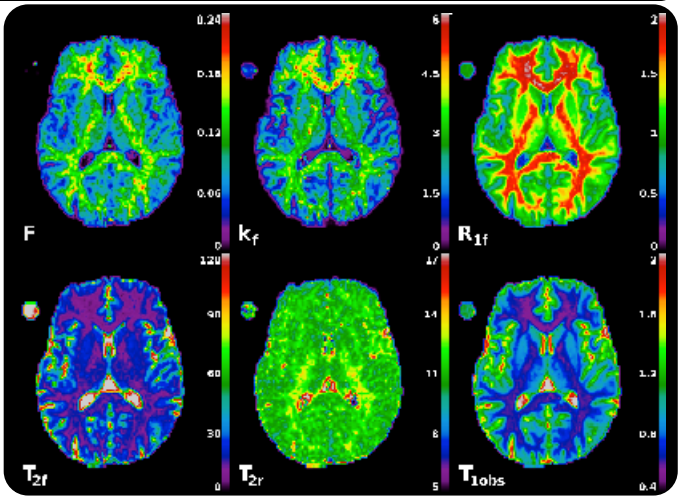

Fig. 5. Example MT parameter maps in a healthy adult from pulsed off-resonance QMTI, at 1.5 T.

References: [1] Wolff & Balaban MRM 10;1989, [2] Henkelman et al. NBM 14;2001 [3] Henkelman et al. MRM 29;1993 [4] Sled & Pike MRM 46;2001, [5] Ramani et al. MRI 20;2001, [6] Yarnykh (2002), [7] Portnoy & Stanisz MRM 58;2007, [8] Cercignani & Barker JMR 191;2008, [9] Bieri et al. MRM 56;2006 [10] Freeman & Hill JMR 4;1971 [11] Gloor et al. MRM 60;2008, [12] Gloor et al. MRM 64;2010 [13] Gochberch et al. MRM 49;2003, [14] Gochberg & Gore MRM 57;2007