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Quantitative in vivo T2 mapping using fast spin echo techniques – A linear correction procedure

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ABSTRACT

A method is presented for correcting the effects of stimulated and indirect echoes on quantitative T2 mapping data acquired with multiple spin echo techniques, such as turbo spin echo. In contrast to similar correction techniques proposed in the literature, the method does not require a priori knowledge of the radio frequency (RF) pulse profiles. In a first step, for the T2 mapping protocol under investigation, signal decay curves S(TE) are simulated for a range of different RF pulse profiles. The actual signal decay S(TE) is then measured on a phantom with known T2, so the approximate RF pulse profiles can be derived via comparison with the simulated decay curves. In a second step, with the RF pulses obtained from step one, signal decay curves S(TE) are simulated for different T2 values and fitted mono-exponentially, thus allowing to deduce the relationship between true T2 and the apparent T2 (T2app) values. Results show that this relationship is approximately linear, allowing for a direct correction of T2app maps. If the amplitude of the transmitted RF field (B1) does not exceed the nominal value by more than 10%, it is shown that a B1-independent correction of T2app maps yields sufficiently accurate results for T2. A B1-dependent version is also presented. The method is tested in vitro on a phantom with different T2 values and in vivo on healthy subjects.

Introduction

Over the last years, quantitative magnetic resonance imaging (qMRI) techniques have been increasingly used to investigate various brain tissue parameters. One frequently mapped parameter is the transverse relaxation time (T2), in particular in clinical studies to compare healthy controls with patients or to observe T2 changes in longitudinal experiments. Applications comprise the investigation of patients with Alzheimer disease (Bauer et al., 2010) and multiple sclerosis (Stevenson et al., 2000; Gracien et al., 2016; Reitz et al., 2016), the measurement of the relative oxygen extraction fraction (Hirsch et al., 2014) and the investigation of T2 development during adolescence, observing gender-dependent differences (Kumar et al., 2011).

In general, techniques for T2 mapping are based on spin echo (SE) sequences (Hahn, 1950). The most basic technique acquires several scans with different echo times (TE) that are achieved by varying the time delays while using a single refocusing pulse, only. The disadvantage of this method is the long experiment duration, leading to a reduced spatial coverage for clinically acceptable scan times. Furthermore, single-refocused SE sequences may be prone to diffusion effects due to increased and variable inter-echo spacings. Faster methods employ the Carr-Purcell-Meiboom-Gill (CPMG) concept (Carr and Purcell, 1954) where a series of refocusing pulses is applied with a certain intermediate echo spacing (ES), so a series of spin echoes can be sampled with increasing TE values that are multiples of ES. This concept can be employed for fast T2 mapping in two ways: (1) the multi echo spin echo (MESE) technique (Feinberg et al., 1985) uses the CPMG concept to acquire a train of spin echoes with different TE but identical degree of phase encoding, so a series of T2-weighted images with different TE can be reconstructed. (2) In turbo spin echo (TSE) sequences, originally dubbed RARE (Hennig et al., 1986), the spin echoes in the CPMG train have different phase encoding, thus allowing for the fast acquisition of a T2-weighted image. TSE based T2 mapping

Abbreviations: qMRI, quantitative magnetic resonance imaging; T2, transverse relaxation time; SE, spin echo; TE, echo time; CPMG, Carr-Purcell-Meiboom-Gill; ES, echo spacing; MESE, multi echo spin echo; TSE, turbo spin echo; RF, radio frequency; B1, transmitted RF field; MR, magnetic resonance; EPG, extended phase graph; S_{acq}(TE), acquired signal decay curve; T1, longitudinal relaxation time; S_{sim}(TE), simulated signal decay curve; T2app, apparent T2; FA_{ex}, nominal excitation angle; FA_{ref}, nominal refocusing angle; FoV, field-of-view; TR, repetition time; BW, receiver bandwidth; EPI, echo planar imaging; B0, static magnetic field; BWDP, bandwidth-duration-product; SLTQ, slice thickness quotient; FWM, frontal white matter; SAR, specific absorption rate; MT, magnetization transfer

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is possible by acquiring several data sets with different TE. In general, TE variations in TSE are not achieved by changing timing parameters, but rather by changing the position of the echo covering the center of k-space within the CPMG train as this echo has the main signal contribution.

Both MESE and TSE have one concept in common: data acquired at different TE do not only differ in the respective TE value but also in the number of preceding refocusing pulses, a feature not present in conventional SE techniques. Severe problems arise in the presence of radio frequency (RF) pulse imperfections, yielding excitation and refocusing angles that deviate from the ideal values of 90° and 180°, respectively, as this can give rise to stimulated echoes, thus distorting the unbiased signal dependence on TE and leading to errors in T2 calculation (Vold et al., 1973; Hennig, 1991; Lebel and Wilman, 2010; Prasloski et al., 2012; McPhee and Wilman, 2015; Petrovic et al., 2015).

Deviations of excitation and refocusing angles from the ideal values can arise from inhomogeneities of the transmitted RF field (B1) or the deliberate choice of reduced angles in TSE (Kumar et al., 2011). A particular problem arises from reduced angles near the slice edges if slice-selective pulses are used. As a consequence, the use of three-dimensional acquisition techniques with non-selective pulses (Prasloski et al., 2012) or the use of single slice measurements with non-selective refocusing pulses (Whittall et al., 1997) has been suggested. The described effects may have an impact on the accuracy of T2 quantification, yielding results that are method-dependent (Hirsch et al., 2014) or show a strong bias on the magnetic resonance (MR) system type and vendor (Bauer et al., 2010) which poses a particular problem in multi-centric studies.

Several correction methods have been proposed in the literature, usually employing the extended phase graph (EPG) method (Hennig, 1991) or the generating function formalism with extension to slice-selective sequences (Petrovic et al., 2015) to simulate the real signal decay curves. Methods were designed for subsequent multi-exponential fitting (Prasloski et al., 2012), or for mono-exponential fitting with the acquisition of relatively few echoes via MESE (Lebel and Wilman, 2010) or TSE (McPhee and Wilman, 2015). In particular the latter method, dubbed ISEC ("Indirect and Stimulated Echo Compensation"), simulates numerically the actual signal decay curves for different T2 and B1 values which are subsequently stored in a catalogue, so real T2 values can be obtained with high accuracy via a look-up method (McPhee and Wilman, 2015). A potential problem may arise from the fact that the simulations require full knowledge of the RF slice profiles. Consequently, these data have to be obtained from the vendor. Alternatively, it has been suggested to use refocusing pulses with increased slice thickness or very high time-bandwidth (Lebel and Wilman, 2010), or to use an oscilloscope to measure the RF-time-profiles (McPhee and Wilman, 2015). In addition, it would also be necessary to measure the slice selection gradients, as frequently an increased slice thickness is chosen for the refocusing pulses (Lebel and Wilman, 2010; McPhee and Wilman, 2015).

The purpose of this study was to find a method for deriving accurate T2 values from TSE or MESE data without a priori knowledge of the RF pulse profiles. In a first step, the problem of missing information on RF slice profiles is circumvented by acquiring actual (i.e. distorted) signal decay curves (S_{acq}(TE)) on a phantom with known longitudinal (T1) and transverse (T2) relaxation times, and to find pairs of excitation and refocusing slice profiles for which simulations yield a comparable simulated signal decay curve (S_{sim}(TE)). In a second step, for these assumed RF pulse shapes, decay curves S_{sim}(TE) are simulated for a range of real T2 values and apparent T2 (T2app) values are obtained by mono-exponential fitting. This allows deducing the relationship between T2 and T2app and thus a correction of T2app maps.

Materials and methods

Description of simulation algorithm

This section describes the simulation algorithm that was used to calculate the actual evolution of SE amplitudes S_{sim}(TE) in a CPMG experiment. In general, a CPMG-based sequence is described by the following parameters: an initial RF excitation pulse rotating the magnetization by a nominal excitation angle (FA_{ex}) is followed by a series of refocusing pulses with a nominal refocusing angle (FA_{ref}). Each refocusing pulse is embedded between two delays of length ES/2 (ES being the echo spacing, i.e. the time difference between subsequent echoes) and flanked by two gradient spoiler pulses, which cause complete spin dephasing across the voxel size. The actual excitation and refocusing angles can deviate from the nominal values FA_{ex} and FA_{ref} due to non-uniformities of B1 and imperfect slice profiles of the RF pulses. In summary, the signal of the n-th SE, acquired at TE = n· ES, is given by

$$S_{sim}(TE = n \cdot ES) = S(RF, FA_{ex}, FA_{ref}, B1, T1, T2, ES, n) \quad (1)$$

In this equation, RF comprises the slice profiles of the excitation and refocusing pulses. Furthermore, it should be noted that B1 is given in relative units, assuming a value of 1.0 if the actual angle matches the nominal value.

The signal decay curve S_{sim}(TE) was calculated with the help of a simulation algorithm that had previously been described in the literature for simulating the effects of stimulated echoes in fast gradient echo imaging (Preibisch and Deichmann, 2009). In summary, the effects of the RF pulses are modelled by solving the Bloch equations numerically with a Runge-Kutta algorithm, as described previously (Deichmann, 2005). The transverse and longitudinal spin relaxations are simulated via respective matrix procedures. The effects of the spoiler gradients are accounted for in the following way: it is assumed that for an individual microscopic spin ensemble the magnetization is rotated by an angle φ in the transverse plane by the spoiler gradient, a process modelled via a respective matrix operation. For this spin ensemble, the evolution of the magnetization vector across all echoes is calculated. This calculation is repeated for different values of φ, covering the full range from 0° to 360°. Subsequently, the results are added. From the resulting magnetization evolution, the modulus of the transverse component is calculated at the position of each SE, thus indicating the respective signal amplitude. In summary, the program allows to calculate the actual evolution of SE amplitudes S_{sim}(TE) in a CPMG experiment, provided the parameters listed in Eq. (1) are known.

Equipment for MRI data acquisition and postprocessing

All measurements were performed on a 3 T whole body MR scanner (Magnetom TRIO, Siemens Medical Solutions, Erlangen, Germany), using a body coil for RF transmission and an 8-channel phased-array head coil for signal reception. Data were analyzed using custom-built programs written in MatLab (MathWorks, Natick, MA). Data coregistration and EPI distortion correction were performed with the FMRIB Software Library (FSL, http://www.fmrib.ox.ac.uk/fsl). Region of interest (ROI) analysis was performed manually with MRIcron (http://www.mccauslandcenter.sc.edu/mricro/mricron).

List of MRI protocols used in this study

If not stated otherwise, for all protocols listed below, FA_{ex} = 90° and FA_{ref} = 180° were chosen.

TSE protocol with ES = 17.1 ms ("TSE_17100"):

The protocol was based on a multi-slice TSE sequence with the acquisition of 11 echoes per excitation ("turbo factor" of 11) and ES = 17.1 ms. The sequence was performed five times and the echo covering