Fast volumetric T_1 and T_2 mapping with variable flip angles and a radial twisted projection imaging sequence design

Philipp Krämer[1], and Lothar R. Schad[1]

[1]*Computer Assisted Clinical Medicine, Heidelberg University, Mannheim, Germany*

Introduction

A twisted projection imaging (TPI) [1] sequence is presented which is used for rapid T_1 and T_2 mapping. The advantages of TPI are ultra-short echo times (TE), density adapted sampling in radial direction and a reduced number of necessary projections to fulfill the Nyquist criterion compared to radial sequences with linear k-space projections. The latter is used to shorten measurement time in 3D proton imaging. Since ultra-short TE are not imperative in proton MRI two radial spokes are acquired each repetition time (TR) to further decrease the acquisition time. This technique requires fewer projections than conventional radial imaging while maintaining image quality [2]. The trajectory has been implemented as a spoiled gradient recalled echo (SPGR) [3] sequence and as a fully balanced steady-state free precession (bSSFP) [4] sequence. The different contrasts of these sequences are used for fast 3D mapping of T_1 and T_2 with a variable flip angle (VFA) approach [3].

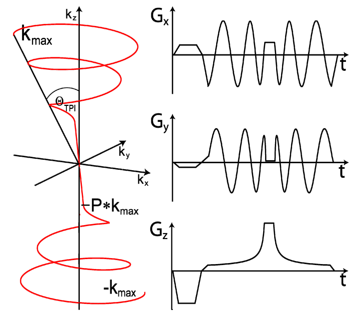

Figure 1: TPI k-Space trajectory and corresponding gradient waveforms

Methods

K-space Trajectory: Figure 1 shows the implemented k-space trajectory and the corresponding gradient waveforms. Two radial spokes are acquired in one TR by dephasing first to the maximum positive k-value k_{max} and then traversing k-space to $-k_{max}$. Sufficient k-space coverage is achieved by rotating this trajectory by polar and azimuthal angles (θ,φ) each TR. The rotation angles are calculated using a recursive algorithm [5] which distributes the starting points of the trajectories uniformly on a spherical spiral.

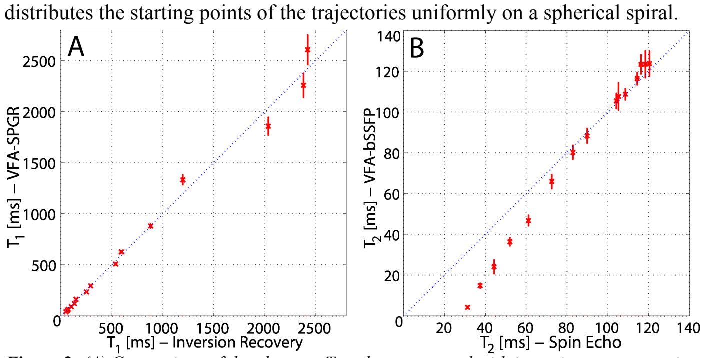

Figure 2: (A) Comparison of the phantom T_1-values measured with inversion recovery spin-echo and VFA-SPGR. (B) Comparison of the phantom T_2-values measured with spin-echo and VFA-bSSFP

VFA Measurement: The Signal behavior of the spoiled sequence is described by the SPGR equation [3] which depends on TR, the flip angle (FA), T_1, and a scaling factor S_0^{SPGR}. By varying the flip angles with fixed TR this equation can be fitted to the measured signals yielding T_1 and S_0^{SPGR}. The signal behavior of the fully balanced sequence is described by the bSSFP equation [4] which depends on the FA, the ratio T_1/T_2 and S_0^{SSFP} in the limit $TR \ll T_1,T_2$. By varying the flip angles, with T_1 known from the SPGR measurement, this equation can be fitted to the measured signals yielding S_0^{SSFP} and T_2.

Experiments: All experiments were performed on a Magnetom Skyra 3T MR Scanner (Siemens Healthcare, Erlangen, Germany). The body coil was used for transmission to achieve maximum B_1 homogeneity for the VFA experiment. A 16-channel head coil was used for reception. All TPI measurements were acquired with an isotropic resolution of 1.5mm. The other parameters for the SPGR and bSSFP TPI protocols are as follows: P_{SPGR}=0.3;TE_{SPGR}/TR_{SPGR}=4.6ms/10ms;P_{SSFP}=0.4;TE_{SSFP}/TR_{SSFP}=2.6ms/5.2 ms. T_1 times of a phantom containing 15 tubes with different concentrations of Gd-DTPA were measured with an inversion recovery spin-echo sequence (10 TI times from 0.02s to 10s, TE/TR=4ms/10s) and with the VFA-SPGR protocol with the FAs 2°, 4°, 15° and 17°. T_2 times of the same phantom were measured with a spin-echo sequence (10 echo times from 8ms to 250ms) and the VFA-bSSFP protocol with the FAs 5°, 15°, 37° and 45°. The flip angles for both measurements were derived by Monte Carlo simulations. A healthy male volunteer was scanned with the mentioned VFA protocols. To fully sample the k-space for a field of view of (22cm)³ 4000 projections had to be acquired for the VFA-SPGR protocol and 8000 projections for the VFA-bSSFP protocol leading to a measurement time of 5 minutes and 20 seconds for all eight 3D datasets.

Postprocessing: All postprocessing steps were performed in MATLAB. The raw data from the TPI measurements were reconstructed with GROG [6]. Before fitting, the datasets have been masked by thresholding. Fitting of the SPGR and bSSFP equations was performed using a Levenberg-Marquardt optimization algorithm.

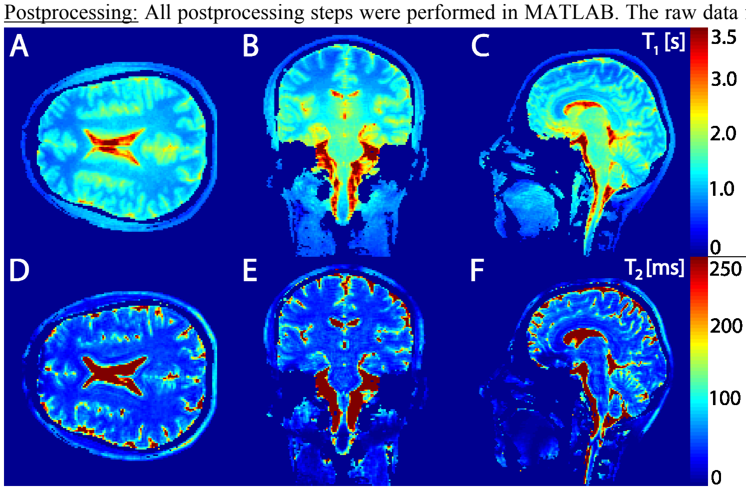

Figure 3: Axial, coronal and sagittal slice of the T_1-map (A-C) obtained from VFA-SPGR and the T_2-map (D-F) obtained from VFA-bSSFP.

Results

Figure 2A shows the phantom T_1 values obtained from the inversion recovery and the VFA-SPGR measurement. The T_1 values are in good agreement. Figure 2B shows the phantom T_2 measurement from the spin-echo and the VFA-bSSFP protocol. A systematic deviation of the VFA-bSSFP measurement can be seen at T_2 below ~70ms. In Figure 3 an axial, coronal and sagittal slice of the T_1-map (A-C) and the T_2-map (D-F) are shown. Two regions of interest have been drawn in gray and white matter tissue with help of the T_1-map. The following values have been measured: T_1^{Gray}=(1390±70)ms; T_1^{White}=(920±20)ms; T_2^{Gray}=(64±10)ms; T_2^{White}=(41±3)ms.

Discussion and Conclusion

The TPI sequence is a very efficient way to sample k-space regarding readout time and k-space coverage. For P=0.3 and TR=10ms the k-space of a 22cm³ volume with an isotropic resolution of 1.5mm can be fully sampled in approximately 40 seconds. This is faster than most Cartesian sequences without parallel imaging. In 3D radial sequences the excitation pulses are applied globally without the need of a slab selection gradient. This property makes the sequence well suited for VFA measurements because no additional flip angle errors are caused by the slab selection. Nevertheless, a low resolution flip angle mapping prior to the VFA measurements could increase accuracy. The phantom T_1-measurements from the VFA-SPGR protocol are in good agreement with the inversion-recovery measurement. Though, at longer T_1, statistical deviations are noticeable because of low signal to noise ratio. The T_2-measurements from the VFA-bSSFP protocol are in good agreement with the spin echo measurements between T_2=80ms and T_2=120ms. A systematic deviation occurs at T_2 below ~70ms. This is due to the fact that the condition $TR \ll T_1,T_2$ is no longer fulfilled. Shortening TR could solve this problem. The measured T_1-values for white and gray matter are in good agreement with literature values [7]. T_2 of gray and white matter might be slightly underestimated because of the systematic deviation in the T_2 range below ~70ms.

References

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