Simulation of the Filtering Effect of the FLASH Readout on Saturation Recovery T_1 Evaluation

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INTRODUCTION

The measurement of T_1 relaxation times can be time-consuming with standard imaging techniques such as inversion recovery spin echo that require measurements times of minutes to hours to acquire a series of images with different T_1 contrasts. Fast imaging sequences that encode more than one k-space line per magnetization preparation (MP) step, e.g. saturation recovery turboFLASH (SRTFL) [1], can be used to shorten the acquisition time. Unfortunately, the prolonged SRTFL readout disturbs the MP by additional radio frequency (RF) pulses. While the first measured k-space line after the preparation is undisturbed, later lines will increasingly deviate from the intended MP state. Thus, the imaging process acts as a filter on the measured k-space data in phase encoding direction [1,2]. The filter effect can be mitigated by a segmented, centric-reordered k-space acquisition scheme [3]. In this work the influence of the segmentation parameters on the filter and the T_1 measurement accuracy is assessed in numerical simulations.

MATERIAL & METHODS

The evolution of the longitudinal magnetization in a SRTFL experiment was simulated, images were calculated at different saturation recovery delays *TS*, and T_1 values were determined from the images using a non-linear fitting procedure. All calculations were done in MATLAB 7.10 (The MathWorks Inc., Natick, MA). A virtual phantom (size: 256×208 pixel, Fig. 1) was created, which contained circular vials with 102 different T_1 values between 0.06 and 20000 ms. The vials were surrounded by a material with T_1 = 375 ms. Regions of Interest (ROIs) were created from the vial areas by an erosion filter, yielding ROIs with a diameter of 7 px.

The phantom was segmented by its T_1 values, since the FLASH steady-state depends on T_1 and is therefore spatially varying. For every T_1 the initial ($k = 1$) longitudinal magnetization at time *TS* after saturation was calculated assuming perfect saturation:

$$M_z^1(x,y) = M_{z,0}\left(1 - e^{-\frac{TS}{T1(x,y)}}\right) \tag{1}$$

All subsequent ($k > 1$) magnetization distributions in this measurement segment were calculated iteratively by element-wise application of functions and matrix multiplications assuming a spoiled gradient echo readout with repetition time TR:

$$M_z^{k+1}(x,y) = M_z^k(x,y)\cos(\alpha)e^{-\frac{TR}{T1(x,y)}} + M_{z,0}\left(1 - e^{-\frac{TR}{T1(x,y)}}\right) \tag{2}$$

The corresponding k-space filter strength for the k^{th} PE line in this segment was given as the ratio of the k^{th} total magnetization and the initial total magnetization that was considered to have ideal contrast:

$$F_k = \sum_{x,y} M_z^k(x,y) \Big/ \sum_{x,y} M_z^1(x,y) \tag{3}$$

This filter was then applied to the k-space representation of the vial with the corresponding T_1. Finally, all filtered k-space representations were added to mimic the total k-space of the virtual phantom in a SRTFL experiment.

The SRTFL was simulated with TR = 2.9 ms, flip angle α = 8°, {1, 3, 5, 13, 23} segments, 256/208 frequency/phase encoded data points. The 27 simulated *TS* values ranged from 20 to 5000 ms. From the series of images with different *TS*, T_1 values were calculated using a non-linear least squares fitting procedure (Levenberg-Marquardt). The fitted T_1 values were plotted against the theoretical values for different segmentation schemes (Fig. 3).

RESULTS AND DISCUSSION

The comparison of the fitted with the theoretical T_1 values in Fig. 3 shows that the precision of the segmented SRTFL T_1 measurement increases with increasing segmentation. As is shown in Fig. 2, an unfiltered T_1-set is achieved for one T_1-dependent *TS* only, when the MP state (Eq. 1) and the FLASH steady-state coincide. In general, k-space is high/low-pass filtered along the PE direction for short/long *TS* times and signal intensities in ROIs get perturbed.

The filter effect can be minimized by increasing the segmentation of k-space; however, this prolongs the total measurement time by the same factor: With 5 segments and 208 PE lines (20% k-space coverage per segment), $T_1 \in [40; 4800]$ ms can be determined within a maximum error level of 8% (Fig. 3) and an acquisition time (*TA*) of 1:30 min. With 13 segments (7.7% coverage per segment), T_1 is measurable with an error level below 3% (data not shown here) and with a lower limit of 20 ms. *TA* is then approximately increased by a factor 20/7.7, yielding 3:58 min. Thus, T_1 precision can be traded dynamically against temporal resolution, so that this technique is suitable for both breath-held acquisitions with lower T_1 precision and minute-long measurements with high T_1 accuracy.

REFERENCES

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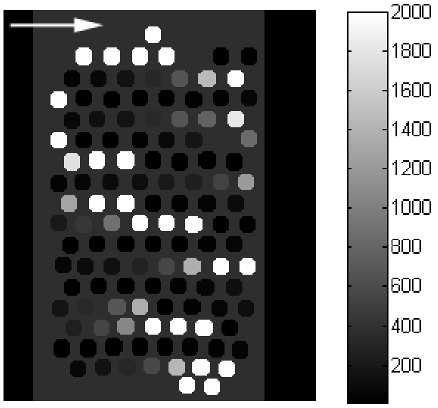

Fig. 1 Virtual phantom with T_1-values ranging from 0.06 ms to 20 s (10 – 2000 ms shown). Arrow: phase encoding (PE) direction

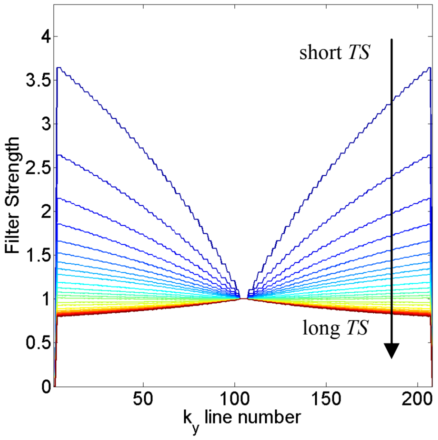

Fig. 2 One line of the average image filter along the phase-encode direction. From blue to red: *TS* increases from 20 ms to 5000 ms. Central line is always ≡ 1 (i.e. no filtering) since full MP contrast is achieved there. Acquisition is simulated with 5 segments. K-space center line is line 104.

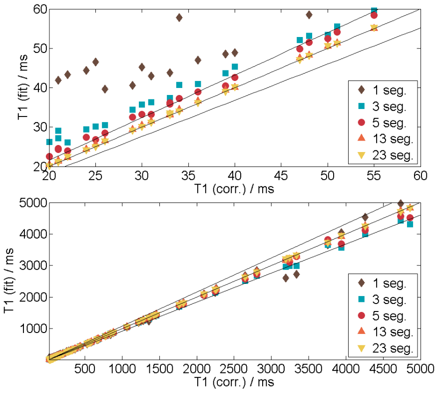

Fig. 3 Comparison of fitted and correct T_1 values for different number of segments. Additional lines: ±8% borders. Top: Same data as bottom, but lower T_1 range is magnified.