TRIPLE ECHO STEADY STATE (TESS) RELAXOMETRY

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Target audience. Scientists and clinicians interested in fast T_1 and T_2 quantification methods.

Purpose. Rapid imaging techniques have attracted increased interest for relaxometry, but none are perfect: they are prone to static (B_0) and transmit (B_1) field heterogeneities, and commonly biased by T_2/T_1. The purpose of this study is the development of a rapid, bias-free T_2 relaxometry method by using a triple echo steady state (TESS) sequence that allows to simultaneously quantify T_1 and T_2 within one single scan.

Methods. Similar to the double echo steady state approach for T_2 quantification (1), the dependencies of the SSFP signal modes on relaxation are used to quantify T_1 and T_2 using TESS. In addition to the lowest order SSFP-FID (F_0) and lowest order SSFP-echo (F_{-1}) modes, a third mode is acquired, namely F_1, according to the sequence setup shown in Fig. 1. Analytical expressions for the modes can be found e.g. in (2),

$$F_0 \propto 1-(E_1-\cos\alpha)\cdot r \quad [1]$$

$$F_{-1} \propto (1-(1-E_1\cos\alpha)\cdot r)E_2^{-1} \quad [2]$$

$$F_1 \propto q^{-1}\cdot\left(p-(p^2-q^2)^{1/2}\right)\cdot(1-(E_1-\cos\alpha)\cdot r) \quad [3]$$

with definitions

$$E_{1,2} := \exp(-TR/T_{1,2}),\ \ p := 1-E_1\cos\alpha - E_2{}^2(E_1-\cos\alpha),$$

$$q := E_2(1-E_1)(1+\cos\alpha),\ \ r := (1-E_2^2)(p^2-q^2)^{-1/2}$$

To calculate T_1 and T_2, the following signal ratios are investigated:

$$s_{T_2}(T_1) := F_1\cdot F_0^{-1},\ s_{T_1}(T_2) := F_{-1}\cdot(F_0-F_1)^{-1} \quad [4]$$

Using an initial global guess for T_1 and a golden section search algorithm, an estimate for T_2 is derived based on the s_{T1} signal ratio. This first guess for T_2 is in turn used to find an updated T_1 value based on s_{T2}. The whole procedure is repeated until the change in both T_1 and T_2 falls below a certain threshold; typically, requiring less than 10 iterations. TESS offers T_1 and T_2 mapping from one scan and without the confounding influence of either T_1 on T_2 or T_2 on T_1. Relaxometry based on TESS is optimized and evaluated from simulations, in vitro studies, and in vivo experiments.

Results. It is found that relaxometry with TESS is not biased by T_2/T_1, is insensitive to B_0 heterogeneities, and, surprisingly, for T_2 not affected by B_1 field errors (see Fig. 2). As a result, excellent correspondence between TESS and reference spin echo data is observed for T_2 in vitro at 1.5T and in vivo at 3T (see Fig. 3 and Table 1), allowing fast high-resolution T_2 imaging of the musculoskeletal system. For multi-contrast spin echo, a pronounced overestimation of about 30 – 40 % is observed for articular cartilage, muscle, and for the internal controls, due to stimulated echo contributions (i.e., imperfect refocusing pulses and thus due to B_1 errors).

Discussion. T_2 relaxometry with TESS revealed to be independent of B_1, whereas T_1 quantification showed the expected pronounced B_1-related estimation errors. This extraordinary feature is not only of special interest for high to ultra-high field T_2 relaxometry, where prominent B_1 variations can be expected and applicability of spin echo techniques might be limited due to SAR constraints, but also provides accurate quantification results in combination with spectral-spatial excitation pulses that typically entail flip angle calibration errors in the presence of B_0 heterogeneities (Fig. 3).

Conclusion. TESS allows rapid, B_0 and B_1 insensitive, bias-free T_2 quantification within one single scan. As a result, the new proposed method is of high interest for fast and reliable T_2 mapping, especially for the musculoskeletal system at high to ultra-high fields.

References. 1. Welsch GH et al. Magn Reson Med 2009;62(2):544–549. **2.** Hänicke W, Vogel HU. Magn Reson Med 2003;49(4):771-775.

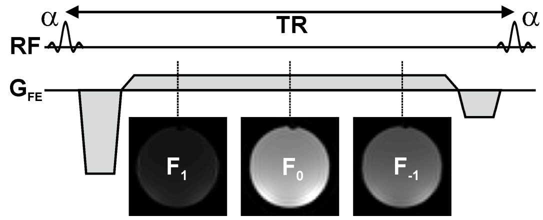

Figure 1: Sequence diagram of a triple echo steady state (TESS) sequence. The center FID (F_0) is flanked by a higher order FID to the left (F_1) and by the lowest order Echo (F_{-1}) to the right.

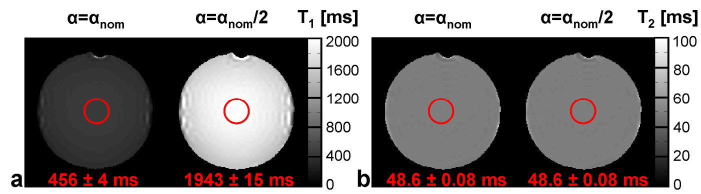

Figure 2: B_1 sensitivity of T_1 (a) and T_2 (b) mapping based on TESS, illustrated exemplarily for a manganese-doped spherical probe (0.25 mM $MnCl_2$ in H_2O) at 1.5T with a nominal T_1 of 456 ms and a nominal T_2 of 48.5 ms, as derived by SE techniques. While TESS-T_2 values prove to be completely unaffected by a recalculation using only half of the nominal flip angle, here 20° instead of 40°, T_1 is considerably overestimated (1943 ms instead of 456 ms for the ROI indicated by the red circle).

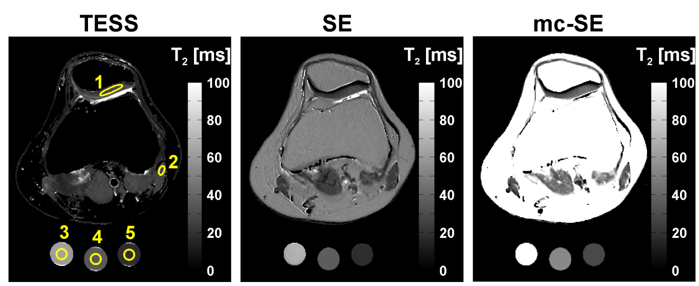

Figure 3: T_2 maps calculated from axial images of the knee joint at 3T, either from TESS base images (F_1, F_0, and F_{-1}, leftmost map), or by using SE-techniques. A single-echo SE approach (middle) is compared to a multi-contrast SE method (right). Manganese-doped test tubes serve as internal controls. For selected ROIs (yellow numbers), T_2 values are summarized in Table 1.

tissue	TESS T_2 [ms]	SE T_2 [ms]	mc-SE T_2 [ms]
cartilage (1)	27.3 ± 3.2	26.5 ± 3.2	40.4 ± 5.2
muscle (2)	26.3 ± 0.6	24.6 ± 1.1	37.6 ± 4.9
0.125 mM $MnCl_2$ (3)	64.2 ± 0.9	69.1 ± 0.6	102.6 ± 0.7
0.250 mM $MnCl_2$ (4)	34.9 ± 0.3	36.6 ± 0.1	53.0 ± 0.3
0.500 mM $MnCl_2$ (5)	18.0 ± 0.2	18.7 ± 0.1	28.9 ± 0.1

Table 1: In vivo comparison of spin echo and TESS T_2 relaxometry data in the knee joint at 3T for the ROIs indicated in Fig. 3 (numbers in brackets refer to the corresponding ROI). Reference SE-T_2 values are derived based on nine single-echo SE scans using a nonlinear least-squares fit with echo times of 10, 20, 30, …, 90 ms (middle column) and on a multi-contrast SE scan (nine echoes: starting from 10 ms, and having an echo spacing of 10 ms, rightmost column).