TRIPLE ECHO STEADY STATE (TESS) RELAXOMETRY
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Target audience. Scientists and clinicians interested in fast T₂ and T₁ quantification methods.

Purpose. Rapid imaging techniques have attracted increased interest for relaxometry, but none are perfect: they are prone to static (B₀) and transmit (B₁) field heterogeneities, and commonly biased by T₂/T₁. The purpose of this study is the development of a rapid, bias-free T₁ relaxometry method by using a triple echo steady state (TESS) sequence that allows to simultaneously quantify T₁ and T₂ within one single scan.

Methods. Similar to the double echo steady state approach for T₂ quantification (1), the dependencies of the SSFP signal modes on relaxation are used to quantify T₁ and T₂ using TESS. In addition to the lowest order SSFP-FID (F₀) and lowest order SSFP-echo (F₁) modes, a third mode is acquired, namely F₁, according to the sequence setup shown in Fig. 1. Analytical expressions for the modes can be found e.g. in (2),

\[ F₀ = 1 - (E₁ - \cos \alpha) \cdot r \]  
\[ F₁ = (1 - (1 - E₁ \cos \alpha) \cdot r) \cdot E₁^2 \]  
\[ F₂ = q^{-1} \cdot (1 - (E₁ - \cos \alpha) \cdot r) \]  

with definitions

\[ E₁ := \exp(-TR/T₁) \cdot \cos \alpha \]  
\[ q = (1 - (1 - E₁ \cos \alpha) \cdot r) \cdot \cos \alpha \]  
\[ \alpha = \frac{\pi}{2} \cdot \sin^{-1} \left( \frac{1}{q} \right) \]

To calculate T₁ and T₂, the following signal ratios are investigated:

\[ s₁(T₁) := \frac{F₁}{F₀} \]  
\[ s₂(T₁, T₂) := \frac{F₂}{F₀} \]

Using an initial global guess for T₁ and a golden section search algorithm, an estimate for T₂ is derived based on the s₂ signal ratio. This first guess for T₂ is in turn used to find an updated T₁ value based on s₁. The whole procedure is repeated until the change in both T₁ and T₂ falls below a certain threshold; typically, requiring less than 10 iterations. TESS offers T₁ and T₂ mapping from one scan and without the confounding influence of either T₀ or T₂ on T₁. 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 T₀/T₂, is insensitive to B₀ heterogeneities, and, surprisingly, for T₂ not affected by B₁ field errors (see Fig. 2). As a result, excellent correspondence between TESS and reference spin echo data is observed for T₁ in vitro at 1.5T and in vivo at 3T (see Fig. 3 and Table 1), allowing fast high-resolution T₁ 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 B₁ errors).

Discussion. TESS relaxometry with TESS revealed to be independent of B₀, whereas T₁ quantification showed the expected pronounced B₀-related estimation errors. This extraordinary feature is not only of special interest for high to ultra-high field T₁ relaxometry, where prominent B₀ 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 B₀ heterogeneities (Fig. 3).

Conclusion. TESS allows rapid, B₀ and B₁ insensitive, bias-free T₁ quantification within one single scan. As a result, the new proposed method is of high interest for fast and reliable T₁ mapping, especially for the musculoskeletal system at high to ultra-high fields.


Figure 1: Sequence diagram of a triple echo steady state (TESS) sequence. The center FID (F₀) is flanked by a higher order FID to the left (F₁) and by the lowest order Echo (F₂) to the right.

Figure 2: T₁ sensitivity of TESS (a) and T₀ (b) mapping based on TESS, illustrated exemplarily for a manganese-doped spherical probe (0.25 mM MnCl₂ in H₂O) at 1.5T with a nominal T₁ of 456 ms and a nominal T₂ of 48.5 ms, as derived by SE techniques. While TESS-T₁ values prove to be completely unaffected by a recalculation using only half of the nominal flip angle, here 20° instead of 40°, T₁ is considerably overestimated (1943 ms instead of 456 ms for the ROI indicated by the red circle).

Figure 3: T₂ maps calculated from axial images of the knee joint at 3T, either from TESS base images (F₁, F₂, and F₃, 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), T₂ values are summarized in Table 1.

<table>
<thead>
<tr>
<th>tissue</th>
<th>TESS [ms]</th>
<th>SE [ms]</th>
<th>mc-SE [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cartilage (1)</td>
<td>27.3 ± 3.2</td>
<td>26.5 ± 3.2</td>
<td>40.4 ± 5.2</td>
</tr>
<tr>
<td>muscle (2)</td>
<td>26.3 ± 0.6</td>
<td>24.6 ± 1.1</td>
<td>37.6 ± 4.9</td>
</tr>
<tr>
<td>0.125 mM MnCl₂ (3)</td>
<td>64.2 ± 0.9</td>
<td>69.1 ± 0.6</td>
<td>102.6 ± 0.7</td>
</tr>
<tr>
<td>0.250 mM MnCl₂ (4)</td>
<td>34.9 ± 0.3</td>
<td>36.6 ± 0.1</td>
<td>53.0 ± 0.3</td>
</tr>
<tr>
<td>0.500 mM MnCl₂ (5)</td>
<td>18.0 ± 0.2</td>
<td>18.7 ± 0.1</td>
<td>28.9 ± 0.1</td>
</tr>
</tbody>
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Table 1: In vivo comparison of spin echo and TESS T₂ 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-T₂ 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).