T2 mapping using T2prepared-SSFP: Optimizing echo time, flip angle and parameter fitting

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Introduction: T2 Mapping using T2-prepared (T2p) Steady State Free Precession (SSFP) has become increasingly popular. In this technique, multiple images are acquired, each with a different T2p time; a mono-exponential decay curve is fit to the pixel-wise intensities to generate a map of the T2 relaxation times. The T2p consists of non-selective rf pulses and is robust against B0 and B1 inhomogeneities. High performance gradient systems have enabled a very fast single-shot SSFP acquisition while the magnetization is in a transient state to preserve effect of the T2p. Several steady-state preparation schemes have been proposed to overcome oscillatory artifacts in the transient state; however, these may alter the T2p magnetization. In addition, the T2p magnetization will be altered by the repeated application of excitation (α) pulses. The perturbation of the magnetization preparation is greater for higher flip angles (1). In this work, the evolution of signal after a T2p is analyzed under the SSFP readout and its effect on T2 quantification studied in Bloch equation simulation, phantom, and human imaging to improve the accuracy of the technique. The technique is optimized for flip angles and the choice of T2p times.

Materials and Methods: The sequence consisted of the following components: T2p, linear flip angle (LFA) series to reduce oscillatory artifacts, SSFP readout (2). It was implemented on a clinical 1.5T scanner (MAGNETOM Avanto, Siemens Healthcare, Erlangen, Germany). The imaging parameters are listed in Table 1. Numerical simulations were performed with different flip angles and the T2 decay curves under the influence of SSFP readout were compared to the theoretical curve [sin(α/2)*exp(-t/T2)]. The sequence was run on phantoms prepared with Nickel Chloride and Agarose (T1/T2 values: 989/50.3 ms for phantom 1 and 949/66.2 ms for phantom 2). The sequence was run with different flip angles (20, 60, 90 degrees) and different sets of T2p times ($\{T2p\}_1$ = {0,24,48,96}ms, $\{T2p\}_2$={0,40,80,120}ms, $\{T2p\}_3$={0,60,120,180}ms; for each case, a pixel-wise T2 map was computed by fitting a mono-exponential decay curve with a constant bias term [$M(t) = M_0 * \exp(-TE_{T2p}/T2) + N$] to the signal intensities using Levenberg-Marquardt algorithm. Mean T2 of the phantoms were computed and the error (actual T2 - mean T2) was reported. Finally, T2 map for a mid-ventricular short axis (SAX) slice was acquired in 5 healthy subjects using the flip angle that gave best results in phantom studies. The map was generated in the Siemens Image Calculation Environment (ICE) with an automatic non-rigid motion correction algorithm applied to compensate in-vivo subject motion. Average T2 values in a septal ROI were computed and reported.

Results: Figure 1 shows the effect of LFA and SSFP readout on the T2 decay curve. Theoretical curves were plotted for comparison. Higher flip angle caused a greater perturbation of the magnetization prepared by the T2p pulse. In phantoms, higher flip angles and higher spacing between T2p times resulted in more accurate T2 quantification; Table 2 lists the results of phantom studies. The T2 in human myocardium was 38.7±4.7 ms for $\{T2p\}_1$, 40.2±1.8 ms for $\{T2p\}_2$ and 43.4±1.3 ms for $\{T2p\}_3$. Figure 2 shows typical myocardial T2 maps acquired with the different sets of T2p times.

Discussion: The excitation pulses used in SSFP readout disturb the magnetization prepared by the T2p pulse, with higher flip angles causing greater perturbation of the T2 decay curve. However, we have shown that despite this perturbation, higher flip angles yielded more accurate results. It may be that the bias term (N) accounts for the systematic impact of a high flip-angle SSFP readout. Longer T2p times increased accuracy; further studies with even longer T2p times are needed to determine the limits of this improvement. Additionally, to limit breath-hold times in cardiac imaging, we have used just four echoes to fit a three-parameter non-linear curve. While four points were sufficient for an accurate fit in phantom images, the in-vivo results showed sporadic noisy pixels within the myocardium that could not be fit correctly; additional echoes would increase the accuracy but also increase the imaging time, a key factor in breath-held cardiac imaging.

Conclusion: We have shown that longer T2p times and higher flip angles result in more accurate quantification of T2. With just 4 echo times, a T2 decay curve can be fit using a non-linear least squares algorithm in phantom images, but is problematic in-vivo cardiac imaging. Further studies of the influences of off-resonance frequencies, the limits on T2p times, and improving the robustness of non-linear fitting with a bias term are necessary.

References
1. Scheffler K, et al. Magn Reson Med. 2001 Apr;45(4):720-3.
2. Kellman P, et al. Magn Reson Med. 2007 May;57(5):891-7.

Table 1: Imaging parameters

Parameter	Value
FOV	~350 mm
Slice	8 mm
Matrix	122 x 192
Partial Fourier	6/8
Parallel Imaging/Factor/Ref lines	GRAPPA/2/24
TE	1.1 ms
TR	3XRR
Shot time	~185 ms
k-space ordering	linear

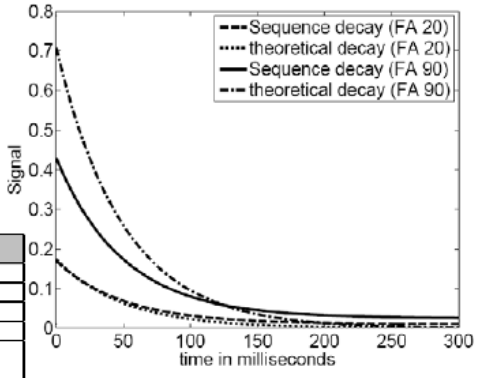

Figure 1: Simulation results. Signal evolution with SSFP readout at different Flip angles is plotted along with theoretical curves for comparison. **FA = Flip angle**

A

Δt (ms)	24	40	60
phantom 1	2.7	1.2	0.4
phantom 2	4.3	3	2.5

B

Flip angle	20°	60°	90°
phantom 1	2.7	0.8	0.4
phantom 2	2.7	3.1	2.5

Table 2: Phantom results. The numbers represent errors (true value – calculated value) in T2 quantification. Each T2 was computed from 4 echoes acquired at T2p times = Δt*[0, 1, 2 ,3]. 2-A shows the effect of increased spacing Δt between T2p times at 90° flip angle. 2-B shows the effect of different flip angles at Δt=60 ms.

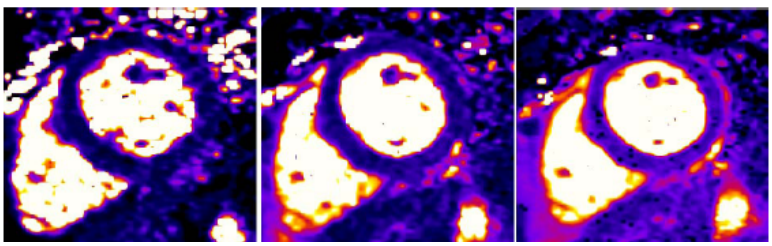

Figure 2: (Best viewed in color) In vivo myocardial T2 maps acquired with three different sets of T2p times: Left - {0, 24, 48, 72} ms, center - {0, 40, 80, 120} and right – {0, 60, 120, 180}ms.