A "Variable Flip Angle" Radial Steady-State Free Precession Technique with Slice Profile Correction

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Introduction: Steady-state free precession (SSFP) techniques have drawn significant attention due to their speed, good tissue contrast and spatial resolution. Recently, it was demonstrated that SSFP methods can be used to estimate MR-dependent tissue parameters [1,2,3]. In [1], it was shown that a "variable flip angle" radial steady-state free precession (RAD-SSFP) method can be used for the discrimination of malignant from benign lesions using a parameter called the *R*-factor. The advantage of the technique is that high resolution *R*-factor maps can be obtained from data acquired in a very short period of time (~ 3-4 s per slice) which makes the technique attractive for tissue characterization in regions of the body where fast imaging is needed. The *R*-factor, however, has a complex relationship to *T1* and *T2*. In this work, we demonstrate the capability of using the "variable flip angle" RAD-SSFP for the direct and fast estimation of the *T1/T2* ratio. The *T1/T2* ratio is a parameter that is more intuitively related to the tissue characteristics. As shown in Table 1, different tissues and pathologies have distinct *T1/T2* ratios, thus the parameter can be used for tissue characterization.

Table 1. *T1/T2* of tissues calculated from *T1* and *T2* values reported in literature

Tissue	Liver	Fat	Muscle (leg)	Hemangioma	Metastatic Lesion
T1/T2	~10.8	~4	~31	5~8.4	8.75~15

Theory: In SSFP, *TR* and *TE* << *T1* and *T2*, thus $e^{-TR/T1} \approx 1 - TR/T1$ and $e^{-TR/T2} \approx 1 - TR/T2$. Therefore, the steady-state equation can be simplified to:

$$I = m' \cdot \sin(\alpha) \Big/ \left(T1/T2 + 1 + (1 - T1/T2)\cos(\alpha) \right) \qquad (1),$$

where I is the signal intensity and m' is a term that depends on proton density, rf coil quality, magnetic field. If data are acquired with a variable flip angle, α, the signal intensity can be fitted to Eq. (1) to obtain the *T1/T2* ratio [4]. Because in SSFP the length of the excitation rf pulse has to be minimized in order to keep *TR* short, the smoothed main lobe of a sinc function is typically used to generate the rf pulse. This results in a slice profile that is far from ideal (red line in Figure 1) which introduces significant error in the estimation of *T1/T2*. The estimation of *T1/T2* can be improved by incorporating the slice profile into Eq. (1). If a triangular function is used as an approximation (blue line in Figure 1) to the actual slice profile, the steady-state equation can be rewritten as follows:

$$I = -m' \Big/ \left((1 - T1/T2)\alpha \right) \cdot \ln\left(\frac{1}{2}\left(T1/T2 + 1 \right) + \frac{1}{2}\left(1 - T1/T2 \right)\cos(\alpha) \right) \qquad (2)$$

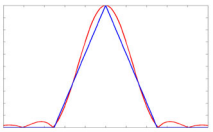

Fig. 1. The slice profile (red) and the triangular approximation (blue).

Methods: A "variable flip angle" RAD-SSFP method was implemented on a 1.5T GE Signa NV-CV/i MRI scanner. Six Nickel-doped agarose gel phantoms, within the range of *T1/T2* ratios found in vivo [5], were used to evaluate the technique. *T1* values for the phantoms were measured using an IR-FSE imaging technique (*ETL*=4, *TR*=5 s, *TE*=15 ms, *TI*=50 to 3000 ms). *T2* values were measured with a SE imaging technique (*TR*=5 s, *TE*=20 to 1320 ms). These *T1* and *T2* values were used to calculate the "expected" *T1/T2* reported on Table 2. Then *T1/T2* ratios were measured using a "variable flip angle" SSFP sequence with flip angle increasing from 0° to 45° in 1024 steps (*TR/TE*: 4.04/1.82 ms). Since the step size is very small (0.0044°), each data point is considered to be collected at steady state. Measurements were performed with (1) a non-slice-selective spectroscopic version of the SSFP sequence, (2) a slice-selective spectroscopic version of the SSFP sequence (slice thickness = 8 mm), and (3) the RAD-SSFP imaging method as proposed in reference [1]. In the spectroscopic experiments 1024 FID's with 256 sample points per FID were acquired. In the imaging experiments 1024 radial views with 256 sample points per view were acquired. Radial k-space data was processed using data sharing techniques as indicated in [1] to generate 8 images at different effective flip angles. Data from the 1024 spectroscopy points (or 8 images) were fitted to Eq. (1) and/or (2) to estimate *T1/T2*.

Results: *T1/T2* ratios are reported in Table 2 (1: *T1/T2* estimated from the non-slice-selective spectroscopic measurement; 2a and 2b: *T1/T2* estimated from the slice-selective spectroscopic measurement without and with triangular correction; 3a and 3b: *T1/T2* estimated from the imaging measurement without and with triangular correction). From these results, we can see that the non-slice-selective spectroscopic results match well the expected *T1/T2*, which validates the theory and our technique. However, once slice selection is added, the estimation of *T1/T2* is poor due to the non-ideal slice profile. Using the proposed triangular approximation of the slice profile, the *T1/T2* estimates are significantly improved. The same phenomenon is observed in the imaging results. More sophisticated correction algorithms could be designed to further improve the estimation accuracy.

Table 2. *T1/T2* ratios measured with conventional imaging method and with the "variable flip angle" SSFP methods

Phantom	1	4	2	5	3	6
Expected T1/T2	4.69	8.19	6.82	10.76	11.54	20.45
T1/T2 (1)	4.75	7.80	6.98	10.17	12.13	21.03
T1/T2 (2a)	2.44	3.65	3.35	4.68	5.51	8.79
T1/T2 (2b)	5.19	8.31	7.53	11.18	13.66	24.09
T1/T2 (3a)	2.30	3.76	3.29	4.64	5.53	8.03
T1/T2 (3b)	4.80	8.62	7.36	11.03	13.70	21.33

Conclusion: In this work, we have demonstrated that the *T1/T2* ratio can be estimated using a "variable flip angle" RAD-SSFP imaging technique. The estimation of *T1/T2*, however, is influenced by the non-ideal slice profile of the rf excitation used in steady-state free precession imaging sequences. This problem can be corrected by including an approximation to the slice profile into the steady-state equation. The method may provide a fast imaging method for characterizing tissues or pathologies based on *T1/T2* ratios.

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