Fast Radio-frequency Enforced Steady State (FRESS) Spin Echo MRI for Quantitative T_2 Mapping

J. S. Cheung[1], E. Wang[1,2], X. Zhang[2], E. Mandeville[3], E. H. Lo[3], A. Sorensen[1], and P. Z. Sun[1]

[1]Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, MGH and Harvard Medical School, Charlestown, MA 02129, United States, [2]Department of Radiology, 3rd Affiliated Hospital, Zhengzhou University, China, People's Republic of, [3]Neuroprotection Research Laboratory, Department of Radiology and Neurology, MGH and Harvard Medical School, Charlestown, MA 02129, United States

Introduction Transverse relaxation time (T_2) is a basic but very informative MRI parameter, widely used in imaging to examine a host of diseases including multiple sclerosis, stroke, and tumor [1-3]. When the repetition time (TR) is very long, T_2 can be derived by fitting T_2-weighted images as a function of echo time (TE). However, short TR is often used to minimize scan time, which may introduce non-negligible errors in T_2 measurement. Our study proposed a fast RF-enforced steady state (FRESS) spin echo (SE) MRI sequence, which saturates the magnetization after the spin echo and ensures a TE-independent steady state.

Theory The steady state Z-magnetization (M_z^{ss}) for SE MRI can be shown as:

$$M_z^{ss}(TR, TE, T_1) = M_0 (1 + e^{-TR/T1} - 2e^{-(TR-(TE/2))/T1}), \quad \text{Eq. [1]}$$

where M_0 is the thermal equilibrium Z-magnetization. If TE is not significantly shorter than TR, the TE dependence of the steady state cannot be neglected and the transverse magnetization is described by:

$$M_{xy}(TR, TE, T_1, T_2) = M_0 (1 + e^{-TR/T1} - 2e^{-(TR-(TE/2))/T1}) \cdot e^{-TE/T2} . \quad \text{Eq. [2]}$$

In fact, M_z^{ss} decreases with TE, which if not properly accounted for, will be mistaken as T_2-induced signal attenuation, leading to T_2 underestimation. To address this, we proposed FRESS-SE MRI (Fig. 1b), which saturates the magnetizations after the spin echo so that spins recover from zero till the next excitation pulse (TR_0), and the steady state Z-magnetization becomes $M_z^{ss}(TR_0, T_1) = M_0(1 - e^{-TR0/T1})$. As such, the steady state Z-magnetization is independent of TE, provided that TR_0 is kept as a constant, and T_2 can be obtained using $M_{xy}(TE,T_2) = M_z^{ss}(TR_0, T_1) \cdot e^{-TE/T2}$.

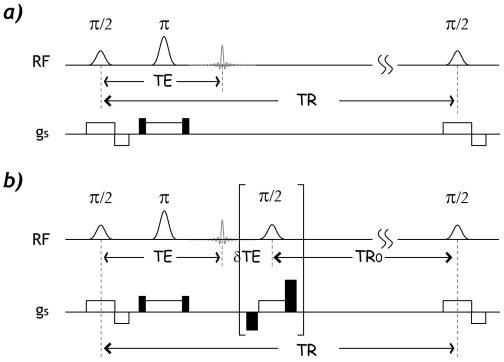

Fig. 1. Pulse sequence diagrams of the conventional SE sequence (**a**) and the proposed fast RF-enforced steady state (FRESS) SE sequence, in which a saturation module that includes a slice-selective π/2 pulse and spoiler gradients was implemented after the spin echo (**b**).

Materials and Methods

Phantom: A triple-compartment phantom was prepared with broad T_2 distribution. It contains two agarose gel (0.5% and 2%) compartments and a third compartment of 3% bovine serum albumin (BSA) solution.

Animal Model: Permanent middle cerebral artery occlusion (MCAO) was induced in adult male Wistar rats (250-300 g; *N* = 5). The animals were scanned at approximately 24 hr (*N* = 5) and again 48 hr (*N* = 4) later.

MRI and Data Analysis: MRI experiments were performed on a 4.7T Bruker MRI scanner. For phantom study, six TEs = 50, 75, 100, 150, 200 and 250 ms were used for both FRESS and conventional SE sequences with single-shot echo-planar imaging (EPI) readout (FOV = 48×48 mm^2, imaging matrix = 64×64, and slice thickness = 3 mm). In addition, TR was serially varied at 15, 12, 9, 6, 4, 3, 2 and 1.6 s with NA = 4 to examine TR dependence of the T_2 measurement. For in vivo imaging, multi-slice single-shot EPI MRI was obtained with four TEs of 30, 60, 90 and 120 ms for both SE sequences, and TR was serially varied at 6, 4, 3, 2, and 1.6 s (FOV = 20×20 mm^2, imaging matrix = 48×48, slice thickness = 1.8 mm, number of slices = 5, and NA = 8). T_2 maps were computed by nonlinear least-square fitting of signal intensities versus TEs, pixel-by-pixel.

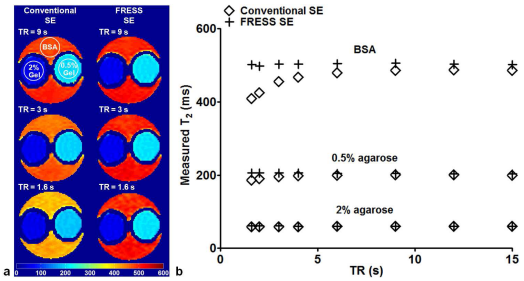

Fig. 2. Comparison of conventional SE and FRESS-SE MRI with a triple-compartment phantom. (**a**) T_2 maps of the triple-compartment phantom with different TRs. (**b**) Comparison of the measured T_2 values using the conventional SE and FRESS SE sequences at different TRs.

Results and Discussions Fig. 2a shows phantom T_2 maps obtained with both the conventional SE and the proposed FRESS SE sequences for three representative TRs of 9, 3, and 1.6 s. Fig. 2b shows TR-dependence of T_2 for the three compartments. For 2% agarose, the T_2 measurements from both sequences were comparable, while the conventional SE MRI showed noticeable underestimation of T_2 for the 0.5% agarose compartment, particularly at short TRs. Most importantly, T_2 of the BSA solution obtained with the FRESS-SE MRI sequence was nearly independent of TR, and persistently higher than T_2 measures acquired using the conventional sequence, especially at short TR. Fig. 3 shows pilot in vivo evaluation of FRESS-SE T_2 MRI in a representative chronic stroke animal model, 24 hr after MCAO. The difference in T_2 between the proposed FRESS-SE and conventional SE sequences (ΔT_2) of short TR was 2.0±2.5 ms ($p<0.01$) and 5.2±6.8 ms ($p<0.01$), for the contralateral normal and ischemic regions, respectively. Therefore, the proposed FRESS-SE MRI significantly improved T_2 measurement, especially when short TR is used. It is important to note that for conventional SE MRI, the long T_2 component is more susceptible to underestimation when short TR is used. In addition, although conventionally long TR is necessary when a specimen of broad T_2 distribution is imaged, the proposed FRESS-SE T_2 MRI technique is capable of quantifying T_2 with very short TR, hence, minimizes the scan time significantly.

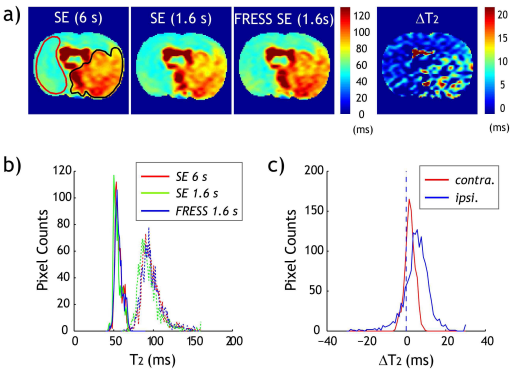

Fig. 3. (**a**) T_2 maps of a rat brain with chronic stroke (~24 hours after onset of permanent MCAO) using conventional SE sequence with TR=6s and TR=1.6s and using the proposed FRESS SE sequence with TR=1.6s. T_2 difference (FRESS SE – conventional SE) map is computed for TR=1.6s. (**b**) T_2 and (**c**) ΔT_2 histograms of the corresponding maps.

Conclusion We elucidated the phenomenon of TR dependence in T_2 measurement for the conventional SE MRI, and developed a FRESS-SE MRI method that allows fast and accurate T_2 mapping. The proposed FRESS-SE T_2 MRI technique was validated experimentally, and is suitable for in vivo application.

References [1] Jackson GD et al. Neurology 1993;43:1793-1799. [2] Loubinoux I et al. Stroke 1997;28:419-426. [3] Ngo FQ et al. MRI 1985;3:145-155.