SWIFT with magnetization preparation: Signal partitioning and 3D measurement of adiabatic T1rho in osteochondral specimen

Jinjin Zhang[1,2], Mikko Johannes Nissi[1,2], Djaudat Idiyatullin[1], Shalom Michaeli[1], Michael Garwood[1], and Jutta Ellermann[1]

[1]*Center for Magnetic Resonance Research, University of Minnesota, Minneapolis, Minnesota, United States,* [2]*Department of Orthopedic Surgery, University of Minnesota, Minneapolis, Minnesota, United States*

Introduction

SWIFT is an emerging technique that allows imaging of almost all biological objects including the tissues having ultrashort T_2 relaxation times (down to a few µs) (1,2). When implemented with appropriate parameters, SWIFT provides nearly pure proton density (PD) weighted imaging, and by utilizing magnetization preparation (MP) blocks embedded within the sequence, different types of contrast can be produced (T_1, T_2, T_{1rho}, T_{2rho} etc.) (3-5). In the present work we describe the theory and experimental setup to generate T_{1rho} contrast in MP-SWIFT images and demonstrate T_{1rho} quantification in osteochondral specimens. Additionally, the same concept of magnetization preparation is utilized to separate the different spin pools in an osteochondral specimen (fast relaxing spins and slow relaxing fatty or non-fat tissue).

Theory

Repeated excitation during regular SWIFT sequence drives the spin system to the steady state with equilibrium magnetization: $A_{ss} = M_0(1-E_1)/(1-E_1\cos\theta)$, where θ is excitation flip angle and $E_1 = exp(-TR/T_1)$. With a T_{1rho} MP block embedded into the sequence after very n SWIFT excitation/readout, the steady-state magnetization will also depend on $E_{MP} = exp(-T_{MP}/T_{1rho})$. By neglecting T_1 relaxation during the MP block, the average steady– state magnetization in this case can be described as:

$$S = A_{ss}(1+E_{MP})(1-E_1^n\cos^n\theta)/(1-E_1^nE_{MP}\cos^n\theta)/2 \quad [1].$$

The variation of parameter T_{MP}, for example, allows variation of the contrast and quantification of T_{1rho} based on equation [1].

Methods

All images were acquired on a 9.4 T Agilent animal MRI scanner. MP-SWIFT was performed on a mature bovine patella cartilage/bone specimen of approximately 2x2x2cm^3 size and a 4-month old pig femoral condole cartilage/bone specimen of similar size. The MP block consisted of sequences of adiabatic inversion pulses of 2.5 ms duration with MLEV-4 phase cycling. MP blocks were added every 16th TR period (n=16 here in equation [1]). Bovine specimen: A variable flip angle method with flip angles =1, 2, 3, 5, 12 and 18º was used to measure T_1 of the specimen. To obtain data for fitting T_{1rho}, images were acquired with MP blocks containing 0, 4, 8, 12, 16 and 24 adiabatic inversion pulses. Acquisition was performed with flip angle=2º, bandwidth=125 kHz, and TR=2.1 ms. For comparison, 2D Fast Spin Echo (FSE) readout following MP blocks of 0, 16, 32, 64, 128 adiabatic pulses were also acquired, with TR=5000 ms, ESL=4, ESP=5.53 ms, bandwidth=130 kHz. Pig specimen: SWIFT images with MP block of 4 adiabatic pulses were acquired at flip angle =10º. SWIFT images with fat on resonance and water on resonance were also acquired separately (4).

Results

T_{1rho} relaxation times measured using SWIFT or FSE as the readout differed markedly in cartilage (Fig.1). The T_{1rho} relaxation time as measured by SWIFT was significantly longer when the first data point (no pulses in the MP block) was removed from the fitting procedure (Fig. 2), indicating potential bi-exponential decay in the full data. An image of the fastest relaxing spins was created by subtracting the image obtained with MP block of 4 adiabatic pulses from the one without pulses (Fig. 3). Separate water-saturated (fat-only) and fat-saturated (water-only) images were created by applying selective saturations on the corresponding frequencies (Fig. 3). A color coded composite image demonstrated the spatial distribution of the different spin pools.

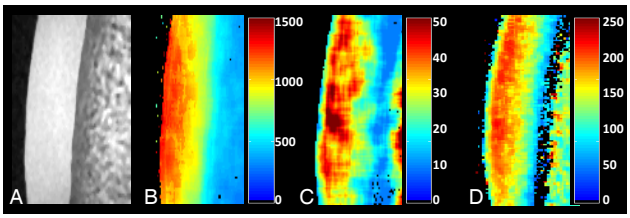

Fig. 1 A) SWIFT magnitude image, B) SWIFT- T_1 map, C) SWIFT- T_{1rho} map and D) FSE- T_{1rho} map of bovine specimen.

Discussion and conclusions

Measurement of T_{1rho} with SWIFT was demonstrated in the present work. The same approach would lend itself to measurement of other (relaxation) parameters that could be implemented with similar MP blocks and have similar signal decay characteristics. The use of the MP block for selective saturation of certain frequencies (such as fat) allows for separating signal arising from structures with different chemical shifts. In addition to selective saturation, separation of fast and slow relaxing spins was demonstrated using the same approach. Similar separation of short T_2 (fast relaxing) has been demonstrated with UTE methods (6). The pool of fast relaxing spins has conventionally been undetected, but with MP-SWIFT or UTE using a similar approach, these pools have become accessible. Several potential applications particularly in the musculoskeletal system have been demonstrated, but the extent of the use of these methods is yet to be shown. Furthermore, T_{1rho} relaxation time has been associated with neurological disorders of brain such as Parkinson's and Alzheimer's disease (7,8) and with proteoglycan content in articular cartilage (9). It was found that the T_{1rho}, as measured with SWIFT is much shorter than that measured using FSE. It is likely that the T_{1rho} relaxation measured with SWIFT has multiple components (10), presently averaged in the fitting procedure, but which are not accessible with FSE-based measurement. In conclusion, a new method for 3D measurement of T_{1rho} using SWIFT was presented and the results indicated that a previously undetected pool of T_{1rho} relaxation can be captured. The MP-SWIFT is likely to be very useful, especially for musculoskeletal applications, assessing the entire spin population, including the abundant tightly bound moieties.

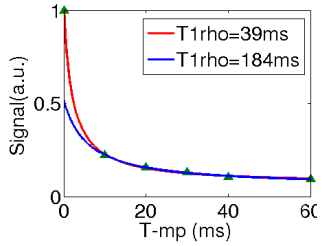

Fig2. SWIFT T_{1rho} fitting. Removal of the first data point results in significantly longer apparent T_{1rho} (blue curve).

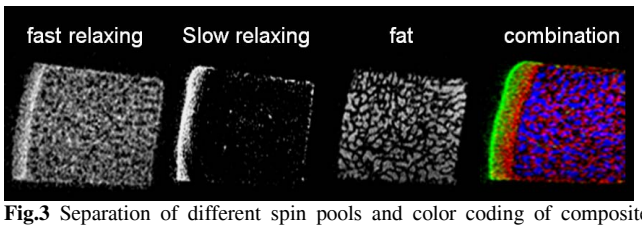

Fig.3 Separation of different spin pools and color coding of composite image of the pig specimen: red= fast relaxing, green=slow relaxing, blue= fat. The first figure shows the fast relaxing components (e.g.bone, calcified layer of the cartilage and tightly bound collagen matrix part).

References [1] Idiyatullin D et al. J Magn Reson 193: 267-273, 2008. [2] Idiyatullin D et al. J Magn Reson 181: 342-349, 2006. [3] Nissi MJ et al. 2011; Montreal, Canada. p 564. [4] Ellermann J et al. 2009; Honolulu, HI, USA. p 849. [5] Kendi AT et al. Archives of otolaryngology--head & neck surgery 137: 916-919, 2011. [6] Du J et al. Magn Reson Med 63: 447-455, 2010. [7] Michaeli et al, Mov Disord. 2007,22(3):334-40. [8]Borthakur A, et al., J Magn Reson Imaging. 2006,24(5):1011-7. [9] Regatte RR et al. Acad Radiol 9: 1388-1394, 2002.[10] Du J et al. Magn Reson Med 67: 645-649, 2012. **Acknowledgments** Support from grant P41 EB015894 gratefully acknowledged.