Quick water-selective excitation in ultrashort echo time (UTE) imaging of tendons and ligaments at 3T

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Purpose

Structure and composition of solid-like tissues (e.g. tendons, ligaments or cortical bone) result in relatively short effective transverse relaxation times (T_2^*) lacking nearly any signal using conventional imaging sequences. By means of ultrashort echo time (UTE) sequences MR signal from these tissues can be acquired even though it decays very rapidly after excitation (typical range $T_2^* \approx 0.5\text{-}5$ ms). Moreover, in case of extremely short T2* values, relaxation of transverse magnetization during RF excitation must also be considered as recently demonstrated [1]. Thus, to improve contrast between tendons and other tissues with rather long transverse relaxation times (i.e. fat, skeletal muscle) a variety of long-T2 suppression techniques have been investigated [2]. However, most of these techniques require presaturation pulses or inversion times which are not feasible in clinical routine especially if 3D UTE-sequences are applied. Therefore, we aimed to improve the visualization of tendons and ligaments with positive contrast by implementing water-selective excitation (WE) pulses into 3D UTE-sequences. First, transverse magnetization in steady-state was analytically described for WE-UTE sequences and results were compared to numerical simulations either of WE-UTE or standard UTE sequence with regular off-resonance fat saturation. Second, examination protocols were optimised accordingly and tendons / ligaments were exemplarily examined in-vivo on a 3T whole-body MR unit.

Materials and Methods

A 1-1-binomial water-selective excitation pulse was incorporated into a 3D UTE sequence with centric radial k-space sampling. Two short non-slice-selective rectangular RF excitation pulses (each of 100µs duration) were implemented with a time interval of 1150µs in between in order to allow a spin dephasing of 180° for spins at 400Hz off-resonance frequency (resonance frequency of methylene protons in fatty tissue at 3T). Gradient and RF spoiling was implemented to dephase transverse magnetization before each excitation block achieving a steady-state only for the longitudinal magnetization. By means of spin rotation matrices an analytical description of the steady-state magnetization could be obtained for variable off-resonance frequencies. The analytical description was subsequently compared to numerical simulations of WE-UTE and regular Gaussian-shaped off-resonance fat saturation pulses using an established Runge-Kutta-algorithm and applying the Bloch-equations. On the basis of the analytical description of the steady-state magnetization parameters of the 3D WE-UTE sequence were optimised for tendons and ligaments to further increase the contrast to surrounding fatty tissue. Results from theoretic optimisation processes were subsequently applied to 3D WE-UTE examination protocols and provided the basis for visualization of tendons / ligaments with increased positive contrast at several musculoskeletal regions. For in-vivo application region selective shimming is mandatory; subsequent local frequency adjustment provides correct off-resonance frequency of fat within the region of interest.

In-vivo measurements of healthy volunteers were performed on a 3 T whole-body MR scanner (Siemens Healthcare, Erlangen, Germany). Exemplarily, an eight-channel transmit-receive knee coil was used for both, RF transmission and signal detection. Parameters of 3D WE-UTE were: TR=10ms, TE=0.07ms, FA=8°, BW=1000Hz, TA=2:05min, FoV=128mm, 0.8mm isotropic resolution.

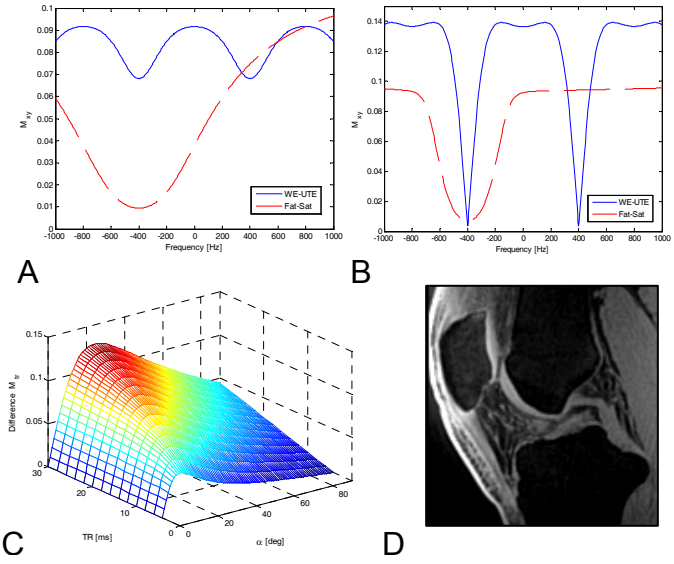

Figure A shows M_{xy} for tendon (T_1=500ms, T_2=1ms) and B for fat (T_1=380ms, T_2=60ms) in steady-state in case of WE-UTE (TR/TE=15/0.07 [ms], FA=20°) and off-resonance fat saturation (T_{sat}=5.120ms, FA=110°). Figure C shows difference in M_{xy} between tendon and fat for various TR and FA. An example of the in-vivo measurements is shown in Figure D.

Results

Analytical description of steady state magnetization in WE-UTE sequences did not show any deviation from numerical simulations. Subsequent analytical investigations showed that even for tissues with short transverse relaxation times (T2 ~ 1ms) a sufficient excitation in combination with fat suppression can be obtained by WE-UTE. Thus, by means of an optimized WE-UTE sequence tendons / ligaments with extremely fast signal decay can be visualized in-vivo with improved contrast to surrounding fat. For example, patellar tendon as well as anterior and posterior cruciate ligament can be clearly visualized as hyperintense structures in Figure D.

Discussion

In musculoskeletal MRI healthy highly-ordered tissues (e.g. tendons and ligaments) usually appear with low signal intensity on conventional images due to their rather short transverse relaxation times. In this work, a newly developed quick water-selective 3D UTE sequence is presented with a binomial excitation pulse and optimized sequence parameters according to the derived analytical description of the steady-state magnetization. Tendons and ligaments, which are of high interest in clinical musculoskeletal MRI, could be successfully visualized as hyperintense structures using the newly developed WE-UTE sequence.

Although a variety of other fat suppression techniques have already been reported for UTE sequences, the presented WE-UTE sequence provides the possibility of 3D visualization of tendons and ligaments in clinically acceptable acquisition times. However, region selective shimming for in-vivo applications is mandatory due to suppression of a rather small frequency range compared to regular Gaussian-shaped off-resonance saturation pulses. But due to relatively short acquisition times additional preparation pulses e.g. off-resonance saturation for magnetization transfer may also be implemented without time constraints in clinical routine and may provide a basis for further characterization of such highly-ordered tissues in-vivo. In conclusion, the presented newly developed WE-UTE sequence is a promising technique which is worth being further evaluated in clinical musculoskeletal MR imaging.

References

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