Experimental Influences on the Anisotropies of Multi-component T2 and T1ρ in Tendon

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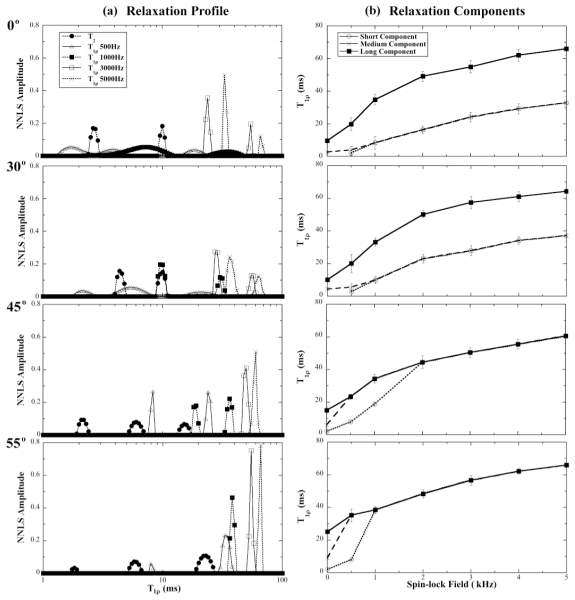
INTRODUCTION

Tendon, which is an important connective tissue that joins muscle and bone to provide force transmission (1), largely consists of a highly ordered collagen structure and anisotropic water molecules (2-5). Since NMR signal depends strongly on the orientational structure of macromolecules, the anisotropic characteristics of the NMR/MRI signal can be used to investigate the interaction of water molecules with the extensive hydrogen-bonded network around collagen molecules. In this project, both microscopic MRI (μMRI) and NMR spectroscopy were used to study the anisotropic characteristics of multi-component $T_{1\rho}$ and T_2 relaxations. A number of experimental issues in the multi-component measurements were investigated, including the effects of echo spacing (0.6 ms to 3 ms), the resolution of MRI experiments (35 μm to 280 μm), the influence of the specimen orientations (0°, 30°, 45°, 55°), and the strengths of different spin-lock frequencies in $T_{1\rho}$ experiments (0.5 kHz to 5 kHz). We aimed to provide a coherent baseline for the complex issues that can influence the measurement of multi-component relaxation in this organized tissue.

MATERIALS AND METHODS

Three canine Achilles tendons were harvested from mature and musculoskeletally healthy dogs that were used for an unrelated biomedical study. These dogs came from a research lab that had provided canine tissue to our studies for more than ten years. NMR spectroscopy and μMRI experiments were conducted at room temperature on a Bruker AVANCE II NMR spectrometer equipped with a 7-Tesla/89-mm superconducting magnet and micro-imaging accessory (Billerica, MA). A homemade 5-mm solenoid coil was used for the experiments, where the long axis of the tendon tissue with respect to B_0 was set at 55° (the magic angle) for MRI experiments. The NMR spectroscopic experiments were conducted at four specimen orientations in the magnetic field (0°, 30°, 45°, 55°). T_2 imaging experiments were performed using a CPMG magnetization-prepared T_2 imaging sequence. The $T_{1\rho}$ imaging sequence was nearly identical to the T_2 imaging sequence, except that it was led by a $T_{1\rho}$-weighting segment, which had a 90° rf pulse followed by a spin-lock pulse. The power of the spin-lock pulse varied from 0.5 to 5 KHz. The 2D imaging parameters were consistent for all experiments: the echo time and repetition time was 3.9 ms and 2 s respectively; the number of scans was 12; and the field of view was 4.5 mm×4.5 mm. T_2 experiments were acquired at four different transverse pixel resolutions (280 μm, 140 μm, 70 μm, and 35 μm). The slice thickness was 1 mm. A minimum SNR of 400 was achieved from all experiments. The non-negative-least-squares method was implemented in the Matlab (Natick, MA) and used to calculate the profiles of T_2 and $T_{1\rho}$ relaxation times.



RESULTS

Since the T_2 data can be considered as the $T_{1\rho}$ data at the spin-lock frequency of zero, the multi-component T_2 and $T_{1\rho}$ relaxations were examined together by both NMR spectroscopy and μMRI, where the $T_{1\rho}$ dispersion phenomenon (the dependency of the relaxation values on the spin-lock frequencies) was observed. The figure on the right shows (a) The T_2 and $T_{1\rho}$ distribution profiles of tendon at four different orientations (0°, 30°, 45°, 55°) by the NNLS calculation using the NMR spectroscopy results. (b) The trends of the relaxation components as the function of the spin-lock frequencies. The general trends in our data were, smaller specimen angles (e.g. 0° and 30°) resulting in more relaxation components, and lower spin-lock frequency (e.g., 500Hz) resulting in more components. The imaging resolution (35 – 280 μm) had little influence in the T_2 experiments. Table 1 summarizes all spectroscopy and imaging results.

$T_{1\rho}$ Dispersion	NMR								MRI	
	0°		30°		45°		55°		55°	
	ms	%	ms	%	ms	%	ms	%	ms	%
T_2 (0.6ms)							2.0±0.5	16.0±2.2		
							8.5±1.0	30.1±3.1		
							24.8±2.5	54.9±3.9		
T_2 (1ms)					2.2±1.6	35.3±3.1	1.8±0.8	9.1±1.8		
	2.6±1.7	57.1±4.9	4.5±2.0	51.3±4.3	6.1±2.0	38.3±4.0	6.8±1.2	31.8±2.9	7.2±0.9	23.4±3.0
	9.7±2.2	42.9±3.5	10.2±2.6	48.7±5.2	15.1±2.8	26.4±2.7	24.7±2.8	59.1±3.6	24.8±3.1	76.6±4.8
T_2 (2 ms)							6.1±1.0	29.0±3.1		
							22.8±2.6	71.0±4.0		
T_2 (3 ms)							5.4±1.4	27.3±3.5		
							21.9±2.7	72.7±4.4		
$T_{1\rho}$ (500 Hz)	2.2±1.7	46.5±4.5	2.8±1.8	19.6±3.5						
	4.1±2.2	30.5±2.8	5.5±2.2	51.3±4.9	7.9±1.8	40.8±4.4	8.0±1.4	13.1±2.7	33.2±3.5	100
	19.8±3.9	23±3.0	20.1±5.6	29.6±3.2	23.4±3.4	59.2±5.7	34.7±3.0	86.9±4.2		
$T_{1\rho}$ (1000 Hz)	8.4±3.8	78.5±4.4	10.0±2.2	69.1±5.4	18.8±3.2	41.1±4.9	38.8±3.3	100	38.3±3.1	100
	34.8±3.2	21.5±3.7	33.2±3.5	30.9±4.1	34.3±4.2	58.9±5.1				
$T_{1\rho}$ (3000 Hz)	24.2±3.3	79.6±5.0	27.9±3.7	67.4±4.5	50.4±5.3	100	56.6±3.1	100	49.9±3.8	100
	54.9±4.0	20.4±3.1	57.5±5.0	32.6±3.4						
$T_{1\rho}$ (5000 Hz)	32.9±3.9	80.6±4.8	37.1±3.8	66.2±4.3	61.6±4.8	100	65.9±4.1	100	60.5±4.9	100
	65.9±4.4	19.4±3.6	64.4±5.3	33.8±2.7						

DISCUSSION

The anisotropic T_2 and $T_{1\rho}$ in tendon are likely the indications of slow macromolecular motion, possibly related to highly constrained and heterogeneous motions of the water molecules in the collagen matrix. The transition between a mono-component and multi-component in this and other recent studies (6) demands the caution in interpreting the multi-component relaxation results, where several experimental factors can influence the measurable values and numbers of the relaxation parameters. One might also be able to use this feature in the clinical MRI study of connective tissues, where the tissue environment is altered due to tissue degradation, such as the loss of proteoglycans and the orientation change of the collagens. The fact that the tendon's relaxation does not depend upon the imaging resolution demonstrates that the high-resolution results from this μMRI project can equally be applied to the clinical MRI research, where the imaging resolution is coarser.

REFERENCES

(1) Kannus P. Scand J Med Sci Sports 2000;10:312-320. (2) Fullerton GD, Cameron IL, Ord VA. Radiology 1985;155:433-435. (3) Peto S, Gillis P, Henri VP. Biophys J 1990;57:71-84. (4) Navon G, Eliav U, Demco DE, Blumich B. J Magn Reson Imaging 2007;25:362-380. (5) Zheng S, Xia Y. J Magn Reson 2009;198:188-196. (6) Wang N, Xia Y. J Magn Reson 2011;212:124-132.

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