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MRI T2 mapping of the asymptomatic supraspinatus tendon by age and imaging plane using clinically relevant subregions

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ABSTRACT

Purpose: Diagnosis of partial rotator cuff tears and tendonopathy using conventional MRI has proven variable. Quantitative T2 mapping may have application for assessing rotator cuff health. In order to evaluate the usefulness of T2 mapping for the rotator cuff, methods must be refined for mapping the supraspinatus tendon, and normative T2 values must first be acquired.
Materials and methods: This study was IRB approved. Thirty asymptomatic volunteers (age: 18–62) were evaluated with sagittal and coronal T2 mapping sequences. Manual segmentation of tendon and muscle as a unit and tendon alone was performed twice by two independent raters. Segmentations were divided into medial, middle and lateral subregions and mean T2 values calculated.
Results: Anatomic comparison of mean T2 values illustrated highest values in the medial region, lowest values in the lateral region, and intermediate values for the middle region upon coronal segmentation ($p < 0.001$). In sagittal segmentations, there were higher values in the medial region and no significant differences between the lateral and middle subregions. No significant differences were found with comparison across age groups. Inter and intra-rater segmentation repeatability was excellent, with coefficients ranging from 0.85 to 0.99.
Conclusion: T2 mapping illustrated anatomic variation along the supraspinatus muscle-tendon unit with low standard deviations and excellent repeatability, suggesting that changes in structure due to degeneration or changes associated with healing after repair may be detectable.

1. Introduction

Evaluation of the rotator cuff has improved with advancements in conventional MRI technology. Clinicians can gain insight into the morphologic status of tendon to attachment with qualitative interpretation of images. However, the sensitivity and specificity of MRI to determine pathology has proven variable, especially in the presence of tendonopathy and partial rotator cuff tears and the evaluation of signal intensity alone may contribute to lack of reliability [1–3]. Furthermore, diagnosis and monitoring of post-repair tendon health with MRI also remains largely subjective [4].

The degenerative process of rotator cuff tendons involves alterations in collagen structure and biochemical composition. Quantitative MRI has demonstrated to be sensitive to biochemical changes in cartilage, recently in cartilage of the glenohumeral joint, and could potentially be used to detect subtle changes in the biochemical composition of tendons associated with tendon degeneration. Initial studies have shown promise for detecting tendon pathology using quantitative MRI [5–10]. Pilot clinical application reported anatomic variation in T2* values within the Achilles tendon-muscle unit in asymptomatic volunteers, and differences in T2* values between asymptomatic volunteers and those with chronic Achilles tendinopathy [7]. To our knowledge, there are no published studies which analyze the rotator cuff tendons using quantitative MRI mapping. Quantifiable, objective data on the health status of the rotator cuff would be exceptionally useful in a clinical setting for the non-invasive diagnosis of injury and tracking post-surgical treatment response. To date, T2 mapping is the most commonly used mapping sequence within clinical practice, thus evaluation of T2 mapping for diagnosing rotator cuff pathology has high clinical relevance and potential for implementation.

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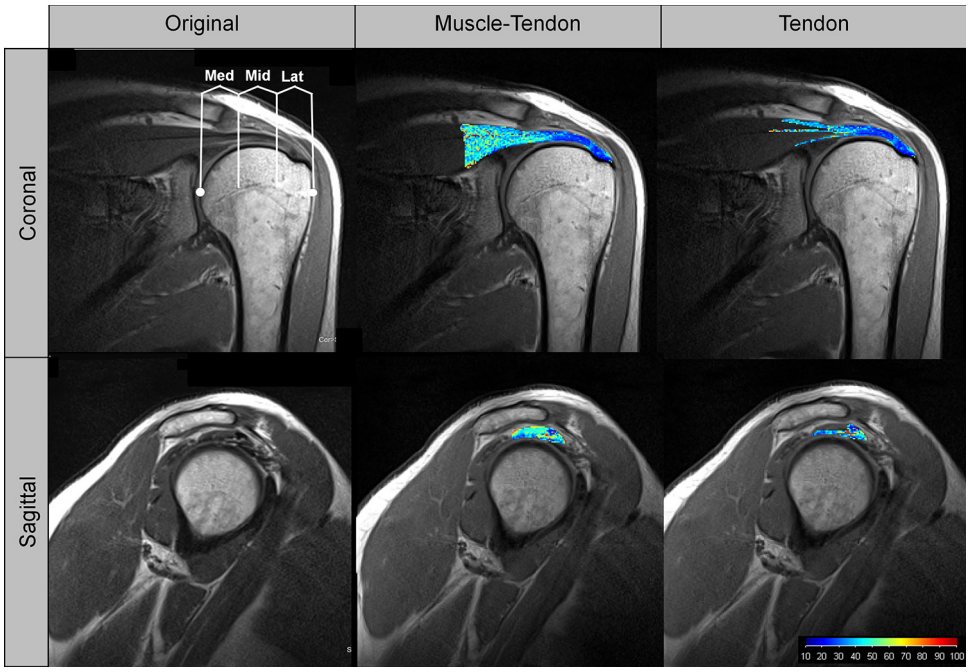

Fig. 1. Example of muscle-tendon and tendon region segmentations. White circles represent landmarks manually selected to divide each region into the following subregions: medial (Med), middle (Mid), and lateral (Lat). An overlay of the T2 values for the muscle-tendon and of the tendon regions are shown in the sagittal and coronal planes.

Before applying T2 mapping scans to the clinical population, it is essential to appreciate normative T2 values and the distribution of these values within the rotator cuff tendons to serve as a baseline, similar to previous normative studies of the tendons utilizing classic MRI technology [11]. Therefore, the objective of this prospective study was evaluate verified asymptomatic volunteers using T2 mapping in order to establish a quantitative MRI protocol using T2 mapping for this purpose and to determine normative T2 values in asymptomatic tendons across age groups. We hypothesized that a normal range and pattern of T2 values exists which correlates to the anatomic structure of the muscle-tendon unit. Additionally, we hypothesized that due to compositional changes which occur during aging, differences in T2 values would be observed across age groups [12]. The results of this study will establish normative, asymptomatic T2 values for the supraspinatus tendon according to age, which can later be used as a reference and baseline for comparison for T2 mapping of damaged rotator cuff tendons and mapping of healing rotator cuff tendons after repair using these clinically relevant subregions.

2. Materials and methods

2.1. Subjects

This study was approved by the Institutional Review Board and all subjects provided informed consent. Thirty recreationally active volunteers who were entirely asymptomatic for rotator cuff pathology of the shoulder were prospectively enrolled in the study. The volunteers were deemed asymptomatic by administering a short questionnaire regarding symptoms and injury history and by verifying a normal clinical examination that was performed by a sports medicine orthopedic surgeon. All volunteers were between the ages of 18–62 (16 female, 15 male; 15 right shoulders, 15 left shoulders) and were grouped into three equal groups with 15 year age spans: 18–32 (5 female, 5 male; 5 left, 5 right), 33–47 (4 female, 6 male; 5 left, 5 right), 48–62 (7 female, 3 male, 5 left, 5 right). Grouping was determined by convenience sampling, as no prior tendon-based T2 mapping studies included similar comparisons that could be used for sample size guidance. Exclusion criteria included previous shoulder surgery or injury, history of glenohumeral joint disease and rotator cuff pathology found on examination of subsequent clinical MRI. No distinction was made between dominant and non-dominant extremity; it was however paramount that the imaged side was asymptomatic. The time delay between physical examination and MR acquisition was limited to 36 h to ensure that the volunteers remained asymptomatic. In addition, volunteers were asked to abstain from heavy lifting or exercise that would involve the upper body on the day of the scan in order to account for any changes in hydration levels due to physical activity.

2.2. Image acquisition

MR imaging was performed with a Siemens Magnetom Verio 3.0T scanner (Siemens Medical Solutions, Erlangen, Germany) with a gradient strength of 40 mT/m, using a four channel small shoulder array coil (Invivo, Gainesville, FL, USA). Volunteers were positioned in the supine position with a sandbag placed in the supinated palm. The scanning protocol included an axial proton-density turbo-spin echo fat saturated sequence, followed by a coronal T2 mapping sequence, and finally a sagittal T2 mapping sequence. The T2 mapping sequence was a multi-echo spin-echo (MESE) sequence (2000 ms repetition time; 10.7, 21.4, 32.1, 42.8, 53.5, 64.2, 74.9 ms echo times; 140 mm field of view; 256 × 256 resolution; 2 mm slice thickness; 18 slices; 50% distance factor; 6:30 min scan time). The axial proton-density turbo-spin echo fat saturated clinical scan and the raw images from the sagittal and coronal MESE T2 mapping scans were reviewed to verify the absence of rotator cuff pathology. Clinical MRI findings of a partial rotator cuff tear or a full rotator cuff tear were grounds for exclusion. Values were calculated from the T2 mapping sequence using Siemens MapIt software (Siemens Medical Solutions, Erlangen, Germany).

2.3. Data analysis

The supraspinatus muscle and tendon were manually segmented with a stylus and touchscreen monitor using Mimics

Table 1
Inter and intra-rater ICC and confidence intervals.

Subregion name		Inter-rater[a]		Intra-rater 1[a]		Intra-rater 2[a]	
		Muscle tendon	Tendon	Muscle tendon	Tendon	Muscle tendon	Tendon
Sagittal	Lateral	0.87 [0.71,0.93]	0.88 [0.76,0.94]	0.89 [0.78,0.95]	0.90 [0.80,0.95]	0.94 [0.87,0.87]	0.94 [0.88,0.97]
	Middle	0.90 [0.79,0.95]	0.94 [0.88,0.97]	0.94 [0.88,0.97]	0.95 [0.90,0.98]	0.97 [0.94,0.99]	0.96 [0.92,0.98]
	Medial	0.95 [0.88,0.97]	0.74 [0.51,0.87]	0.97 [0.94,0.99]	0.84 [0.69,0.92]	0.98 [0.96,0.99]	0.88 [0.77,0.95]
Coronal	Lateral	0.93 [0.85,0.97]	0.94 [0.88,0.97]	0.98 [0.97,0.99]	0.97 [0.93,0.98]	0.97 [0.93,0.99]	0.96 [0.93,0.98]
	Middle	0.95 [0.90,0.98]	0.91 [0.81,0.96]	0.98 [0.95,0.99]	0.94 [0.88,0.97]	0.95 [0.90,0.98]	0.96 [0.92,0.98]
	Medial	0.96 [0.91,0.98]	0.86 [0.72,0.93]	0.98 [0.95,0.99]	0.92 [0.83,0.96]	0.98 [0.96,0.99]	0.90 [0.80,0.95]

[a] 95% CIs for inter-rater and intra-rater ICCs [LB, UB].

software (Materialize, Plymouth, MI, USA). Segmentation involved manually drawing a region of interest on the third echo of the mapping sequence. Each observer segmented two regions on the sagittal and coronal scans: a region capturing the supraspinatus muscle and tendon together (muscle-tendon segmentation) and a region including the tendon alone (tendon segmentation) (Fig. 1). The segmentations were performed by two raters (a musculoskeletal radiologist with 13 years of experience and an orthopedic surgeon with 6 years of experience) and were repeated after a minimum of four weeks interval to assess intra-rater and inter-rater reliability.

In order to evaluate variability in T2 values based on anatomic location, the segmented regions were further divided into three subregions. To do this, the raters manually selected two landmarks on both the coronal and sagittal scan; one on the most lateral aspect of the greater tuberosity and one on the most medial aspect of the humeral head. The coordinates of these two landmarks were exported and used to divide the segmentation into the following three subregions: the lateral supraspinatus, the middle supraspinatus, and the medial supraspinatus (Fig. 1). Customized software using Matlab (Mathworks, Natick, MA) was used to calculate the mean T2 values and standard deviation for each clinically relevant subregion (Fig. 1).

2.4. Statistical analysis

All statistics were performed with the use of SPSS statistics software (Version 20, IBM Corporation, Armonk, NY, USA). Means for the average T2 value of each subregion were calculated and compared using one-way repeated measures ANOVA with subregion as a factor. Bonferroni corrections were applied to post hoc comparisons between subregions. A mixed effects ANOVA model with age group as a between subject factor was used to assess differences in T2 values based on age. Differences between regions with a p-value of less than 0.05 were considered statistically significant. To assess the repeatability of the segmentations in a manner that can be generalized to a single future rater from the population of qualified raters, a two-way random effects model was used to calculate the single measures intra-class correlation coefficient (ICC) for each subregion's mean T2 value. The ICC values were graded as follows: excellent reliability ($0.75 > ICC \leq 1$), fair to good reliability ($0.4 \geq ICC \leq 0.75$), poor reliability ($0 \geq ICC < 0.4$) [13].

3. Results

All 30 volunteers were found to be asymptomatic for rotator cuff pathology upon questionnaire analysis and clinical exam. However, two of the 30 volunteers were excluded due to an evident full thickness supraspinatus tear found during the subsequent morphologic MRI evaluation. Both subjects had small isolated supraspinatus tendon tears with intrasubstance degeneration, and fatty infiltration and atrophy of the musculotendinous junction but no gross retraction of the tendon. For the 28 volunteers without tears, the inter-rater correlation coefficients and intra-rater correlation coefficients were all excellent except the medial subregion of the tendon alone segmentations which had fair-good repeatability (Table 1).

In the coronal plane, mean T2 values of the muscle-tendon segmentations decreased significantly from medial to lateral for all three subregions ($p < 0.001$) (Fig. 2A). For the tendon segmentations, mean T2 values of the middle and lateral subregions were lower than the medial subregion ($p < 0.001$), though not significantly different from each other ($p = 0.1$) (Fig. 2B).

In the sagittal plane, mean T2 values of the muscle-tendon segmentations were significantly higher in the medial region compared to the middle and lateral regions ($p < 0.001$), but no statistical difference was found between the middle and lateral regions ($p = 1.0$) (Fig. 2C). For the tendon segmentations, the lateral and medial subregions had higher T2 values than the middle region ($p < 0.001$), and these two regions were not significantly different from each other ($p = 0.4$) (Fig. 2D).

When comparing the tendon and muscle-tendon segmentations to each other, the values for middle and medial subregions of the muscle-tendon segmentations were higher than the tendon segmentations ($p < 0.001$) and the lateral subregions were not significantly different ($p = 1.0$) in the sagittal plane. The same results were true for the coronal plane except the medial subregions were also not significantly different from each other ($p = 0.7$). No significant differences were found in mean T2 values between different age groups for either plane.

4. Discussion

The present study applied T2 mapping to asymptomatic human rotator cuff tendons in vivo. T2 values in the rotator cuff tendons demonstrated significant variation based upon anatomic subregion, with higher values in the more medial subregions and lower values in the more lateral subregions. This variation is expected as the medial subregion contains more muscle than tendon, and thus has inherently higher water content. Structures with high water content have been shown to have increased T2 values compared with soft tissue structures of lower water content. These results are in support of the hypothesis in that T2 values would vary with varying tissue structure. The ability to detect significant differences across the subregions provides indication that T2 mapping may be useful in the clinical setting for detecting structural variation in the tendon and muscle.

It was unexpected that no significant differences were observed in T2 values between age groups since histological studies have shown changes in the biochemical composition of rotator cuff tendons with age [12]. A potential reason for these results was the strict inclusion criteria to ensure volunteers truly had asymptomatic and therefore likely healthier supraspinatus tendons. There were two subjects with asymptomatic tears, who were in the age group 51–66. A similar rate of asymptomatic tears has been documented in this age group, with a rate of 23% in a sample of subjects older

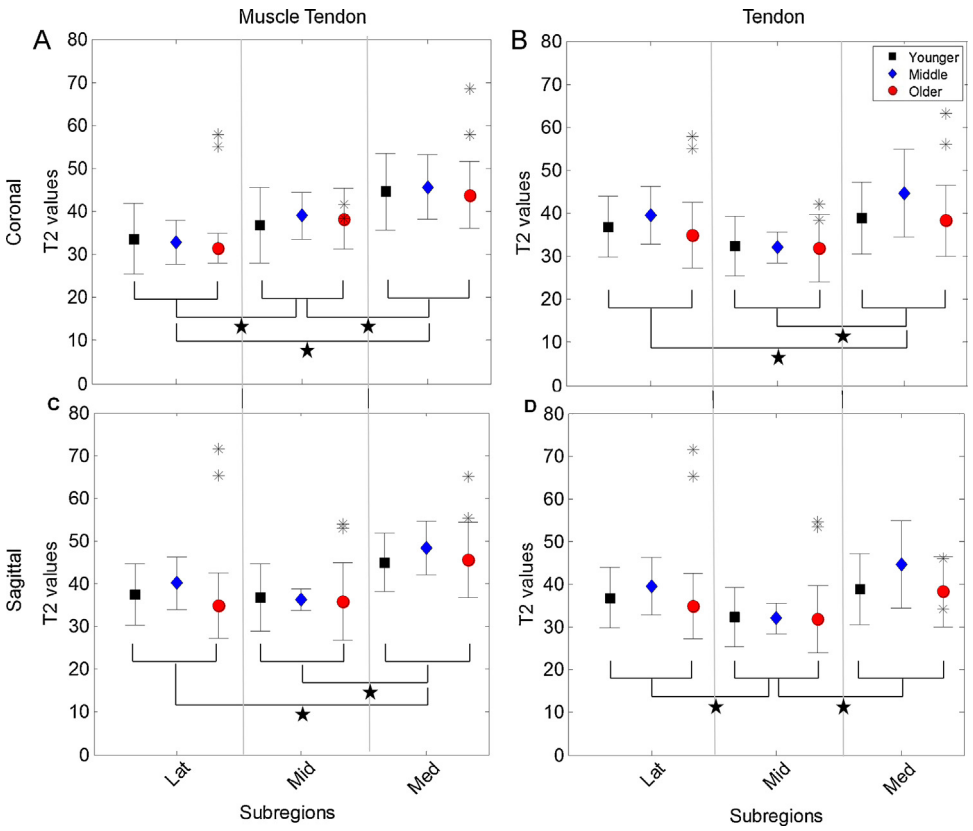

Fig. 2. Mean (±STD) T2 values of subregions using coronal muscle-tendon (A), coronal tendon (B), sagittal-muscle tendon (C), and sagittal tendon (D) regions. Stars represent statistical difference between subregions. Asterisks represent mean T2 values from two subjects excluded due to MRI evidence of supraspinatus tears.

than 50 years [14]. Review of the clinical MRI exams of both subjects in this cohort revealed full thickness tears with no gross retraction which caused the data from these subjects to be removed from the study. Although excluded for statistical analysis, the mean T2 values of the two volunteers with MRI findings of a supraspinatus tear were substantially higher than the standard deviations for all regions in the remaining asymptomatic volunteers except for the middle subregion (coronal plane). The mean T2 values from these volunteers are shown in Fig. 2.

T2 mapping scans were acquired in both the sagittal and coronal planes in order to determine an optimal plane for analysis and use in clinical practice. While the inter-rater and intra-rater correlation coefficients were mostly excellent for both planes indicating robustness of the manual segmentation and landmark selection, the raters felt more confident with segmenting the footprint of the tendon in the coronal plane. On the most lateral slices of the sagittal sequence, the raters reported difficulty separating tendon and bone at the footprint. This was due to the increase in tendon curvature out of the slicing plane and associated partial volume averaging and may have affected the T2 values in this region. For this reason, the authors believe the coronal sequence may be optimal for analyzing T2 values of the supraspinatus footprint. It should be noted that differentiation between the supraspinatus and infraspinatus is difficult in the coronal plane, because of partial volume averaging with the coronal orientation of the supraspinatus and infraspinatus. For investigations involving more medial regions or where muscle differentiation is imperative, the sagittal plane may be optimal since the entire musculotendinous cross section is easily visualized and can be reliably segmented.

The tendon and muscle-tendon segmentations were both obtained in order to evaluate the reliability of the segmentation method (i.e. tendon and muscle plus tendon combined). The inter-rater and intra-rater correlation coefficients were excellent for both segmentations, except for the medial subregion of the tendon segmentations which was fair-good. In general, the raters were more confident segmenting the muscle and tendon together in the medial subregions and noted that it was very difficult to distinguish the developing tendon and slips from the muscle about the myotendinous junction.

A limitation of the study is that biochemical validation of T2 mapping of the rotator cuff has not been performed to verify that variation in values has clinical meaning. Such validation would require histologic specimens in an animal or cadaveric human model. While the majority of research and clinical applications of quantitative MRI have focused on cartilage, initial efforts toward utilizing T2 mapping in the analysis of tendon health have been promising [6,15].

Asymptomatic subject data was collected in this study and thus we cannot conclude whether T2 mapping will be useful for detecting rotator cuff pathology. Results were promising, however, in that differences in T2 values were observed between subregions with known structural variation and were performed with good to excellent inter-rater and intra-rater correlation. However, analysis of the oldest age group may have been limited due to the exclusion of two volunteers with asymptomatic tears reducing the number of volunteers analyzed in this group. Future directions include evaluating patients with documented rotator cuff pathology to enable comparison. Ultimately, automated segmentation and automated landmark detection would be ideal for use of this technique in the clinical setting.

5. Conclusions

In conclusion, this study provides initial normative T2 values for asymptomatic supraspinatus tendons using clinically relevant subregions. Variability of T2 values between subregions is

consistent with the muscle/tendon composition. Age was not a factor as it did not have a significant effect on T2 values in this asymptomatic cohort. The values from this study can be used for comparison to identify rotator cuff degeneration in patients presenting with abnormalities of the shoulder. Further studies are needed to analyze T2 mapping to document its clinical utility and value to improving assessment of rotator cuff pathology and post-repair healing.

Conflicts of interest

All work was performed at the Steadman Philippon Research Institute. The authors and Institute report no conflicts of interest pertaining to this work.

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