Progression of Fatty Muscle Degeneration in Atraumatic Rotator Cuff Tears

Jonah Hebert-Davies, MD, FRCSC, Sharlene A. Teefey, MD, Karen Steger-May, MA, Aaron M. Chamberlain, MD, William Middleton, MD, Kathryn Robinson, MD, Ken Yamaguchi, MD, MBA, and Jay D. Keener, MD

Investigation performed at Washington University, St. Louis, Missouri

Background: The purpose of this prospective study was to examine the progression of fatty muscle degeneration over time in asymptomatic shoulders with degenerative rotator cuff tears.

Methods: Subjects with an asymptomatic rotator cuff tear in 1 shoulder and pain due to rotator cuff disease in the contralateral shoulder were enrolled in a prospective cohort. Subjects were followed annually with shoulder ultrasonography, which evaluated tear size, location, and fatty muscle degeneration. Tears that were either full-thickness at enrollment or progressed to a full-thickness defect during follow-up were examined. A minimum follow-up of 2 years was necessary for eligibility.

Results: One hundred and fifty-six shoulders with full-thickness rotator cuff tears were potentially eligible. Seventy shoulders had measurable fatty muscle degeneration of at least 1 rotator cuff muscle at some time point. Patients with fatty muscle degeneration in the shoulder were older than those without degeneration (mean, 65.8 years [95% confidence interval (CI), 64.0 to 67.6 years] compared with 61.0 years [95% CI, 59.1 to 62.9 years]; $p < 0.05$), and the median size of the tears at baseline was larger in shoulders with degeneration than in shoulders that did not develop degeneration (13 and 10 mm wide, respectively, and 13 and 10 mm long; $p < 0.05$). Tears with fatty muscle degeneration were more likely to have enlarged during follow-up than were tears that never developed muscle degeneration (79% compared with 58%; odds ratio, 2.64 [95% CI, 1.29 to 5.39]; $p < 0.05$). Progression of fatty muscle degeneration occurred more frequently in shoulders with tears that had enlarged (43%; 45 of 105) than in shoulders with tears that had not enlarged (20%; 10 of 51; $p < 0.05$). Additionally, tears with enlargement and progression of muscle degeneration were more likely to extend into the anterior supraspinatus than were those without progression (53% and 17%, respectively; $p < 0.05$); however, this relationship was lost when controlling for tear size ($p = 0.56$). The median time from tear enlargement to progression of fatty muscle degeneration was 1.0 year (range, −2.0 to 6.9 years) for the supraspinatus and 1.1 years (range, −1.8 to 8.5 years) for the infraspinatus muscle ($p = 0.98$).

Conclusions: Progression of fatty muscle degeneration is more common in tears that are larger at baseline, enlarge over time, and undergo a larger magnitude of enlargement. Our study findings also suggest that an often rapid progression of muscle degeneration occurs in relation to a clinically relevant increase in tear size in some degenerative cuff tears.

Level of Evidence: Prognostic Level II. See Instructions for Authors for a complete description of levels of evidence.

Peer Review: This article was reviewed by the Editor-in-Chief and one Deputy Editor, and it underwent blinded review by two or more outside experts. It was also reviewed by an expert in methodology and statistics. The Deputy Editor reviewed each revision of the article, and it underwent a final review by the Editor-in-Chief prior to publication. Final corrections and clarifications occurred during one or more exchanges between the author(s) and copyeditors.

Degenerative rotator cuff tears are at risk for the development of progressive muscle degeneration; however, the timeline and specific risks for progression are ill-defined[1]. Although the severity of fatty muscle[2,3] infiltration has important implications on the success of rotator cuff repairs, little longitudinal information regarding the risks for progression of muscle degenerative changes is available. Currently, surgical indications for rotator cuff treatment vary widely. The

Disclosure: The study was funded by the National Institutes of Health (R01 AR051026). On the **Disclosure of Potential Conflicts of Interest** forms, *which are provided with the online version of the article*, one or more of the authors checked "yes" to indicate that the author had a relevant financial relationship in the biomedical arena outside the submitted work and "yes" to indicate that the author had other relationships or activities that could be perceived to influence, or have the potential to influence, what was written in this work (http://links.lww.com/JBJS/D493).

argument for early surgery is, generally, to intervene when the likelihood of successful tendon healing is maximized. Several studies have examined the factors associated with decreased healing rates following cuff repair surgery. Among these, patient age, tear size, and fatty infiltration have consistently been shown to negatively impact healing[2,4-6]. While previous studies have examined the progression of tear size over time as well as the association of fatty muscle infiltration in relation to tear size, to our knowledge none have looked specifically at the temporal progression of muscle degeneration[1,7,8].

Rotator cuff tears are usually degenerative in nature and affect a large number of patients, many of whom are asymptomatic[1,9]. Recent natural history studies have demonstrated a time-dependent risk of tear enlargement[1,10-12]. Additionally, studies have correlated tear enlargement with the development or progression of fatty muscle infiltration[1,10,13]. The recent improved understanding of the natural history of degenerative rotator cuff disease has allowed clinicians to better counsel patients regarding treatment options[1,14]. However, many questions regarding progression of muscle degeneration remain unanswered. Fatty infiltration is associated with decreased healing and worse functional outcome following rotator cuff repair[15,16]. Multiple studies have suggested that muscle infiltration beyond grade 2, according to the Goutallier classification[17], represents an inflection point at which healing becomes less consistent[2,4]. Determining factors related to the development and timing of muscle degeneration is potentially important for counseling patients with regard to optimal surgical timing. Patients with asymptomatic degenerative rotator cuff tears represent an ideal cohort for studying the natural history of rotator cuff muscle degeneration as treatment is unnecessary, given the absence of clinical symptoms.

The primary purposes of this study were to examine the rate of progression of fatty muscle degeneration in patients with degenerative rotator cuff tears and to establish a temporal profile for this progression. Secondarily, we analyzed factors associated with these changes to better identify higher-risk tears. We hypothesized that progression of fatty muscle degeneration is more likely to occur in full-thickness tears that enlarge than in stable tears.

Materials and Methods

Institutional review board approval was obtained prior to study initiation. This study represents a subanalysis of a cohort with degenerative rotator cuff tears. Our cohort consisted of subjects with an asymptomatic full-thickness rotator cuff tear, identified with an ultrasound examination, who presented for evaluation of pain in the contralateral shoulder due to rotator cuff disease. Exclusion criteria included any past or current pain in the asymptomatic shoulder, trauma to the asymptomatic shoulder, inflammatory arthritis, radiographic evidence of osteoarthritis in the asymptomatic shoulder, upper-extremity weight-bearing demands, and the presence of a massive rotator cuff tear or grade-IV fatty muscle degeneration (using a previously validated measurement tool described in Table I[18,19]).

Each subject was evaluated at baseline and annually thereafter for assessment of pain and shoulder function, and underwent shoulder ultrasonography to determine specific rotator cuff tear and muscle characteristics. This analysis was specifically related to ultrasound data regarding tear size and the presence or progression of fatty muscle degeneration. Because previous work has shown muscle degeneration to be almost exclusive to full-thickness tears[8], we included only tears that were full-thickness at baseline or progressed to full-thickness during follow-up. We required a minimum of 2 years of follow-up for all tears, either from the time of enrollment or after conversion to a full-thickness tear. A measurable tear size and a confirmatory subsequent annual ultrasound evaluation after a tear enlargement event occurred were required for inclusion in this study. Additionally, for partial-thickness tears progressing to full-thickness tears, we included only those tears with ultrasound assessment of muscle degeneration prior to and following full-thickness progression.

Each subject underwent a standardized shoulder ultrasound (see Appendix). Tear dimensions were reviewed annually, and enlargement was defined as an increase in size of ≥5 mm in any direction compared with baseline for full-thickness tears and conversion to a full-thickness defect for partial tears. Fatty degeneration of the rotator cuff was evaluated using the echogenicity and architecture of the supraspinatus and infraspinatus muscles, and each was graded with a previously validated, modified 3-point scale[18,19]. Both tear size and echogenicity were evaluated by the same radiologist. The evaluators were blinded to previous measurements. The echogenicity was graded in comparison with overlying muscle (the trapezius for the supraspinatus and the deltoid for the infraspinatus) (Table I).

Statistical Analysis

Patient demographics and follow-up length were compared for subjects with and without muscle degeneration using the unpaired t test (for normally

TABLE I Classification of Rotator Cuff Muscle Degeneration by Ultrasound Examination*

Grade†	Echogenicity‡	Architecture
0	Isoechoic to the overlying muscle	Clearly visible intramuscular tendons and identifiable muscle pennate pattern
1	Slightly increased echogenicity compared with the overlying muscle	Partially visible intramuscular tendons and muscle pennate pattern
2	Markedly increased echogenicity compared with the overlying muscle	No discernible tendons or muscle pennate pattern

*Reproduced from: Wall LB, Teefey SA, Middleton WD, Dahiya N, Steger-May K, Kim HM, Wessell D, Yamaguchi K. Diagnostic performance and reliability of ultrasonography for fatty degeneration of the rotator cuff muscles. J Bone Joint Surg Am. 2012 Jun 20;94(12):e83. †Total grade is formed from adding the scores of both echogenicity (0-1-2) and architecture (0-1-2) to create a combined grade from 0 to 4. ‡The trapezius was used as a reference for determining the echogenicity of the supraspinatus, and the deltoid was used as the reference for determining the echogenicity of the infraspinatus and teres minor.

distributed variables), the Wilcoxon test (for non-normally distributed variables), or the chi-square test (for categorical variables).

The occurrence of tear enlargement for subjects with and without muscle degeneration progression was compared using logistic regression with enlargement as the dependent variable and muscle progression as the independent variable. The age of the patient at the time of study enrollment, dominant study side, sex, and tear width at the first visit as a full-thickness tear were included as covariates. Hand dominance in the study side was included as a covariate as previous research from this cohort demonstrated a higher risk of tear enlargement in the dominant shoulder[1].

For tears with enlargement, baseline tear size and change in tear dimensions were compared for shoulders with and without muscle degeneration progression using nonparametric analysis of covariance[20] in which the tear size was the dependent variable, muscle degeneration status (presence or absence) was the independent variable, and age, sex, and dominant study side were covariates. Logistic regression with age, sex, baseline tear size (width), and dominant study side as covariates compared the proportion of subjects with anterior supraspinatus involvement for shoulders with and without muscle degeneration progression.

Tears with progression of fatty muscle degeneration were classified by the muscle that underwent progression. If muscle degeneration progression occurred in both muscles, the tear was classified as undergoing progression in each muscle and, therefore, contributed nonindependent data for each muscle. To account for the lack of independence, the time between tear enlargement and muscle degeneration progression was compared for tears with progression of the supraspinatus and tears with progression of the infraspinatus, using generalized estimating equations with a normal distribution, identity link function, and unstructured correlation among nonindependent observations. This comparison was repeated for tears with progression of muscle degeneration in a single muscle (i.e., tears with progression in both muscles were excluded) using the Wilcoxon 2-sample test.

A post hoc power analysis was performed to examine the relationship of tear enlargement and the progression of fatty muscle degeneration (a demonstrated p value of 0.01). With a sample size of 51 subjects without and 105 subjects with tear enlargement, the study had 85% statistical power to detect the observed difference in muscle degeneration progression of 23.3% using a 2-tailed t test at alpha = 0.05. The study had 80% statistical power to detect a difference of 21.7% between groups.

Results

Demographics

Of the 188 shoulders with a full-thickness tear during surveillance and a minimum follow-up of 2 years, a total of 156 tears met our inclusion and exclusion criteria and were included in the analysis. Twenty-eight shoulders were excluded because of a lack of annual ultrasound evaluation, preventing specific temporal data from being interpreted. Four other shoulders were excluded from analysis because of grade-4 muscle degeneration of either the supraspinatus or infraspinatus muscles at baseline, thus preventing analysis of progression. Eighty-six of these tears had no fatty degeneration of either the supraspinatus or infraspinatus muscles at any point during surveillance. The

TABLE II Patient Demographics and Length of Follow-up Compared with Muscle Degeneration

		Muscle Degeneration at Any Study Time Point		
Variable Description	Entire Cohort (N = 156)	Absent (N = 86)	Present (N = 70)	P Value
Mean age (and standard deviation) *(yr)*				
At time of study enrollment	63.2 (8.7)	61.0 (9.0)	65.8 (7.7)	0.0005*
At time of 1st visit as full-thickness tear	63.6 (8.5)	61.4 (8.7)	66.4 (7.5)	0.0002*
Study duration† *(yr)*				
From study enrollment to most recent visit	6.0 (5.1)	5.9 (5.5)	6.2 (4.7)	0.14‡
From 1st visit as full-thickness tear to most recent visit	4.2 (5.4)	4.2 (5.1)	5.0 (5.2)	0.16‡
Sex§ *(no.)*				0.04#
Male	96 (62%)	59 (69%)	37 (53%)	
Female	60 (38%)	27 (31%)	33 (47%)	
Tear at 1st visit as full-thickness tear† *(mm)*				
Width	10.0 (9.0)	10.0 (5.0)	13.0 (12.0)	0.0002‡
Length	11.0 (9.0)	10.0 (6.0)	13.0 (15.5)	0.0001‡
Tear enlargement during study period *(no.)*				0.007#
Yes	105 (67%)	50 (58%)	55 (79%)	
No	51 (33%)	36 (42%)	15 (21%)	
Time from tear enlargement to most recent follow-up† *(yr)*	2.0 (2.9)	1.9 (4.0)	2.2 (2.7)	0.22‡

*P value is for the comparison of the absence and presence of muscle atrophy by the unpaired t test. †The values are given as the median, with the interquartile range (calculated as the 75th percentile minus the 25th percentile) in parentheses. ‡P value is for the comparison of the absence and presence of muscle atrophy by the Wilcoxon 2-sample test. §The values are given as the number of subjects with usable measurements. #P value is for the comparison of the proportion of patients with and without muscle atrophy with the chi-square test.

TABLE III Muscle Degeneration Data by Tear Enlargement at Any Time During the Study Period

Variable	Tears with No Enlargement During Study Period (N = 51)	Tears with Enlargement During Study Period (N = 105)	P Value*
Progression of muscle degeneration *(no.)*			0.003
No progression	41 (80%)	60 (57%)	
Progression	10 (20%)	45 (43%)	
Patients with progression of muscle degeneration† *(no.)*			0.87
Infraspinatus only	3 (30%)	11 (24%)	
Supraspinatus only	2 (20%)	12 (27%)	
Both infraspinatus and supraspinatus	5 (50%)	22 (49%)	

*P value is for comparison of the proportion of patients in each group for tears that did not enlarge and those with tears that did enlarge by logistic regression with the following covariates: age at study enrollment, dominant study side, sex, and tear width at 1st visit as full-thickness tear. †Ten patients had progression of muscle degeneration with no enlargement, and 45 had tears with enlargement during study period.

remaining 70 shoulders had measurable degeneration of 1 or both muscles.

The median duration of follow-up was 6.0 years from enrollment (Table II). Patients with fatty muscle degeneration of the shoulder at any time point were older (mean, 65.8 years; 95% confidence interval [CI], 64.0 to 67.6 years) than patients without degeneration (61.0 years; 95% CI, 59.1 to 62.9 years; $p < 0.05$). The prevalence of fatty degeneration was greater in women than in men ($p < 0.05$). There was no difference in follow-up length between shoulders with and without fatty muscle degeneration ($p = 0.14$). The median size of the tears at baseline was larger for those with fatty muscle degeneration than for those without degeneration (13.0 versus 10.0 mm in width [$p < 0.05$] and 13.0 versus 10.0 mm in depth [$p < 0.05$]).

TABLE IV Statistical Comparisons of Characteristics by Muscle Degeneration Progression for Patients with Tear Enlargement

Variable Description	Tear Enlargement by Muscle Degeneration Progression: Enlargement without Progression (N = 60)	Tear Enlargement by Muscle Degeneration Progression: Enlargement with Progression (N = 45)	P Value
Tear size at 1st full-thickness measurement* *(mm)*			
Width	10.0 (5.0)	15.0 (12.0)	0.0002†
Length	10.0 (5.0)‡	13.0 (17.0)	0.003†
Anterior supraspinatus tendon involvement at 1st full-thickness measurement§ *(no.)*			0.56#
Spared	38 (83%)	14 (47%)	
Disrupted	8 (17%)	16 (53%)	
Change in tear size from 1st full-thickness measurement to enlargement event* *(mm)*			
Width**	5.0 (7.0)	9.0 (8.5)	0.009††
Length‡‡	6.0 (7.0)	6.0 (9.5)	0.39††

*The values are given as the median, with the interquartile range in parentheses. †Because of non-normal data distributions for the outcome variable, the p value is for the comparison of tears with no muscle degeneration progression and those with progression by nonparametric covariance analysis with age at study enrollment, dominant study side, and sex as covariates. ‡Data were available for only 59 tears. §Data are for 46 tears of the anterior supraspinatus tendon that had enlargement without progression and for 30 tears that had enlargement with progression. #P value is for the comparison of the proportion of involved anterior supraspinatus for tears with no muscle degeneration progression and those with progression by logistic regression with the following covariates: age at study enrollment, dominant study side, sex, and tear width at 1st visit as full-thickness tear. **Data on width were available for 57 tears that had enlargement without progression and for 44 tears that had enlargement with progression. ††Because of the non-normal data distributions for the outcome variable, the p value is for the comparison of tears with no muscle degeneration progression and those with progression by nonparametric covariance analysis with the following covariates: age at study enrollment, dominant study side, sex, and the value of the outcome variable at the 1st visit as full-thickness (i.e., tear width and tear length, respectively). ‡‡Data on the length were available for 57 tears that had enlargement without progression and for 40 tears that had enlargement with progression.

Muscle Degeneration and Tear Enlargement

Of the 156 full-thickness tears, 105 (67%) enlarged at least 5 mm (width, length, or both) during follow-up (Table II). The median period of follow-up from the time a tear was identified as full-thickness to tear enlargement was 2.0 years. The tears that had fatty muscle degeneration of any grade (at any time point) were more likely to have had an increase in tear size during follow-up (79% [55 of 70]) than were tears that never developed muscle degeneration (58% [50 of 86]); the difference was significant ($p < 0.05$) (odds ratio [OR] = 2.64; 95% CI, 1.29 to 5.39).

Fifty-five (79%) of the 70 shoulders with fatty muscle degeneration demonstrated progression of degeneration during follow-up (see Appendix). Of the 105 tears that enlarged, 60 had no progression of fatty muscle degeneration and 45 had progression. Subjects with tear enlargement and fatty muscle degeneration progression were older at the time of enrollment (mean, 66.0 years) than were those with no progression (mean, 61.6 years); the difference was significant ($p < 0.05$) (Table II). Accounting for age, sex, and study side dominance as covariates, the tears with enlargement and progression of fatty muscle degeneration had a larger initial tear width (median, 15.0 versus 10.0 mm) and length (median, 13.0 versus 10.0 mm) ($p < 0.05$ for both) than did the tears that enlarged but had no increase in muscle degeneration. Accounting for covariates, tears that enlarged were more likely to demonstrate progression of fatty muscle degeneration (43%; 45 of 105) than were shoulders without enlargement of tears (20%; 10 of 51); the difference was significant ($p < 0.05$) (Table III). Additionally, tears with enlargement and progression of fatty muscle degeneration were more likely to involve the anterior supraspinatus than were those without muscle degeneration progression (53% versus 17%); however, this did not reach significance when accounting for tear size ($p = 0.56$) (Table IV). The magnitude of width enlargement for tears with progression of fatty muscle degeneration (median, 9.0 mm) was larger than that for tears without progression (median, 5.0 mm); the difference was significant ($p < 0.05$). However, there was no difference in the change in tear length (retraction) between groups (median, 6.0 mm in each group) ($p = 0.39$).

Temporal Progression of Muscle Degeneration

The temporal relationship of the first tear enlargement and progression of fatty muscle degeneration was examined in the 45 shoulders in which both occurred (Table V). Progression of fatty muscle degeneration occurred in both the supraspinatus and infraspinatus in 22 shoulders, while isolated progression was seen in the supraspinatus in 12 shoulders and in the infraspinatus in 11 shoulders (Table III). For the supraspinatus, fatty muscle degeneration progression occurred after enlargement (median, 2.0 years) in 21 shoulders (62%). Six shoulders

TABLE V Analysis of Temporal Relationship of Tear Enlargement and Progression of Muscle Degeneration

Variable Description	No.	Time from Tear Enlargement to Progression of Muscle Degeneration in Supraspinatus* *(yr)*	No.	Time from Tear Enlargement to Progression of Muscle Degeneration in Infraspinatus* *(yr)*	P Value†
Using 1st tear enlargement event					NA
Progression of muscle degeneration after tear enlargement	21	2.0 (1.8; 0.6 to 6.9)	20	3.1 (2.6; 0.6 to 8.5)	
Simultaneous progression of muscle degeneration and enlargement	6	0.0 (0.0)	7	0.0 (0.0)	
Progression of muscle degeneration before tear enlargement	7	1.0 (1.0; 0.5 to 2.0)	6	0.9 (0.4; 0.5 to 1.8)	
No progression of degeneration in the specific muscle	11	NA	12	NA	
Muscle‡					
All tears with progression of muscle degeneration and tear enlargement	34	1.0 (2.1; −2.0 to 6.9)	33	1.1 (3.2; −1.8 to 8.5)	0.98§
Tears with progression of degeneration in a single muscle and enlargement	12	1.4 (2.6; −2.0 to 4.6)	11	3.1 (4.9; 0.0 to 5.4)	0.10#

*The values are given as the median, with the interquartile range and the minimum and maximum measurements in parentheses. NA = not applicable. Progression was defined for each muscle separately. Tears with progression of the supraspinatus only or both the supraspinatus and infraspinatus were classified as having supraspinatus progression. Tears with progression of the infraspinatus only or both the supraspinatus and infraspinatus were classified as having infraspinatus progression. †NA = not applicable. ‡Tears with muscle degeneration progression before the 1st tear enlargement are reported with a negative time. Tears with muscle degeneration progression after the 1st tear enlargement are reported with a positive time. Tears with simultaneous progression of muscle degeneration and 1st tear enlargement are reported with a zero time. §P value is for the comparison of the supraspinatus and the infraspinatus muscle by generalized estimating equations. #P value is for the comparison of the supraspinatus and the infraspinatus muscle according to the Wilcoxon 2-sample test.

had concurrent tear enlargement and muscle progression, and 7 shoulders had muscle progression prior to enlargement (median, 1.0 year). For the infraspinatus, progression of fatty muscle degeneration occurred after enlargement (median, 3.1 years) in 20 shoulders (61%). Seven shoulders had simultaneous tear enlargement and muscle progression, and 6 shoulders had muscle progression prior to enlargement (median, 0.9 year). The median time for fatty muscle progression was 1.0 year for tears involving the supraspinatus and 1.1 years for those involving the infraspinatus (p = 0.98). For tears with progression of fatty muscle degeneration occurring in a single muscle only, the median time from enlargement to progression was 1.4 years for the supraspinatus compared with 3.1 years for the infraspinatus (p = 0.10).

Discussion

The present study demonstrates important associations between the temporal progression of fatty muscle degeneration and rotator cuff tear enlargement and is the first, to our knowledge, to do so using rigorous prospective evaluation. Specific factors related to the progression of fatty muscle degeneration include a larger baseline tear size, interval tear enlargement, and larger magnitudes of tear enlargement. Fatty muscle degeneration of the rotator cuff is clinically relevant, given a known detrimental relationship of advanced fatty infiltration on healing rates and functional outcomes and given that fatty changes do not regress following cuff repair surgery[9,21,22]. Our study results reinforce and clarify several notions about fatty muscle degeneration in atraumatic rotator cuff tears. The presence of fatty muscle degeneration is more common in larger tears and in older patients[23,24], and progression is more frequent with tear enlargement[1,13].

The relatively small size of the tears in this study, a mean tear width between 10 and 15 mm, may account for the modest prevalence of muscle degeneration (45%) in this cohort. Previous studies have shown that tear size and location are determining factors in the development of muscle infiltration and degeneration[8,21,23,25,26]. Nakagaki et al. reported that larger tear size was associated with greater muscle infiltration in cadavers[27]. Rulewicz et al. found a similar correlation for the supraspinatus on magnetic resonance imaging (MRI) evaluation[21]. Another study found that muscle infiltration correlated with increased age and larger tear size[26]. Previous analysis of the present cohort demonstrated that tear size was the most important predictor of infraspinatus fatty muscle degeneration, while anterior supraspinatus tendon integrity was most strongly correlated with supraspinatus fatty muscle degeneration[8].

This prospective analysis of rotator cuff tear enlargement and fatty muscle degeneration revealed several clinically relevant findings. Notably, tear enlargement is a risk factor for progression of muscle degeneration independent of the effect of age. Fatty muscle degeneration advanced at least 2 grades in many shoulders, which is likely clinically relevant. Several natural history studies have also shown a link between tear enlargement and advancing fatty muscle infiltration or degeneration[1,11,25]. Our data showed that tears with progressive fatty muscle degeneration were initially larger than tears that enlarged without progressive muscle changes. Tears of approximately 15 mm in width that continue to enlarge appear to be at higher risk for advancing fatty muscle degeneration. Lastly, the magnitude of tear enlargement may be important for muscle degeneration, specifically, the tear width (size) as opposed to retraction. Progressive fatty muscle degeneration was more commonly seen in tears that enlarged approximately 1 cm compared with enlargement of 5 mm. Collectively, our study results suggest that tears that are larger than 1 cm and enlarge ≥1 cm are at higher risk for fatty muscle degeneration progression than are smaller tears that are stable or minimally enlarged.

The rotator cable has been theorized to have a stress-shielding effect, maintaining the force couple in tears isolated within the rotator crescent[28]. The anterior aspect of the supraspinatus tendon is the strongest region of the tendon[29], and studies have shown increased gapping and strain in tears involving the rotator cable compared with isolated crescent tears[30]. Previous research has demonstrated the importance of the anterior aspect of the supraspinatus tendon (anterior cable) in preserving the health of both of the supraspinatus and infraspinatus muscles[1,10]. Kim et al. demonstrated that tears not involving the anterior aspect of the supraspinatus are 96% less likely to have fatty muscle degeneration[7]. In our series, tear enlargement involving the anterior aspect of the supraspinatus had a threefold greater risk of fatty muscle degeneration progression compared with tears that enlarged but spared the anterior aspect of the supraspinatus. However, when accounting for tear size as a covariate, this relationship failed to reach significance. This confirms the finding of a previous study of this cohort that showed that tears with disruption of the anterior aspect of the supraspinatus are larger than tears isolated to the rotator crescent (19.0 compared with 10.0 mm)[31].

Our prospective study design allowed a novel analysis of the temporal relationship of fatty muscle degeneration progression compared with tear enlargement. For most tears, the development or progression of fatty muscle degeneration occurred after an enlargement event. However, in approximately 20% of tears with both enlargement and progression, progression of muscle degeneration occurred prior to enlargement, with another 20% demonstrating simultaneous enlargement and muscle deterioration. The time to progression of fatty muscle degeneration averaged approximately 1 year after enlargement for both the supraspinatus and infraspinatus muscles when examining the groups as a whole. Since this cohort consists of atraumatic degenerative cuff tears and we captured shoulders in varying stages of disease, we recognize that it is arbitrary to designate 1 enlargement event as a baseline. However, we believe our findings to be clinically relevant, highlighting the fact that progression of fatty muscle degeneration may occur in a close timeline to tear enlargement. Melis et al. were the first to examine the temporal nature of fatty infiltration of the supraspinatus and infraspinatus from the onset of symptoms[23,24]. They concluded that muscle infiltration occurred 3 years after pain development in the supraspinatus and 2.5 years after for the infraspinatus. Their findings are somewhat limited by retrospective analysis, potential recall bias for the onset of pain, and the heterogeneity (both traumatic and atraumatic) of tears.

Our study has several limitations. There are missing data regarding fatty muscle degeneration in some subjects, as the collection of fatty muscle degeneration data began only after ultrasound findings were validated with MRI findings[19]. Another limitation is the unknown chronicity of the tears at enrollment. Given that tears in this cohort are degenerative and asymptomatic, the age of most tears is unknown. This makes it difficult to ascertain the exact temporal relationship between tear enlargement and the onset of muscle degeneration. This limitation is partially overcome by defining a clinically important tear enlargement event and then following potential muscle changes over a longer period; in this study, follow-up was 6 years. The relatively small number of shoulders analyzed (n = 45) for the temporal relationship of enlargement to progression of fatty muscle degeneration certainly limits definitive conclusions regarding this relationship. The classification system for this study is based on ultrasound evaluation rather than computed tomography (CT) scanning or MRI, which are more commonly utilized grading systems. Although ultrasonography has been validated against MRI for assessing cuff muscle degenerative changes, the ultrasound grading system has not been correlated to surgical outcomes. Additionally, it should be noted that both CT scan and MRI assess fatty infiltration, whereas ultrasonography is a measure of both fatty infiltration and muscle architectural changes (degeneration). Lastly, our study findings pertain to subjects with bilateral degenerative cuff tears and may not be directly comparable with other studies that may include a more heterogeneous population of rotator cuff tears.

In conclusion, this prospective analysis of asymptomatic degenerative rotator cuff tears revealed several clinically relevant findings. Progression of fatty muscle degeneration is more common in tears that are larger at baseline, in tears that enlarge over time, and in tears with a larger magnitude of enlargement. Although the integrity of the anterior supraspinatus tendon is important for the preservation of muscle health, the effect of anterior cable integrity on muscle changes is more reflective of the larger tear sizes seen in cable-disrupted tears. Our study findings also suggest an often rapid progression of fatty muscle degeneration in relation to a clinically relevant increase in tear size in some degenerative cuff tears. Active surveillance or early surgical intervention should be considered for painful tears with these risk factors.

Appendix

eA A description of the shoulder ultrasonography protocol for tear dimensions and location (including references 32, 33, and 34, which are cited only in the Appendix) and a table with data on the magnitude of rotator cuff muscle degeneration progression during follow-up are available with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/C848). ■

Jonah Hebert-Davies, MD, FRCSC[1]
Sharlene A. Teefey, MD[2]
Karen Steger-May, MA[3]
Aaron M. Chamberlain, MD[1]
William Middleton, MD[2]
Kathryn Robinson, MD[2]
Ken Yamaguchi, MD, MBA[1]
Jay D. Keener, MD[1]

[1]Shoulder and Elbow Service, Department of Orthopaedic Surgery, Washington University, St. Louis, Missouri

[2]Mallinckrodt Institute of Radiology, Washington University, St. Louis, Missouri

[3]Division of Biostatistics, Washington University School of Medicine, St. Louis, Missouri

E-mail address for J. Hebert-Davies: jdavies2@uw.edu

References

1. Keener JD, Galatz LM, Teefey SA, Middleton WD, Steger-May K, Stobbs-Cucchi G, Patton R, Yamaguchi K. A prospective evaluation of survivorship of asymptomatic degenerative rotator cuff tears. J Bone Joint Surg Am. 2015 Jan 21;97(2):89-98.

2. Voigt C, Bosse C, Vosshenrich R, Schulz AP, Lill H. Arthroscopic supraspinatus tendon repair with suture-bridging technique: functional outcome and magnetic resonance imaging. Am J Sports Med. 2010 May;38(5):983-91.

3. Chung SW, Oh JH, Gong HS, Kim JY, Kim SH. Factors affecting rotator cuff healing after arthroscopic repair: osteoporosis as one of the independent risk factors. Am J Sports Med. 2011 Oct;39(10):2099-107. Epub 2011 Aug 3.

4. Cho NS, Rhee YG. The factors affecting the clinical outcome and integrity of arthroscopically repaired rotator cuff tears of the shoulder. Clin Orthop Surg. 2009 Jun;1(2):96-104. Epub 2009 May 30.

5. Oh JH, Kim SH, Kang JY, Oh CH, Gong HS. Effect of age on functional and structural outcome after rotator cuff repair. Am J Sports Med. 2010 Apr;38(4):672-8.

6. Nho SJ, Shindle MK, Adler RS, Warren RF, Altchek DW, MacGillivray JD. Prospective analysis of arthroscopic rotator cuff repair: subgroup analysis. J Shoulder Elbow Surg. 2009 Sep-Oct;18(5):697-704. Epub 2009 Mar 9.

7. Kim HM, Dahiya N, Teefey SA, Middleton WD, Stobbs G, Steger-May K, Yamaguchi K, Keener JD. Location and initiation of degenerative rotator cuff tears: an analysis of three hundred and sixty shoulders. J Bone Joint Surg Am. 2010 May;92(5):1088-96.

8. Kim HM, Dahiya N, Teefey SA, Keener JD, Galatz LM, Yamaguchi K. Relationship of tear size and location to fatty degeneration of the rotator cuff. J Bone Joint Surg Am. 2010 Apr;92(4):829-39.

9. Dunn WR, Schackman BR, Walsh C, Lyman S, Jones EC, Warren RF, Marx RG. Variation in orthopaedic surgeons' perceptions about the indications for rotator cuff surgery. J Bone Joint Surg Am. 2005 Sep;87(9):1978-84.

10. Moosmayer S, Tariq R, Stiris M, Smith HJ. The natural history of asymptomatic rotator cuff tears: a three-year follow-up of fifty cases. J Bone Joint Surg Am. 2013 Jul 17;95(14):1249-55.

11. Maman E, Harris C, White L, Tomlinson G, Shashank M, Boynton E. Outcome of nonoperative treatment of symptomatic rotator cuff tears monitored by magnetic resonance imaging. J Bone Joint Surg Am. 2009 Aug;91(8):1898-906.

12. Safran O, Schroeder J, Bloom R, Weil Y, Milgrom C. Natural history of nonoperatively treated symptomatic rotator cuff tears in patients 60 years old or younger. Am J Sports Med. 2011 Apr;39(4):710-4. Epub 2011 Feb 10.

13. Mall NA, Kim HM, Keener JD, Steger-May K, Teefey SA, Middleton WD, Stobbs G, Yamaguchi K. Symptomatic progression of asymptomatic rotator cuff tears: a prospective study of clinical and sonographic variables. J Bone Joint Surg Am. 2010 Nov 17;92(16):2623-33.

14. Kim HM, Teefey SA, Zelig A, Galatz LM, Keener JD, Yamaguchi K. Shoulder strength in asymptomatic individuals with intact compared with torn rotator cuffs. J Bone Joint Surg Am. 2009 Feb;91(2):289-96.

15. Charousset C, Bellaïche L, Kalra K, Petrover D. Arthroscopic repair of full-thickness rotator cuff tears: is there tendon healing in patients aged 65 years or older? Arthroscopy. 2010 Mar;26(3):302-9.

16. Jost B, Pfirrmann CW, Gerber C, Switzerland Z. Clinical outcome after structural failure of rotator cuff repairs. J Bone Joint Surg Am. 2000 Mar;82(3):304-14.

17. Goutallier D, Postel JM, Bernageau J, Lavau L, Voisin MC. Fatty muscle degeneration in cuff ruptures. Pre- and postoperative evaluation by CT scan. Clin Orthop Relat Res. 1994 Jul;304:78-83.

18. Strobel K, Hodler J, Meyer DC, Pfirrmann CWA, Pirkl C, Zanetti M. Fatty atrophy of supraspinatus and infraspinatus muscles: accuracy of US. Radiology. 2005 Nov;237(2):584-9. Epub 2005 Sep 28.

19. Wall LB, Teefey SA, Middleton WD, Dahiya N, Steger-May K, Kim HM, Wessell D, Yamaguchi K. Diagnostic performance and reliability of ultrasonography for fatty degeneration of the rotator cuff muscles. J Bone Joint Surg Am. 2012 Jun 20;94(12):e83.

20. Koch GG, Tangen CM, Jung JW, Amara IA. Issues for covariance analysis of dichotomous and ordered categorical data from randomized clinical trials and non-parametric strategies for addressing them. Stat Med. 1998 Aug 15-30;17(15-16):1863-92.

21. Rulewicz GJ, Beaty S, Hawkins RJ, Kissenberth MJ. Supraspinatus atrophy as a predictor of rotator cuff tear size: an MRI study utilizing the tangent sign. J Shoulder Elbow Surg. 2013 Jun;22(6):e6-10. Epub 2013 Jan 23.

22. Gerber C, Schneeberger AG, Hoppeler H, Meyer DC. Correlation of atrophy and fatty infiltration on strength and integrity of rotator cuff repairs: a study in thirteen patients. J Shoulder Elbow Surg. 2007 Nov-Dec;16(6):691-6. Epub 2007 Oct 10.

23. Melis B, DeFranco MJ, Chuinard C, Walch G. Natural history of fatty infiltration and atrophy of the supraspinatus muscle in rotator cuff tears. Clin Orthop Relat Res. 2010 Jun;468(6):1498-505.

24. Melis B, Wall B, Walch G. Natural history of infraspinatus fatty infiltration in rotator cuff tears. J Shoulder Elbow Surg. 2010 Jul;19(5):757-63. Epub 2010 Apr 2.

25. Meyer DC, Pirkl C, Pfirrmann CWA, Zanetti M, Gerber C. Asymmetric atrophy of the supraspinatus muscle following tendon tear. J Orthop Res. 2005 Mar;23(2):254-8.

26. Barry JJ, Lansdown DA, Cheung S, Feeley BT, Ma CB. The relationship between tear severity, fatty infiltration, and muscle atrophy in the supraspinatus. J Shoulder Elbow Surg. 2013 Jan;22(1):18-25. Epub 2012 Apr 25.

27. Nakagaki K, Ozaki J, Tomita Y, Tamai S. Fatty degeneration in the supraspinatus muscle after rotator cuff tear. J Shoulder Elbow Surg. 1996 May-Jun;5(3):194-200.

28. Burkhart SS, Barth JRH, Richards DP, Zlatkin MB, Larsen M. Arthroscopic repair of massive rotator cuff tears with stage 3 and 4 fatty degeneration. Arthroscopy. 2007 Apr;23(4):347-54.

29. Itoi E, Berglund LJ, Grabowski JJ, Schultz FM, Growney ES, Morrey BF, An KN. Tensile properties of the supraspinatus tendon. J Orthop Res. 1995 Jul;13(4):578-84.

30. Mesiha MM, Derwin KA, Sibole SC, Erdemir A, McCarron JA. The biomechanical relevance of anterior rotator cuff cable tears in a cadaveric shoulder model. J Bone Joint Surg Am. 2013 Oct 16;95(20):1817-24.

31. Keener JD, Hsu JE, Steger-May K, Teefey SA, Chamberlain AM, Yamaguchi K. Patterns of tear progression for asymptomatic degenerative rotator cuff tears. J Shoulder Elbow Surg. 2015 Dec;24(12):1845-51.

32. Teefey SA, Rubin DA, Middleton WD, Hildebolt CF, Leibold RA, Yamaguchi K. Detection and quantification of rotator cuff tears. Comparison of ultrasonographic, magnetic resonance imaging, and arthroscopic findings in seventy-one consecutive cases. J Bone Joint Surg Am. 2004 Apr;86(4):708-16.

33. Teefey SA, Hasan SA, Middleton WD, Patel M, Wright RW, Yamaguchi K. Ultrasonography of the rotator cuff. A comparison of ultrasonographic and arthroscopic findings in one hundred consecutive cases. J Bone Joint Surg Am. 2000 Apr;82(4):498-504.

34. Prickett WD, Teefey SA, Galatz LM, Calfee RP, Middleton WD, Yamaguchi K. Accuracy of ultrasound imaging of the rotator cuff in shoulders that are painful postoperatively. J Bone Joint Surg Am. 2003 Jun;85(6):1084-9.