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SCIENTIFIC ARTICLE

Patterns of tendon retraction in full-thickness rotator cuff tear: comparison of delaminated and nondelaminated tendons

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Abstract

Objective To analyze full-thickness rotator cuff tears, compare retraction patterns in delaminated and nondelaminated tendons, and correlate retraction distances with anteroposterior tear lengths.

Materials and methods In 483 MR examinations reported as showing full-thickness cuff tear, two musculoskeletal radiologists independently characterized tendons as delaminated or nondelaminated. Tendon delamination was defined as either horizontal intra-substance splitting of bursal and articular layers by an intervening plane of fluid, or differential retraction of bursal and articular layers. In a subset of 144 shoulders with surgically proven full-thickness cuff tears (45 delaminated, 99 nondelaminated tendons), matched cohorts ($n = 45$) were further analyzed to compare tendon retraction distance, anteroposterior tear length and retraction ratios (retraction distance/anteroposterior length).

Results Delamination was present in 13% of 483 total tears, and 31% of 144 operated tears ($p = 0.001$). In nondelamination and delamination cohorts, mean anteroposterior tear length measured 30.0 and 31.5 mm respectively ($p = 0.6$). Although nondelaminated tendons showed mean retraction 31.5 mm, articular and bursal layers of delaminated tendons showed mean retractions 36.3 mm and 21 mm respectively ($p < 0.0001$). Anteroposterior tear length and retraction distance were significantly associated in all cuff tears ($p < 0.0001$). Retraction ratio for nondelaminated tendons (1.05) was significantly different from retraction ratios for articular (1.21) and bursal (0.70) layers of delaminated tendons ($p < 0.0001$).

Conclusion In full-thickness rotator cuff tear, delaminated and nondelaminated tendons show significant differences in retraction distances, despite similarities in anteroposterior dimensions. Delaminated tendons are important to identify and report because they are more likely to fail conservative treatments and undergo operative repairs.

Keywords Shoulder · Rotator cuff tear · Tendon delamination · MRI

Introduction

The layered, or laminated, structure of the rotator cuff was described in 1992 [1]. Two years later, in a cadaveric study of normal supraspinatus tendons, investigators examining bursal and articular layers described distinct histological differences that could explain common tear configurations, including delamination (horizontal splitting) [2]. In 2003, in a cadaveric study investigating differential strain as a causative factor in rotator cuff tear, researchers demonstrated that shearing between the layers of supraspinatus led to tendon delamination and intratendinous tear propagation [3].

Delamination is common in patients undergoing rotator cuff repair, ranging in incidence from 38 to 82% [4–7], and is defined as the dissociation of bursal and articular layers (Fig. 1) [3, 5–9]. Delamination is reported as a negative prognostic factor that decreases tendon quality and complicates cuff repair [4, 5, 8] by creating a synovialized intratendinous space with poor healing potential [3, 6]. Surgical outcome has been improved when specialized, but challenging, techniques are used to manage the delaminated tendon, such as the curettage of synovialized surfaces before layer-to-layer suturing [6, 7].

Magnetic resonance imaging (MRI) can be used to guide therapeutic decision-making and plan surgery based on imaging features that have prognostic implications, such as the

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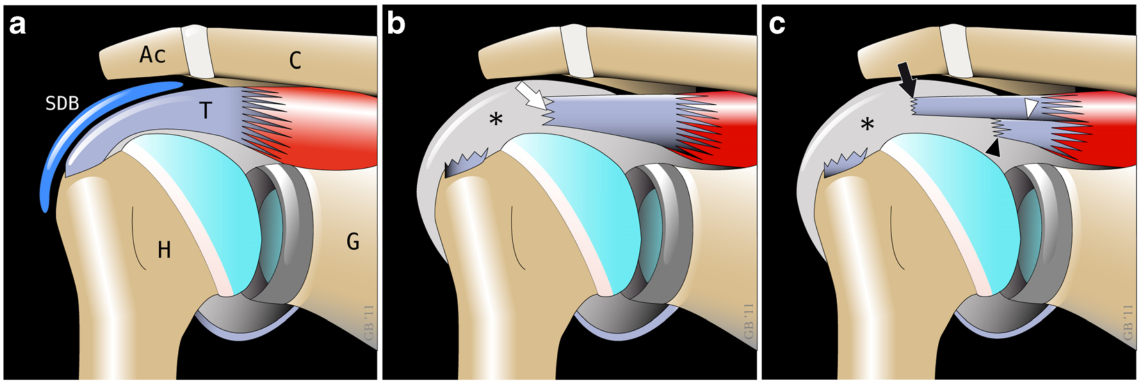

Fig. 1 **a** Drawings of the shoulder depicting normal rotator cuff tendon and full-thickness rotator cuff tears with and without delamination. **a** In the normal rotator cuff, the tendon (*T*) can be followed from the muscle–tendon junction to its attachment site at the greater tuberosity. *H* humeral head, *G* glenoid, *SDB* subacromial–subdeltoid bursa, *Ac* acromion, *C* clavicle. **b** In full-thickness rotator cuff tear (*asterisk*) without delamination, the retracted tendon margin (*arrow*) is uniform in thickness and surrounded by fluid. **c** In full-thickness rotator cuff tear (*asterisk*) with delamination, the bursal (*black arrow*) and articular (*black arrowhead*) layers show either differential retraction, as shown here, and/or fluid in the space between the bursal and articular layers (*white arrowhead*)

anteroposterior (AP) length of tear, extent of tendon retraction, and degree of fatty muscle atrophy [10–15]. Increasing attention has been given to the presence of delamination as a prognostic factor [5–7, 9, 16]. Previous MRI studies have described the appearances of delaminated tendons in partial- and full-thickness rotator cuff tears [16–21]. To our knowledge, no previous study has compared tendon retraction in delaminated and nondelaminated cuff tendons.

Therefore, the purpose of this study was to evaluate delaminated and nondelaminated tendons in shoulders with full-thickness cuff tears (FT-RCT), compare patterns of retraction, and correlate tendon retraction distance with AP tear length and fatty muscle infiltration. We tested the hypothesis that retraction ratios (retraction distance/AP length) were different in delaminated and nondelaminated tendons.

Materials and methods

Patient selection

The institutional review board approved this Health Insurance Portability and Accountability Act-compliant, retrospective study and waived the need to obtain written informed consent. Using our picture archiving and communication system (PACS) and hospital information system (HIS), which are integrated at our institution, we reviewed the reports of all non-arthrographic MRI examinations ($n = 3{,}152$) performed between January 2008 and December 2010 to identify shoulders with full-thickness tears of the supraspinatus and/or infraspinatus tendons. Based on imaging reports, exclusion criteria included: nonstandard MRI protocol, incomplete or poor-quality examination, and previous surgery. We identified a total of 483 full-thickness rotator cuff tears in 480 patients (3 patients had bilateral full-thickness tears).

After a preliminary teaching session, two musculoskeletal radiologists (William E. Palmer (reader 1) and Guillaume Bierry (reader 2), with 25 and 10 years of experience in musculoskeletal MRI respectively), who were blinded to whether shoulders underwent rotator cuff repair, independently reviewed the 483 MRI examinations in chronological order.

After confirming the diagnosis of full-thickness rotator cuff tear, the torn tendon was classified as delaminated or nondelaminated (Fig. 1). FT-RCT was defined as a focal defect that extended across the entire tendon substance on a single image or multiple sequential images. This defect demonstrated fluid-like signal intensity on fat-suppressed T2-weighted images. Using oblique coronal MRI, tendon delamination was defined as either horizontal intrasubstance splitting of bursal and articular layers by an intervening plane of fluid, or differential retraction of bursal and articular layers with or without the presence of an intervening plane of fluid (Fig. 2) [16]. Tendons were not included in the delamination cohort unless the intervening plane of fluid measured at least 1 cm in length, or the bursal and articular layers showed a minimum differential retraction measuring 1 cm.

After a 2-week interval, reader 2 reviewed the MR examinations in reverse order and repeated the classification of torn tendons to determine intra-observer variability. Classification discrepancies between readers were resolved in consensus before final MR image analysis.

In Fig. 3, a flowchart illustrates our study population. Among 483 shoulders with FT-RCTs, 64 (13%) met our criteria for tendon delamination. We identified 326 shoulders that did not undergo surgical cuff repair within 3 months following MRI examinations, and 13 additional shoulders that showed post-operative changes (none was a rotator cuff repair) not mentioned in the

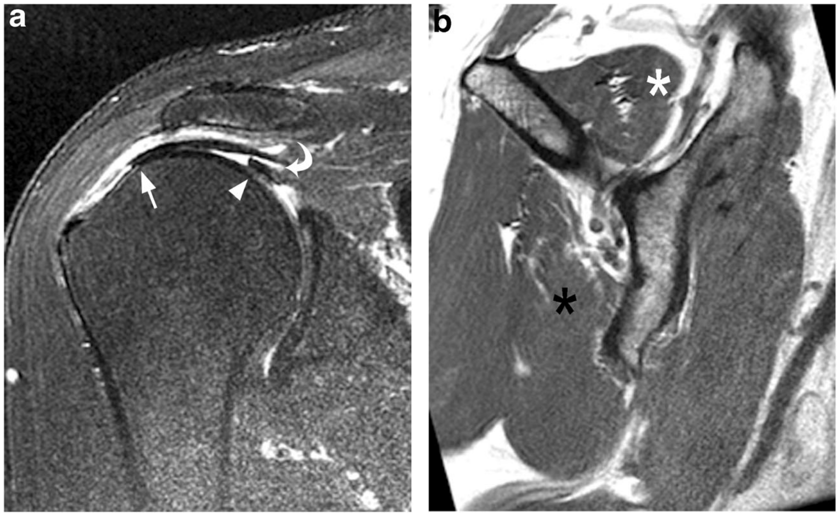

Fig. 2 Non-arthrographic MRI show full-thickness rotator cuff tear (arthroscopically proven) with tendon delamination and fatty muscle infiltration in a 58-year-old man. **a** Oblique coronal fat-suppressed T2-weighted MRI demonstrates differential retraction of bursal (*straight arrow*) and articular (*arrowhead*) fibers in addition to fluid in the space (*curved arrow*) between the bursal and articular fibers. Both readers categorized this tendon as delaminated. **b** Oblique sagittal T1-weighted MRI shows fatty infiltration involving the supraspinatus (*white asterisk*) and infraspinatus (*black asterisk*) muscles. Both readers scored the degree of fatty infiltration as 2 (fatty replacement less than 50% of residual muscle volume) based on the Goutallier classification

original MRI reports. Among the remaining 144 shoulders with surgically confirmed FT-RCTs, 99 (69%) had nondelaminated tendons and 45 (31%) had delaminated tendons. Six different orthopedists performed the surgeries. None of these orthopedists listed delamination as a pre-operative diagnosis or described it as a reason for surgical management.

MRI protocol

Magnetic resonance imaging examinations were performed using dedicated shoulder coils and either 1.5-T magnets (Signa, GE Medical Systems, Milwaukee, WI, USA; Avanto, Siemens Medical Solutions, Erlangen, Germany) or

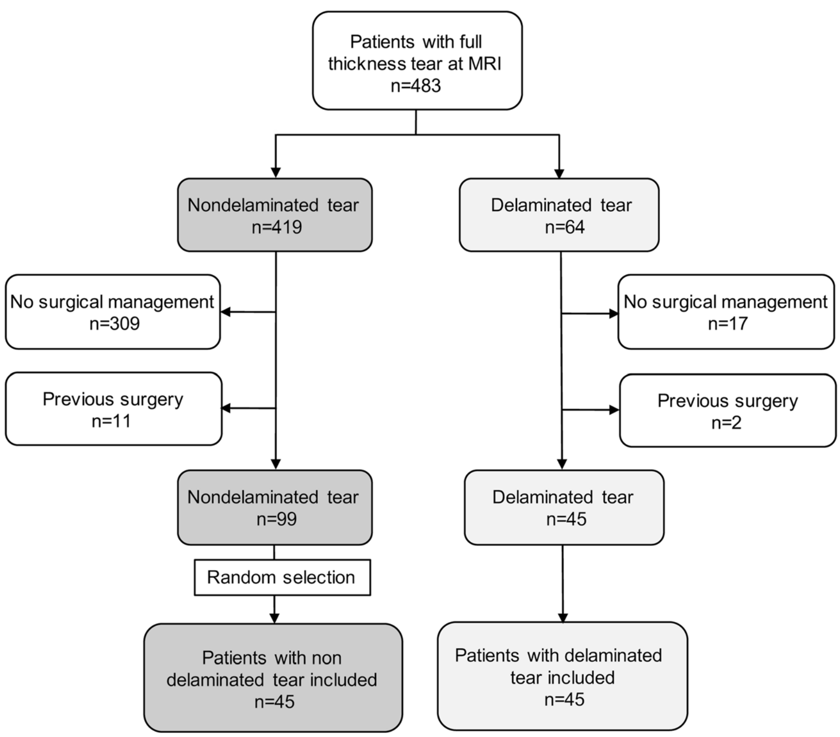

Fig. 3 Flowchart of the study population

a 3-T magnet (Trio, Siemens Medical Solutions). At 1.5 T, the following parameters were prescribed:

1. Oblique coronal proton density-weighted repetition time/echo time (TR/TE) 2,700–3,200/14–20 ms, field-of-view 16 cm, matrix 384 x 324, slice 3 mm (33% interslice gap), echo-train 6, bandwidth 150 Hz/pixel
2. Oblique coronal fat-suppressed T2-weighted TR/TE 4,000–4,500/45–55 ms, field-of-view 16 cm, matrix 384 x 256, slice 3 mm, (33% gap), echo-train 12, bandwidth 120 Hz/pixel
3. Oblique sagittal T1-weighted TR/TE 450–600/9–14 ms, field-of-view 14 cm, matrix 448 × 324, slice 4 mm (25% gap), echo-train 3, bandwidth 150 Hz/pixel
4. Oblique sagittal fat-suppressed T2-weighted TR/TE 4,200–4,500/45–55 ms, field-of-view 14 cm, matrix 324 × 256, slice 4 mm (25% gap), echo-train 12, bandwidth 120 Hz/pixel
5. Axial gradient echo T2*-weighted TR/TE 500–700/15 ms, flip-angle 20°, field-of-view 14–16 cm, matrix 324 × 256, slice 3 mm (33% gap)

At 3-T, the major protocol difference involved receiver bandwidth, which was approximately doubled.

MR image analysis

Of the 144 shoulders with arthroscopically proven FT-RCTs, our analysis group comprised all 45 shoulders with delaminated tendons (delamination cohort) and an equal number of shoulders with nondelaminated tendons (nondelamination cohort; Fig. 3). The nondelamination cohort arbitrarily included the first 15 shoulders with nondelaminated tears from each of the years 2008, 2009 and 2010.

Magnetic resonance imaging examinations of these 90 shoulders were saved as a PACS work-list that could be accessed from any PACS workstation. Readers 1 and 2 independently reviewed the examinations in three sessions separated by at least 1 week. Between each session, MRI examinations were reordered based on patient age, patient name or scanner location. In the first session, readers measured the AP tear length. In the second session, readers measured the tendon retraction distance. In the third session, readers graded the degree of fatty muscle infiltration. At least 2 weeks after completing the first set of three sessions, reader 2 repeated the three sessions to determine intra-observer variability.

Measurement of the AP tear length

The cuff tear was measured from anterior to posterior (AP) along the greater tuberosity. Although tendon abnormalities often extended posterior to the full-thickness defect, only the full-thickness defect was measured [22]. The biceps tendon groove was defined as the leading edge of the supraspinatus tendon. Tear margins were defined as transition points where the tendon attachment sites became indistinct. The PACS cross-reference tool was used to identify these transition points by correlating oblique coronal, oblique sagittal, and axial images. The full-thickness defect was measured by using digital calipers available in PACS. The same process was applied to the nondelamination and delamination cohorts.

Measurement of tendon retraction distance

Tendon retraction was measured between the greater tuberosity and torn cuff margin in the oblique coronal plane [22]. In both cohorts, we selected the lateral-most edge of the footprint as the point of measurement on the greater tuberosity [22].

In the nondelamination cohort, tendon retraction was measured on the oblique coronal image that demonstrated maximum separation between the greater tuberosity and retracted tendon margin [22]. The retracted tendon margin was usually surrounded by fluid (Fig. 4). This interface between tendon and fluid was selected as the point of measurement. Thin, frayed fibers projecting laterally were disregarded [22, 23].

Fig. 4 Non-arthrographic MRI shows effusion and full-thickness rotator cuff tear (arthroscopically proven) without tendon delamination in a 62-year-old woman. Oblique coronal fat-suppressed T2-weighted MRI demonstrates a retracted tendon margin (*arrow*) that is sharply delineated and surrounded by fluid. The tendon margin is irregular, but the difference in retraction of bursal and articular fibers measures less than 1 cm. Both readers categorized this tendon as nondelaminated

In the delamination cohort, using the same process, we identified the oblique coronal image that demonstrated maximum separation between the greater tuberosity and lateral margin of the retracted tendon. This same image was used to measure retraction of both bursal and articular layers. By selecting one image, we attempted to standardize our measurement process.

Evaluation of fatty muscular infiltration

Fatty muscle infiltration was evaluated on oblique sagittal T1-weighted images according to the Goutallier classification [24]. The measurement was made using the lateral-most image, which showed the scapular spine in continuity with the body of the scapula (Y-view). The classification was developed for CT and later validated for MRI by Fuchs et al. [11]. The technique is semi-quantitative and based on a five-point scale assessing the amount of fat in relation to the amount of muscle: grade 0, no fatty infiltration; grade 1, some fatty streaks; grade 2, fatty replacement less than 50% of residual muscle volume (less fat than muscle); grade 3, fatty replacement equaling 50% of residual muscle volume (as much fat as muscle); and grade 4, fatty infiltration greater than 50% of residual muscle volume (more fat than muscle). We graded the degree of fatty infiltration of both supraspinatus and infraspinatus muscles.

Statistical analysis

Statistical analyses were performed using SAS software (SAS Institute, Cary, NC, USA). For all tests, a two-tailed p value less than 0.05 represented a statistically significant difference. In the analyses of tendon retraction, AP size of tear and FMI, we used the mean values of measurement data generated by reader 1 and the first set of measurement data generated by reader 2. Tendon retraction, AP, and FMI were compared between cohorts using the t test. In each cohort, linear regression was used to determine the relationship between AP and retraction. Relationships between delamination and age and gender were determined using logistic regression and the Chi-squared test. Relationships between FMI and age, gender, delamination, retraction, and AP were assessed using generalized linear models. Receiver operating characteristic (ROC) analysis was performed to test the ability of retraction ratios (retraction distance/AP length of the tear: L/AP, A/AP, and B/AP) to help differentiate shoulders with delaminated tendons from nondelaminated tendons. Optimal thresholds were calculated using the Youden index [25].

Intra- and inter-observer agreements were calculated using κ-weighted coefficient for the occurrence of delamination and Pearson correlation for length estimation. κ was not defined for muscular fatty infiltration, as there were incomplete classes of possible responses available in each evaluation; therefore, agreement was expressed as frequencies of identical responses. Inter-observer variability was assessed comparing data from reader 1 with the first set of data from reader 2. Agreements were interpreted as poor if less than 0.20; fair, 0.21–0.40; moderate, 0.41–0.60; good, 0.61–0.80; and very good, 0.81–1.00 [26].

Results

Study population

Delamination was present in 13% of 483 shoulders with FT-RCTs, and 31% of the subset of 144 shoulders that underwent surgical cuff repair ($p = 0.001$). Delamination was present in only 5% of the subset of 339 shoulders that did not undergo surgical cuff repair.

In the classification of delamination, intra- and interobserver agreements were very good (0.95 [95%CI 93–97%] and 0.92 [95%CI 90–94%] respectively). Only one tendon was classified as delaminated based solely on intratendinous fluid. In all other cases, delaminated bursal and articular layers showed differential retraction >1 cm (Figs. 2, 5, and 6). Nondelaminated tendons could demonstrate frayed margins and small regions of intra-substance fluid that did not meet our minimum 1-cm threshold (Fig. 4).

Fig. 5 Non-arthrographic MRI shows effusion and full-thickness rotator cuff tear (arthroscopically proven) with tendon delamination in a 63-year-old man. Oblique coronal fat-suppressed T2-weighted MRI demonstrates differential retraction of bursal (*straight arrow*) and articular (*arrowhead*) fibers in addition to fluid in the space (*curved arrow*) between the bursal and articular fibers. Both readers categorized this tendon as delaminated. This image was selected to measure retraction because it showed the greatest extent of retraction of the bursal fibers

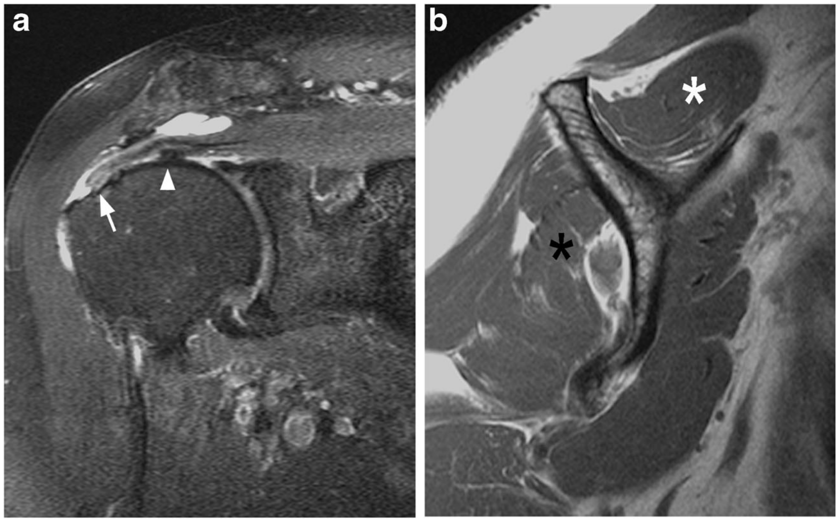

Fig. 6 Non-arthrographic MRI show full-thickness rotator cuff tear (arthroscopically proven) with tendon delamination and fatty muscle infiltration in a 72-year-old woman. **a** Oblique coronal fat-suppressed T2-weighted MRI demonstrates differential retraction of bursal (*arrow*) and articular (*arrowhead*) fibers. Both readers categorized this tendon as delaminated. This image was selected to measure retraction because it showed the greatest extent of retraction of bursal fibers. **b** Oblique sagittal T1-weighted MRI shows fatty infiltration involving the supraspinatus (*white asterisk*) and infraspinatus (*black asterisk*) muscles. Both readers scored the degree of fatty infiltration of the supraspinatus as 1, and infraspinatus as 2 based on the Goutallier classification

In the final study population comprising 90 shoulders that underwent repair of FT-RCTs (two cohorts of 45 shoulders with and without delaminated tendons), patients included 48 men (53%) and 42 women (47%) with an average age 60.7 years (range, 41–83 years). In the nondelamination cohort ($n = 45$), 26 men and 19 women had a mean age of 61.3 years (range, 43–83 years). The average age of men was 58.8 years (range, 43–75 years), and the average age of women was 64.7 years (range, 45–83 years; $p = 0.3$). In the delamination cohort ($n = 45$), 22 males and 23 females had mean age 60.1 years (range, 41–78). Average age of men was 60.1 years (range, 45–78 years), and average age of the women was 60.1 years (range, 41–77 years) ($p = 0.3$). Analysis of variance demonstrated no statistically significant association of delamination with age and gender ($p = 0.58$ and $p = 0.52$ respectively).

Image analysis

Anteroposterior tear length and tendon retraction distance

Results are listed in Table 1. The mean AP length of the rotator cuff tear measured 31.5 mm ± 13.2 mm in nondelaminated tendons, and 30.0 mm ± 9.7 mm in delaminated tendons ($p = 0.6$).

In nondelaminated tendons, mean retraction measured 31.5 mm ± 13.8 mm, resulting in a retraction ratio (retraction distance/AP length) equaling 1.0. In delaminated tendons, articular-sided layers were always retracted more than bursal-sided layers. Mean retraction of bursal layers measured 21 mm ± 10.1 mm and mean retraction of articular layers measured 36.3 mm ± 10.3 mm, resulting in retraction ratios of 0.70 and 1.21 respectively. Comparing bursal and articular layers, there were significant differences in both retraction distances ($p < 0.001$), and retraction ratios ($p < 0.001$). This

Table 1 Summary of MR| imaging measurements in delamination and nondelamination cohorts

	AP (mm)[a]	A (mm)[a]	B (mm)[a]	D (mm)[a]	A/AP[b]	B/AP[b]	L (mm)[a]	L/AP[b]	FMI SS[a, c]	FMI IS[a, c]
Delamination	30 (15–51)	36.3 (20–68)	21 (5–48)	15.3	1.21	0.70		–	1.8 (0–3)	1.9 (0–4)
Nondelamination	31.5 (10–56)	–	–	–	–	–	31.5 (9–51)	1.00	1.7 (0–3)	1.7 (0–4)

AP anteroposterior tear length, *A* retraction of articular fibers in delaminated tears, *B* retraction of bursal fibers in delaminated tears, *D* A–B, *L* retraction of the tendon in nondelaminated tears, *FMI SS* fatty muscle infiltration of supraspinatus, *FMI IS* fatty muscle infiltration of the infraspinatus

[a] Data are means with ranges in parentheses

[b] Retraction ratios are calculated from mean values

[c] Data are based on the Goutallier classification modified by Fuchs

differential retraction between articular and bursal fibers concurs with a previous surgical study [27].

Mean retraction of nondelaminated tendons was significantly different from mean retractions of the bursal ($p < 0.0001$) and articular ($p < 0.0001$) layers of delaminated tendons. Retraction ratio (retraction distance/AP length) of nondelaminated tendons was significantly different from retraction ratios of the bursal ($p < 0.0001$) and articular ($p < 0.0001$) layers of delaminated tendons. In the quantitative assessments of nondelaminated and delaminated tendons, intra- and inter-observer agreements were very good (Table 2).

Linear regression demonstrated significant relationships between AP tear lengths and retraction distances of both nondelaminated tendons ($r^2 = 0.92$, $p < 0.0001$), in addition to the bursal ($r^2 = 0.62$, $p < 0.0001$) and articular ($r^2 = 0.59$, $p < 0.0001$) layers of delaminated tendons. Linear regression also revealed a significant relationship between retraction distances of the bursal and articular layers of delaminated tendons ($r^2 = 0.88$, $p < 0.0001$).

Receiver operating characteristic analysis of retraction ratios showed that, based on the Youden index, an optimal lower threshold of 0.86 and an optimal upper threshold of 1.14 resulted in sensitivities of 78% (95% CI 63–89%) and 64% (95% CI 49–78%), and specificities of 89% (95% CI 76–96%) and 87% (95% CI 73–95%) respectively, in the discrimination between delaminated and nondelaminated tendons. Ratios of 0.70, 0.80, and 0.90 corresponded to diagnostic sensitivities of 52% (95% CI 36–67%), 70% (95% CI, 56–82%), and 78% (95% CI 63–89%) for tendon delamination respectively, and specificities of 96% (95% CI 85–99%), 93% (95% CI, 82–99%), and 78% (95% CI 63–89%).

Fatty muscle infiltration

The results for fatty muscle infiltration were calculated from the average of grades generated independently by readers 1 and 2 (only the first analysis performed by reader 2; Table 1; Figs. 2 and 6). Reader agreements were very good (Table 3). In the nondelamination cohort, mean grade was 1.7±0.9 for the supraspinatus (SS), and 1.7±1.0 for the infraspinatus (IS). In the delamination cohort, the mean grade was 1.8 ± 0.8 for SS and 1.9 ± 0.8 for IS. Differences between cohorts were not statistically significant ($p = 0.08$).

Statistical determinants of fatty muscle infiltration are presented in Table 4. For SS muscle, grade of fatty muscle infiltration had no relationships to age, gender or delamination. For IS muscle, grade was related to age ($p = 0.03$), but not to gender or delamination. Both SS and IS fatty muscle infiltration were statistically related to AP tear lengths and retraction distances of nondelaminated ($p < 0.001$) and delaminated ($p < 0.001$) tendons.

Discussion

In our study population of patients with full-thickness rotator cuff tears, tendon delamination occurred in 31% of 144 shoulders that went on to undergo rotator cuff repair compared with 5% of 339 shoulders that did not go on to undergo rotator cuff repair. Because readers were blinded to treatment regimens during their independent MRI reviews, this statistically significant difference was not biased by knowledge of surgical management. Our findings suggest that delaminated tendons are important to identify and report because they are more likely to fail conservative treatments and undergo operative repairs compared with nondelaminated tendons. Therefore, surgeons may benefit from the knowledge of tendon delamination by operating on larger delaminated cuff tears more promptly, and operating on smaller delaminated cuff tears after shorter trials of conservative management.

The incidence of delamination (31%) in our surgical population was lower than incidences (38–82%) reported in the orthopedic literature [4–7, 28]. Arthroscopic studies reporting the highest incidences defined delamination as edge fraying and cleavage tearing more than several millimeters [6, 28]. Because we lacked a surgical gold standard for delamination, we applied conservative MRI criteria to increase diagnostic specificity and minimize false-positives. As a result, we may

Table 2 Inter- and intra-observer agreements in measurements of tears

	AP[a]	95%CI	AP[b]	95%CI	A[a]	95%CI	B[a]	95%CI	L[b]	95%CI
Inter-observer	0.96 $p < 0.0001$*	0.88–1.00	0.86 $p < 0.0001$*	0.74–1.00	0.96 $p < 0.0001$*	0.84–0.99	0.97 $p < 0.0001$*	0.91–1.00	0.98 $p < 0.0001$*	0.95–1.00
Intra-observer	0.96 $p < 0.0001$*	0.88–1.00	0.86 $p < 0.0001$*	0.70–1.00	0.99 $p < 0.0001$*	0.95–1.00	0.96 $p < 0.0001$*	0.84–1.00	0.99 $p < 0.0001$*	0.96–1.00

AP anteroposterior tear length, *A* retraction of articular fibers, *B* retraction of bursal fibers, *L* retraction of nondelaminated tendon, *95%CI* 95% confidence interval

*Pearson correlation, $p < 0.05$ represented statistical significance

[a] Delamination cohort

[b] Nondelamination cohort

Table 3 Inter- and intra-observer agreements in assessments of fatty muscle infiltration

	Delamination cohort		Non-delamination cohort	
	SS	IS	SS	IS
Inter-observer	0.93 (42/45)	0.93 (42/45)	0.96 (43/45)	0.93 (42/45)
Intra-observer	0.88 (40/45)	0.87 (39/45)	0.93 (42/45)	0.88 (40/45)

Data are frequencies of concordant responses, with numbers of concordant responses/total number of shoulders in parentheses

SS supraspinatus muscle, *IS* infraspinatus muscle

have classified fewer tendons as delaminated compared with arthroscopists. We did not include arthrographic MRI examinations, which may have increased our numbers of delaminated tendons by better demonstrating intrasubstance fluid [18–20]. We limited our analysis to non-arthrographic examinations as most orthopedists at our institution reserve MR arthrography for younger patients with suspected glenohumeral instability.

Mean AP tear lengths along the greater tuberosity were nearly identical in our delamination and nondelamination cohorts, which agrees with findings in a large surgical study of 263 shoulders in which delaminated and nondelaminated full-thickness tears demonstrated statistically similar sizes along the greater tuberosity [6]. In contrast, delaminated and nondelaminated tendons demonstrated different patterns of retraction. In nondelaminated cuff tears, we found a 1:1 relationship between AP tear length and retraction distance. This retraction ratio of 1 agrees with a previous surgical study reporting that AP tear length was comparable with tendon retraction in 12 cadaveric shoulders with torn cuffs [29]. Based on our study population, we can generalize that full-thickness tears maintain this 1:1 relationship as they propagate posteriorly and increase in size along the greater tuberosity.

In delaminated tendons, excluding one tendon that showed equal retraction of articular and bursal layers, articular layers were always retracted more than bursal layers, corresponding to reports in the surgical literature [6, 7, 16, 28]. Articular fibers were retracted more than AP length (retraction ratio 1.21), whereas bursal fibers were retracted less than AP length (retraction ratio 0.70). According to our ROC analysis, a retraction ratio of 0.80 corresponded to a diagnostic sensitivity of 70% and specificity of 93% for tendon delamination.

Tendon delamination has emerged, along with AP tear length, tendon retraction distance, and fatty muscle atrophy [5, 10–15], as another prognostic factor that has a negative impact on surgical outcomes [4–6, 8]. In our study, fatty muscle infiltration demonstrated strong associations with both AP tear length and tendon retraction distance, but showed no significant association with the presence of delamination. This lack of association suggests independent influences on prognosis. Whereas fatty muscle infiltration is prevalent in the later stages of rotator cuff disease when tendon tears are larger [10, 14], delamination is implicated in the earlier stages of cuff tear before the onset of fatty muscle infiltration [3, 8, 14, 30, 31]. Exposed tendon surfaces can become synovialized, which is believed to decrease healing potential following surgical repair [7, 9]. Specialized surgical techniques, such as resection of the synovial lining before layer-to-layer suturing, have increased the technical difficulty of arthroscopic management and caused some authors to recommend mini-open procedures [4, 6, 7, 9].

Our retrospective study had several limitations. First, we lacked a gold standard proving that we correctly classified rotator cuff tears as delaminated or nondelaminated. In the absence of surgical confirmation, we applied conservative diagnostic criteria. Previous MRI studies involving delamination also lacked surgical confirmation [16, 18, 20]. In one of these studies, all 16 patients underwent arthroscopy but only 2 patients had horizontal splitting described in arthroscopic reports [18]. Unfortunately, many orthopedic surgeons, even specialists in the upper extremity, remain unfamiliar with delamination and its management options [9, 32]. Moreover, depending on the arthroscopic viewing portal, posterior (infraspinatus) delamination can be overlooked at surgery [33].

Second, readers could not be blinded to the appearance of the rotator cuff when measuring AP tear length, tendon retraction, and fatty muscle infiltration. Although data were collected in three separate sessions to decrease the likelihood that one measurement would have a direct impact on others, readers were able to see all MRIs and, therefore, could have been influenced by the presence or absence of delamination.

In summary, it is important to identify and report delaminated tendons, because, compared with nondelaminated tendons, they

Table 4 Associations of fatty muscle infiltration with patient demographics and MRI measurements

	Age	Gender	Presence of delamination	Delamination cohort						Nondelamination cohort		
				AP	A	B	D	A/AP	B/AP	AP	L	L/AP
Supraspinatus	0.07	0.52	0.57	<0.001	<0.001	<0.001	0.15	0.40	0.12	<0.001	<0.001	0.56
Infraspinatus	0.03	0.46	0.51	<0.001	<0.001	<0.001	0.56	0.42	0.02	<0.001	<0.001	0.80

Data are p values calculated using generalized linear models. $p < 0.05$ represented statistical significance

AP anteroposterior tear length, *A* retraction of articular fibers, *B* retraction of bursal fibers, *D* A–B, *L* retraction of nondelaminated tendons are more likely to fail conservative treatments and undergo operative repairs. In shoulders with full-thickness cuff tears, delaminated and nondelaminated tendons show significant differences in retraction distances, despite similarities in AP dimensions. A critical feature of the delaminated tendon is the increased retraction ratio (retraction distance/AP length) of the articular layer compared with the nondelaminated tendon, which shows equal retraction distance and AP length.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflicts of interest.

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