Radiology

Predicting Retear after Repair of Full-Thickness Rotator Cuff Tear: Two-Point Dixon MR Imaging Quantification of Fatty Muscle Degeneration—Initial Experience with 1-year Follow-up[1]

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Purpose: To determine the degree of preoperative fatty degeneration within muscles, postoperative longitudinal changes in fatty degeneration, and differences in fatty degeneration between patients with full-thickness supraspinatus tears who do and those who do not experience a retear after surgery.

Materials and Methods: This prospective study had institutional review board approval and was conducted in accordance with the Committee for Human Research. Informed consent was obtained. Fifty patients with full-thickness supraspinatus tears (18 men, 32 women; mean age, 67.0 years ± 8.0; age range, 41–91 years) were recruited. The degrees of preoperative and postoperative fatty degeneration were quantified by using a two-point Dixon magnetic resonance (MR) imaging sequence; two radiologists measured the mean signal intensity on in-phase [$S(\text{In})$] and fat [$S(\text{Fat})$] images. Estimates of fatty degeneration were calculated with "fat fraction" values by using the formula $S(\text{Fat})/S(\text{In})$ within the supraspinatus, infraspinatus, and subscapularis muscles at baseline preoperative and at postoperative 1-year follow-up MR imaging. Preoperative fat fractions in the failed-repair group and the intact-repair group were compared by using the Mann-Whitney *U* test.

Results: The preoperative fat fractions in the supraspinatus muscle were significantly higher in the failed-repair group than in the intact-repair group (37.0% vs 19.5%, $P < .001$). Fatty degeneration of the supraspinatus muscle tended to progress at 1 year postoperatively in only the failed-repair group.

Conclusion: MR imaging quantification of preoperative fat fractions by using a two-point Dixon sequence within the rotator cuff muscles may be a viable method for predicting postoperative retear.

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Rotator cuff tear is a common cause of shoulder pain and disability and is among the most common conditions that affect the shoulder (1). The incidence of such injuries increases with age, reducing the quality of life because of shoulder pain and weakness with shoulder flexion and abduction.

Since the introduction of innovative arthroscopic techniques, minimally invasive arthroscopic rotator cuff repair is increasingly popular for treatment of full-thickness rotator cuff tears (2). However, outcomes are far from perfect, with a mean retear rate of 26.6% at 2 years after surgery (3). Postoperative retears are associated with greater fatty degeneration, larger tears, and advanced patient age (3–11). Of late, research related to fatty degeneration has received greater attention.

In clinical practice, evaluation of fatty degeneration within the rotator cuff muscles is often qualitatively determined by using magnetic resonance (MR) imaging and the Goutallier or modified Goutallier classification (6,12). However, reproducibility is poor (13), and better methods to quantify fatty degeneration are needed. Recently, several methods that involve quantifying the fat within tissue by using MR imaging have been introduced and applied to clinical research in the fields of abdominal imaging and musculoskeletal imaging (14). Several recent reports (15–17) suggest that the degree of fatty degeneration within rotator cuff muscles can be quantified by using chemical shift–based multipoint water-fat separation techniques. Specifically, a two-point Dixon MR imaging sequence is a proton chemical shift imaging technique that produces separated water-only and fat-only images from a dual-echo acquisition that is based on technology first described by Dixon in 1984 (18). However, to our knowledge, there have been no studies that compared quantitative fat fraction values between pre- and postoperative MR imaging in patients undergoing rotator cuff repair.

The purpose of our study was to determine the degree of preoperative fatty degeneration using a two-point Dixon sequence within muscles, postoperative longitudinal changes in fatty degeneration, and differences in fatty degeneration between patients who did and those who did not experience a retear postoperatively. We hypothesized that measurement of preoperative fat fraction values of the rotator cuff muscles would be one of determinants predicting retear. We also hypothesized that arthroscopic rotator cuff repair prevents the progression of fatty degeneration.

Advances in Knowledge

- Quantifying the degree of fatty degeneration of rotator cuff muscles is possible by using a two-point Dixon MR imaging sequence.
- At two-point Dixon MR imaging, preoperative fat fractions in the supraspinatus muscle were significantly higher in patients who underwent repair and eventually experienced retear than in those who did not experience retear (37.0% vs 19.5%, $P < .001$).
- Fat fractions in the supraspinatus muscle tended to worsen at 1-year postoperative follow-up in the failed-repair group, while they remained stable in the intact-repair group.
- Sites of retear in the repaired supraspinatus tendon were proximal to the insertion on the humeral head in all occurrences.

Implications for Patient Care

- We may be able to preoperatively predict the risk of a supraspinatus retear by evaluating preoperative fat fractions using a two-point Dixon sequence, aiding in treatment selection.
- The optimal cut points for predicting supraspinatus and infraspinatus retears were estimated, with best performance at fat fractions of 26.6% (sensitivity, 0.706; specificity, 0.80) and 31.0% (sensitivity, 0.931; specificity, 0.65), respectively, with two-point Dixon MR imaging quantification.
- Successful arthroscopic rotator cuff repair will halt the progression of fatty degeneration; or, alternatively, progression of fatty degeneration after repair leads to failure.

Materials and Methods

Patients

Our prospective study was approved by our institutional review board, and informed consent was obtained. We conducted the research in accordance with the Committee for Human Research. Fifty-six patients with rotator cuff tears were recruited for our study from January 2012 to June 2014. Criteria for study enrollment included suspicion, on the basis of clinical and radiologic findings, of a full-thickness tear involving at least the supraspinatus tendon at shoulder MR imaging that was subsequently confirmed at arthroscopy to represent at least a supraspinatus full-thickness rotator cuff tear. Exclusion criteria included prior surgery to the shoulder or repeated injuries to the shoulder during the follow-up period. We excluded six

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Abbreviations:
AUC = area under the ROC curve
ROC = receiver operating characteristic
ROI = region of interest

Author contributions:
Guarantors of integrity of entire study, T.N., T.H., Y.S., H.Y.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; agrees to ensure any questions related to the work are appropriately resolved, all authors; literature research, T.N., J.S., Y.S.; clinical studies, T.N., A.T., S.H., J.O., H.Y.; experimental studies, T.N., S.H., T.H., H.Y.; statistical analysis, T.N., T.H.; and manuscript editing, T.N., A.T., J.S., Y.S., H.Y.

Conflicts of interest are listed at the end of this article.

patients from our study because of technical errors in MR imaging acquisition (four patients with inadequate coverage of the anatomic area of interest and two patients with oblique MR images obtained at an incorrect angle). In total, 50 patients (mean age, 67.0 years ± 8.0 [standard deviation]; age range, 41–91 years) were included (18 men [mean age, 63.7 years ± 8.5; age range, 41–74 years] and 32 women [mean age, 68.9 years ± 7.2; age range, 51–91 years]). The age of the women was significantly higher than that of the men (P = .035).

All patients underwent arthroscopic rotator cuff repair with the suture bridge technique, performed by one orthopedic surgeon (A.T., with 18 years of experience), followed by the standard postoperative rehabilitation protocol of our hospital.

MR Imaging

All MR imaging examinations were performed with a 3.0-T unit (Magnetom Verio, version VB17; Siemens, Erlangen, Germany) by using a four-channel flex coil (Siemens). All patients were imaged prior to arthroscopic rotator cuff repair and at 1 year after surgery. The average time between preoperative baseline MR imaging and arthroscopic rotator cuff repair was 64.7 days ± 38.7. Standard MR imaging examinations included fast spin-echo proton density–weighted imaging in the oblique coronal and sagittal planes (matrix, 320 × 320; repetition time msec/echo time[s] msec, 2500/19; field of view, 180 mm; number of acquisitions, one; section thickness, 3 mm), fat-saturated fast spin-echo proton density–weighted imaging in the oblique coronal and sagittal planes (matrix, 320 × 320; 2500/37; field of view, 180 mm; number of acquisitions, one; section thickness, 3 mm), and a T2*-weighted sequence in the axial plane (matrix, 320 × 320; 900/13; field of view, 180 mm; number of acquisitions, one; section thickness, 3 mm). We also a performed a three-dimensional two-point Dixon volumetric interpolated breath-hold examination sequence in the oblique sagittal plane. The two-point Dixon sequence used an acquisition matrix of 128 × 128; 6.5/1.225, 2.4; flip angle, 10°; field of view, 196 mm; number of acquisitions, one; section thickness, 2.5 mm; and acquisition time, 2 minutes 30 seconds. From the two-point Dixon sequence, water-only, fat-only, in-phase (water and fat), and out-of-phase (water minus fat) images were produced.

MR Image Interpretation

Evaluation of rotator cuff tear and fatty degeneration at preoperative baseline and 1-year postoperative follow-up MR imaging was performed independently by two board-certified radiologists with subspecialization in musculoskeletal radiology (T.N. and J.O., with 13 and 10 years of experience, respectively). One of the two readers (J.O.) was blinded to all clinical information and read all studies twice with a 1-month interval so we could evaluate intrarater reliability.

Discrepancies were resolved by means of consensus. Specifically, according to the definition of full-thickness rotator cuff tear at MR imaging (19), the same two radiologists (T.N. and J.O.) performed a second reading together carefully for exceptional cases only. At preoperative MR imaging, seven cases (two supraspinatus, three infraspinatus, and two subscapularis tears) were reevaluated. At postoperative MR imaging, eight cases (two supraspinatus, five infraspinatus, and one subscapularis tears) were reevaluated.

We graded the full-thickness rotator cuff tears at preoperative MR imaging as massive or nonmassive tears according to the Cofield grading system (Fig 1a, b) (20); a massive rotator cuff tear was defined as a tear of a single tendon more than 5 cm in length or a tear involving two or more tendons.

Follow-up Tendon Status Categories

We graded the tendon status at 1-year postoperative follow-up using the classification system of Sugaya et al (21) (Table 1) and then assigned the tendon to one of the following three categories (Table 2): *(a)* A normal tendon denoted a tendon with a history of neither tear nor intervention; all patients, in accordance with our inclusion criterion, had supraspinatus tears, but the other tendons were sometimes normal. *(b)* A tendon with intact repair was defined as a Sugaya type 1–3 tendon. *(c)* A tendon with failed repair was defined as a Sugaya type 4 or 5 tendon, with confirmation at physical examination by the orthopedic surgeon.

Retear Location

In patients who experienced retear of the supraspinatus tendon, we evaluated the tear location by measuring the distance from the footprint of the humeral head where suture anchors were placed and tear length (Fig 1f, g).

Quantification of Fatty Degeneration

The degree of fatty degeneration was quantified on the two-point Dixon MR images after mean signal intensities were measured independently by a board-certified radiologist (T.N.) and a resident in radiology (S.H., with 3 years of experience) on a picture archiving and communication system (Centricity, version 4.0; GE Healthcare, Barrington, Ill) with an ROI that was placed over the supraspinatus, infraspinatus, and subscapularis muscles on the most lateral image in which the scapular borders were still visible on the oblique sagittal sections. Each radiologist segmented rotator cuff muscles on the preoperative baseline and 1-year follow-up MR imaging studies. One of the radiologists (S.H.) performed measurements twice so that we could investigate intrarater reproducibility. ROIs for the supraspinatus, infraspinatus, and subscapularis muscles were drawn over the surface of each muscle as visually determined on the proton density–weighted images; fat regions in the periphery of the muscle compartments were excluded from the ROIs, as previously reported (15). In the segmentation of the subscapularis muscle, the caudal boundary was defined as a horizontal line passing through the tip of the scapula (Fig 1c, h). The mean signal intensity of the two-point Dixon MR in-phase [S(In)] and fat and water [S(Fat) and S(Water), respectively] images was assessed (Fig 1d, e). The amount of fat contained in each rotator cuff muscle

Figure 1

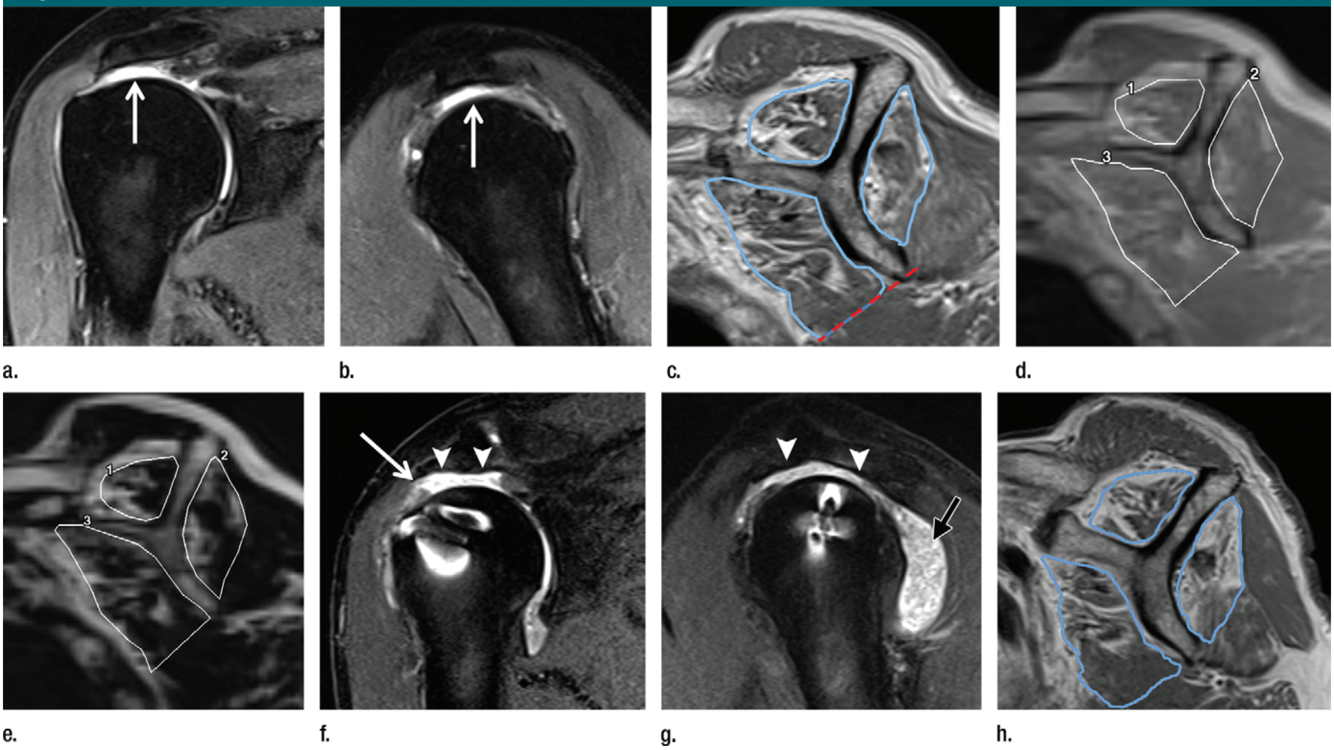


Figure 1: Images in 74-year-old man with massive rotator cuff tear. **(a, b)** Preoperative MR imaging showed discontinuity of the supraspinatus and infraspinatus tendons and fluid retention in the subacromial bursa (arrow) on oblique (**a**) coronal and (**b**) sagittal fat-saturated proton density–weighted images. **(c)** Oblique sagittal proton density–weighted MR image shows muscle regions and segmented areas (blue lines). Red dashed line = caudal boundary of the subscapularis muscle, defined as a horizontal line passing through the tip of the scapula. These findings are compatible with a modified-Goutallier scale stage 2 tear. **(d, e)** Measurements of signal intensity within regions of interest (ROIs) over the supraspinatus, infraspinatus, and subscapularis muscles were performed on oblique sagittal images on (**d**) an in-phase image and on (**e**) a fat image acquired with the two-point Dixon sequence. Each signal intensity value was represented as *S*(In) and *S*(Fat), and we calculated the fat fraction in each rotator cuff muscle with the formula *S*(Fat)/*S*(In). Fat fractions were 0.494, 0.386, and 0.246 in the supraspinatus, infraspinatus, and subscapularis muscles, respectively. **(f, g)** Postoperative MR imaging shows retear of the supraspinatus and infraspinatus tendons and fluid retention in the subacromial bursa (arrowheads) on oblique (**f**) coronal and (**g**) sagittal fat-saturated proton density–weighted images. There is synovial proliferation, which is seen as intermediate signal intensity (arrow in **g**) and an increase in joint fluid. It indicates chronic synovitis. The retear point (arrow in **f**) is proximal from the footprint of the humeral head, in which the suture anchors were placed. **(h)** Postoperative oblique sagittal proton density–weighted MR image shows the progress of fatty degeneration within the infraspinatus muscle. In contrast, we cannot confirm definite changes of fatty degeneration within the supraspinatus and subscapularis muscles qualitatively. Fat fractions were 0.571, 0.593, and 0.266 in the supraspinatus, infraspinatus, and subscapularis muscles, respectively.

was calculated with the following equations: $S(\text{In}) = S(\text{Water}) + S(\text{Fat})$ and fat fraction = $S(\text{Fat})/[S(\text{Water}) + S(\text{Fat})] = S(\text{Fat})/S(\text{In})$. So that we could assess interobserver reproducibility in measurement of fatty degeneration, both readers segmented each rotator cuff muscle independently and were blinded to each other's results.

Arthroscopic Rotator Cuff Repair

Arthroscopic rotator cuff repair was performed with the patient in the beach chair position and receiving general anesthesia. After sufficient subacromial bursectomy and intra-articular soft tissue release, the rotator cuff was evaluated. Débridement of the tendon stump was performed, and metal suture anchors were placed at the anatomic footprint of the humeral head to repair the torn tendon. Subacromial decompression was also performed in some cases. All patients underwent the standard postoperative rehabilitation protocol of our institution: An abduction pillow was used for 3–4 weeks postoperatively. Passive range of motion exercises were started 2 weeks after surgery, and active elevation in a sitting position from the adducted position was started 6–8 weeks after surgery. Isometric cuff exercises were allowed starting at 8–10 weeks after surgery.

Statistical Analysis

First, the Shapiro-Wilk test was performed to evaluate the normality of the results of statistical analysis for fat fractions and sizes of tendon retraction. The Mann-Whitney *U* test was used to compare preoperative fat fractions between failed-repair and intact-repair groups. The Wilcoxon signed-rank test was used to compare fat fractions

Table 1

Repaired Cuff Integrity: Sugaya Classification

Type	Criteria
1	Repaired cuff of sufficient thickness with a homogeneously low signal intensity in each image
2	Sufficient thickness associated with a partial high-signal-intensity area
3	Insufficient thickness without discontinuity
4	Minor discontinuity in more than one section, suggestive of a small tear
5	Major discontinuity in each image, suggestive of a medium-to-large tear

Table 2

Criteria for Assigning a Tendon to One of Three Categories

Tendon Category	Baseline Tendon Status	Treatment	12-month Follow-up
Normal tendon	No tear	None	No tear
Intact repair	Full-thickness tear	ARCR	No tear (Sugaya type 1–3)
Failed repair	Full-thickness tear	ARCR	Retear (Sugaya type 4 or 5)

Note.—Normal tendon denotes a tendon with a history of neither tear nor intervention, tendons with intact repair were defined as Sugaya type 1–3 tendons, and tendons with failed repair were defined as Sugaya type 4 or 5 tendons, with confirmation at physical examination by an orthopedic surgeon. ARCR = arthroscopic rotator cuff repair.

Table 3

Preoperative Tear Combinations

Type of Tear*	SSP Tendon	ISP Tendon	SSC Tendon	No. of Tendons
Nonmassive tear	Tear	Normal	Normal	30
Massive tear	Tear	Tear	Tear	11
	Tear	Tear	Normal	5
	Tear	Normal	Tear	4

Note.—ISP = infraspinatus, SSC = subscapularis, SSP = supraspinatus.

* The definitions of massive and nonmassive tears are based on the Cofield classification system.

Table 4

Fat Fractions in Each Rotator Cuff Muscle for Normal, Intact-Repair, and Failed-Repair Tendons

Tendon and Group	Patient Age (y)	Preoperative Fat Fraction	Postoperative Fat Fraction	*P* Value*
Supraspinatus tendon				
Normal ($n = 0$)	NA	NA	NA	NA
Intact repair ($n = 39$)	67.1 ± 8.6	0.195 ± 0.100	0.193 ± 0.109	.951
Failed repair ($n = 11$)	66.7 ± 5.7	0.370 ± 0.144	0.428 ± 0.085	.083
Infraspinatus tendon				
Normal ($n = 34$)	67.2 ± 8.7	0.156 ± 0.091	0.166 ± 0.073	.228
Intact repair ($n = 9$)	68.7 ± 6.9	0.328 ± 0.116	0.371 ± 0.146	.164
Failed repair ($n = 7$)	64.3 ± 5.6	0.446 ± 0.088	0.526 ± 0.106	.297
Subscapularis tendon				
Normal ($n = 35$)	66.0 ± 7.7	0.123 ± 0.052	0.122 ± 0.057	.878
Intact repair ($n = 15$)	69.5 ± 8.5	0.197 ± 0.073	0.213 ± 0.063	.229
Failed repair ($n = 0$)	NA	NA	NA	NA

Note.—Data are means ± standard deviations. NA = not applicable.

* For the difference between pre- and postoperative fat fractions in each group.

between baseline and 1-year follow-up MR imaging. One-way analysis of variance and the Scheffe method were used for comparison of fat fractions among the three tendon status categories. Additionally, we performed receiver operating characteristic (ROC) curve analysis to evaluate the diagnostic performance of fat fractions in predicting retear. Intra- and interobserver reliability in the quantification of fatty degeneration was determined with intra- and interclass correlation coefficients, with $R < 0.40$ indicating poor agreement; $R > 0.40$, fair agreement; $R > 0.60$, good agreement; and $R > 0.75$, excellent agreement. Intra- and interobserver reliability in the qualitative evaluation of rotator cuff tears was determined with the Cohen κ value. The following ratings for the interpretation of κ were used: $\kappa < 0.40$ Indicated poor agreement; κ = 0.40–0.59, moderate agreement; κ = 0.60–0.80, good agreement; and $\kappa > 0.80$, excellent agreement. We calculated the diagnostic accuracy of the presence of full-thickness rotator cuff tear at preoperative MR imaging using surgical findings as a reference standard. All statistical analyses were performed by using R for Windows software, version 3.0.2 (R Development Core Team, Vienna, Austria). The level of significance for all calculations was defined at $P < .05$.

Results

Pre- and Postoperative Status of Rotator Cuff and MR Findings of Failed Repair

Patient demographic data are summarized in Tables 3 and 4. Of 50 patients at baseline, 30 had isolated nonmassive supraspinatus tears. The remaining 20 patients had massive tears; 11 patients had involvement of all three tendons, five patients had supraspinatus and infraspinatus tendon tears, and

Figure 2

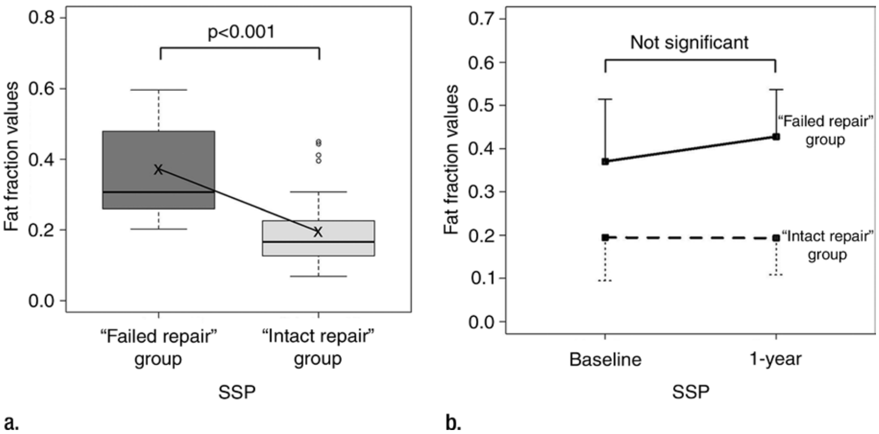


Figure 2: **(a)** Graph shows comparison of preoperative fat fractions in the supraspinatus muscle between the failed-repair group and the intact-repair group. The fat fractions were significantly higher in the failed-repair group than in the intact-repair group. X = average fat fraction. **(b)** Graph shows change in fat fractions in the supraspinatus muscle between baseline and 1-year follow-up MR imaging. There was no significant difference in the longitudinal change of fat fractions from baseline to 1-year follow-up between the failed-repair group and the intact-repair group, although it tended to be worse in the failed-repair group.

four patients had supraspinatus and subscapularis tendon tears (Table 3). Seven of 11 patients with failed repair of the supraspinatus had simultaneous infraspinatus retears (Table 4). No normal tendons had new tears at follow-up MR imaging. There was no significant difference in age among patients according to tendon status (normal tendon, failed repair, or intact repair).

Of 11 patients with failed supraspinatus tendon repair, nine had massive tears and two patients had isolated nonmassive supraspinatus tears. There was no significant difference in the retear rate between men and women (P = .701 for supraspinatus, P = .619 for infraspinatus, and P = .563 for subscapularis). In all patients with failed repair, postoperative cuff integrity was Sugaya type 5. The supraspinatus tear location was 12.4 mm ± 4.8 proximal to the footprint, and the average tear length was 20.4 mm ± 7.4.

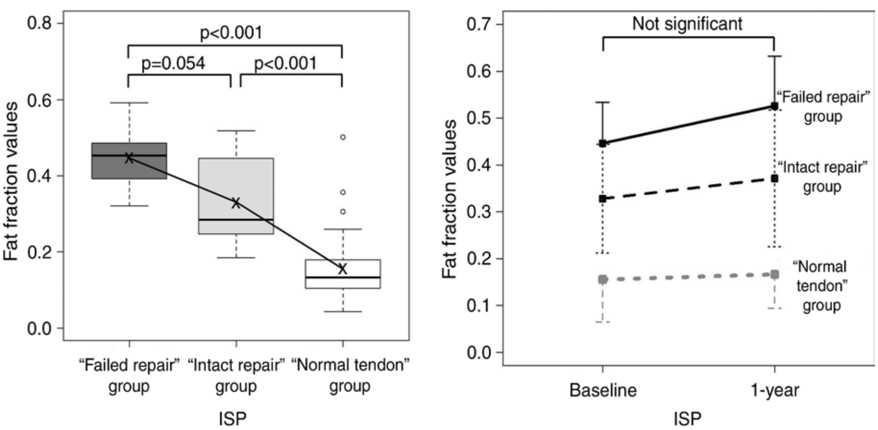
Longitudinal Change in Fat Fractions within Rotator Cuff Muscles between Baseline and 1-Year Follow-up Postoperative MR Imaging

Supraspinatus muscle.—At arthroscopy, all patients had full-thickness supraspinatus rotator cuff tears (Table 4). Of 50 patients, 11 had failed repair of the supraspinatus tendon as seen at postoperative MR imaging. The preoperative fat fractions of the supraspinatus muscle were significantly higher in the failed-repair group than in the intact-repair group (37.0% vs 19.5%, $P < .001$) (Fig 2a). The ROC curve performance of fat fraction in the supraspinatus muscle for predicting retear was high, with an average area under the ROC curve (AUC) of 0.827. The Youden index was calculated to find the optimal cut point for predicting supraspinatus retear, with the best performance at a fat fraction of 26.6% (sensitivity, 0.706; specificity, 0.80). The postoperative fat fractions in the supraspinatus muscle at 1-year follow-up MR imaging were significantly higher in the failed-repair group than in the intact-repair group (42.8% vs 19.3%, $P < .001$). Fatty degeneration tended to progress at 1 year postoperatively only in the failed-repair group, although this trend did not reach statistical significance (Fig 2b).

Infraspinatus muscle.—Of the 50 patients, 16 patients had a concurrent infraspinatus tendon tear at arthroscopy and the remainder had a normal tendon. The diagnostic accuracy of the qualitative evaluation at preoperative MR imaging was 92% (46 of 50 patients). All patients with tear of the infraspinatus tendon underwent repair; failed repair was seen in seven. The preoperative fat fractions in the infraspinatus muscle were 44.6% in the failed-repair group, 32.8% in the intact-repair group, and 15.6% in the normal tendon group (Fig 3a). Fat fractions in the infraspinatus muscle trended higher in the failed-repair group than in the intact-repair group, although there was no statistically significant difference. The ROC performance of fat fraction in the infraspinatus for predicting retear was high, with an average AUC of 0.829. The Youden index was calculated to find the optimal cut point for predicting infraspinatus retear, with the best performance at a fat fraction of 31.0% (sensitivity, 0.931; specificity, 0.65). The postoperative fat fractions of the infraspinatus muscle at 1-year follow-up MR imaging were 52.6% in the failed-repair group, 37.1% in the intact-repair group, and 16.6% in the normal tendon group. There was no significant difference in the longitudinal change in fat fractions postoperatively in any group, although fatty degeneration tended to progress at 1 year postoperatively in the failed-repair group (Fig 3b).

Subscapularis muscle.—Of the 50 patients, 15 had a concurrent subscapularis tendon tear at arthroscopy and the remainder had a normal tendon. The diagnostic accuracy of the qualitative evaluation at preoperative MR imaging was 88% (44 of 50 patients). All 15 patients underwent repair; all patients had intact repair at 1-year follow-up MR imaging. The preoperative fat fractions in the subscapularis muscle were significantly higher in the intact-repair group than in the normal tendon group (19.7% vs 12.3%, $P < .001$) (Fig 4a). The postoperative fat fractions of the subscapularis muscle at 1-year follow-up MR imaging were significantly higher in the intact-repair group than

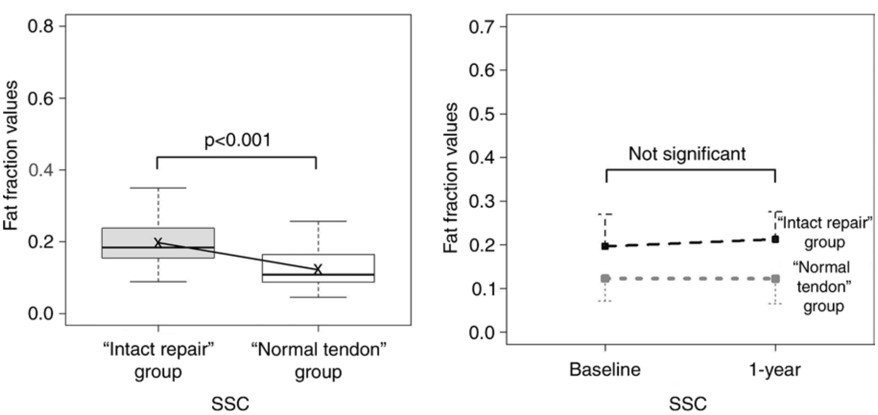
Figure 3



a. b.

Figure 3: **(a)** Graph shows comparison of preoperative fat fractions in the infraspinatus muscle among the failed-repair group, the intact-repair group, and the normal tendon group. Fat fractions in the infraspinatus muscle were higher in the failed-repair group than in the other two groups. X = average fat fraction. **(b)** Graph shows change in fat fractions in the infraspinatus muscle between baseline and 1-year follow-up MR imaging. There was no significant difference in the longitudinal change of fat fractions from baseline to 1-year follow-up among the three groups, although it tended to be worse in the failed-repair group.

Figure 4



a. b.

Figure 4: **(a)** Graph shows comparison of preoperative fat fractions in the subscapularis muscle between the intact-repair group and the normal tendon group. The preoperative fat fractions were significantly higher in the intact-repair group than in the normal tendon group. X = average fat fraction. **(b)** Graph shows change in fat fractions in the subscapularis muscle between baseline and 1-year follow-up MR imaging. There was no significant difference in the longitudinal change of fat fractions from baseline to 1-year follow-up MR imaging between the intact-repair group and the normal tendon group.

in the normal tendon group (21.3% vs 12.2%, $P < .001$). There was no significant difference in the longitudinal change of fat fractions from baseline to the 1-year follow-up MR imaging in either group (Fig 4b).

Reproducibility of Qualitative Evaluation of Rotator Cuff Tears and Quantitative Measurement of Fatty Degeneration

Table 5 shows the results of the reproducibility of the evaluation of the rotator cuffs at MR imaging. There was excellent intra- and interobserver reproducibility in the measurement of fatty degeneration of the rotator cuff muscles and in the qualitative evaluation of rotator cuff tears.

Discussion

We used a two-point Dixon quantitative MR imaging sequence to measure the rotator cuff muscle fat fractions pre- and postoperatively. The preoperative fat fractions within the rotator cuff muscles were significantly higher in patients whose repair failed. Fatty degeneration also tended to worsen in patients with failed repair at 1-year follow-up. This suggests that either successful arthroscopic rotator cuff repair halts the progression of fatty degeneration or, alternatively, that progression of fatty degeneration after repair leads to failure.

Fatty degeneration of the rotator cuff muscles is a prognostic factor for reparability of tears and better postrepair shoulder function (5,8,9,22). Patients with severe fatty degeneration associated with large or massive rotator cuff tears have less satisfactory outcomes (10,23,24). In a prior study (16), we investigated the relationship between fat fractions and age, tear grade, and muscular volume using multiple regression analysis and showed that an increase in supraspinatus muscle fatty degeneration was correlated with the severity of supraspinatus tears and was moderately correlated with muscular atrophy. Hence, in our current study, we focused on postoperative longitudinal changes in fat fractions and in predicting retear using a two-point Dixon MR imaging quantification. There have been several studies (25,26) of the relationship and longitudinal change in fatty degeneration between pre- and postoperative MR imaging involving qualitative methods; our results support previous research that suggests that the preoperative severity of fatty degeneration is associated with an increased rate of retear. It may be reasonable to consider rotator cuff tears of Goutallier stage 3 or 4 as relative contraindications for rotator cuff repair (27). New surgical

Table 5

Reproducibility of Measurement of Fat Fractions and Qualitative Evaluation of Rotator Cuff Tears at MR Imaging

Tendon, Parameter, and Analysis	Preoperative MR Imaging	Postoperative MR Imaging
Supraspinatus tendon		
Fat fraction		
Intrarater intraclass CC	0.910 (0.816, 0.957)	0.928 (0.851, 0.966)
Interrater interclass CC	0.873 (0.763, 0.934)	0.908 (0.827, 0.952)
Diagnosis		
Intrarater κ value	0.93	0.95
Interrater κ value	0.95	0.95
Infraspinatus tendon		
Fat fraction		
Intrarater intraclass CC	0.927 (0.849, 0.965)	0.977 (0.952, 0.989)
Interrater interclass CC	0.936 (0.863, 0.969)	0.938 (0.792, 0.975)
Diagnosis		
Intrarater κ value	0.98	0.98
Interrater κ value	0.93	0.89
Subscapularis tendon		
Fat fraction		
Intrarater intraclass CC	0.952 (0.901, 0.978)	0.895 (0.789, 0.950)
Interrater interclass CC	0.894 (0.755, 0.950)	0.804 (0.602, 0.903)
Diagnosis		
Intrarater κ value	0.98	0.95
Interrater κ value	0.95	0.98

Note.— CC = correlation coefficient. Numbers in parentheses are 95% confidence intervals.

techniques are likely necessary for lasting repair in patients with severe fatty degeneration.

Research regarding postoperative longitudinal change in fatty degeneration is conflicting: Some researchers report that fatty degeneration within muscle does not change after repair (6,22), while others contend it improves (25). Furthermore, there have been several reports (5,26) of progression of fatty degeneration even in patients with successful repair. However, in all of these studies, evaluation of fatty degeneration was qualitative. It is well known that intra- and interrater reliabilities in Goutallier classification are insufficient (13), so the accuracy of fatty degeneration assessment in these studies is questionable. In contrast, the intra- and interobserver reliability of fat fraction measurements was excellent in our study. Therefore, by using a two-point Dixon sequence, investigators can more precisely evaluate fatty degeneration than by using qualitative methods.

In our study, at 1-year follow-up, the fat fractions tended to progress in the failed-repair group, while they tended to be stable in the intact-repair group (although there was no significant difference). Our results support the data reported by Gladstone et al (5) and Gerber et al (28), who also found that fatty degeneration progressed significantly if repair failed. The fat fractions were higher in the infraspinatus muscle than in the supraspinatus muscle. This is likely because of our study inclusion criteria; all patients who participated were required to have a full-thickness tear of the supraspinatus tendon. Thus, patients in the infraspinatus group actually had more extensive involvement (and, by our definition, a massive tear). Hence, the infraspinatus fatty degeneration was likely more advanced on average because the comparison group included some patients with less extensive, isolated tears of the supraspinatus tendon. Indeed, our prior research (16) has demonstrated that rotator cuff muscle fatty infiltration is significantly correlated with the severity of rotator cuff tears.

Although it has been reported that the suture-tendon interface is the weakest point in repaired tendons (2), none of our patients had a retear at the anatomic footprint of the humeral head where the suture anchors were placed; instead, the retear sites were proximal from the tendon's insertion. We speculate that this may imply that the strength of the tendon was compromised because of the progression of fatty degeneration, although pathologic confirmation is needed.

MR imaging–based fat quantification can be achieved by using various methods (15,16,29,30). We chose a two-point Dixon-based MR imaging quantification method for our study on the basis of prior reports of its high accuracy (31,32). In addition, the two-point Dixon sequence is fast enough to be clinically feasible, and it had an acquisition time of 2 minutes 30 seconds in our study. However, this area is rapidly evolving, and recently, three-point or multipoint water-fat separation techniques such as IDEAL and IDEAL-IQ have been reported for the MR imaging quantification of fatty degeneration, which may enable more precise measurements through improvements such as T2* correction, iterative approximation, and algorithms to maximize noise performance (15,33).

As for the clinical implications of our findings, we speculate that the risk of repair failure can be estimated by using the preoperative fat fractions yielded by a two-point Dixon sequence, allowing appropriate treatment selection.

Our study had several limitations. First, we included a small number of patients. For the estimation of the risk of repair failure using preoperative MR imaging, we need to analyze large samples in the future. Second, we do not know when the retear occurred. Although one study reported that most retears occur within 3 months after repair (34), the postoperative fat fractions in our patients with failed repair potentially include everything from acute to chronic retears. Furthermore, the chronologic relationship to fatty degeneration and tear could not be ascertained (Did fatty degeneration progress and then retear occur? Did retear occur and then fatty degeneration progress? Or both?). Third, the follow-up period was not sufficiently long to fully evaluate fatty degeneration. Longer follow-up will be needed to observe significant changes in fatty degeneration. Fourth, we measured the fat fraction values on the most lateral sagittal Y-view. It has been reported that the measurement of muscular atrophy by using a conventional Y-view is influenced by retraction of the torn tendon (35). Therefore, there is a possibility of location discrepancy in measurements between pre- and postoperative MR imaging, although this measurement point would be easily applied in the clinical setting. We need to further study how the measurement region affects fat fractions. Fifth, there was bias in our patient selection process and diagnostic performance. Patients in whom supraspinatus tear was missed at MR imaging (false-negative results), patients without supraspinatus tear who were given a diagnosis of tear at MR imaging (false-positive results), and referred patients who had undergone only MR imaging performed elsewhere were excluded. We also excluded patients with technically inadequate MR imaging studies, although to some extent, this was inevitable. Sixth, we did not compare fat fractions with the Goutallier system, nor did we investigate the relationship between retears and various clinical parameters, including surgical technique. Last, κ values and intra- and interclass correlation coefficients were high for all parameters, but there were only two observers. We need to investigate the reproducibility for more observers.

In conclusion, MR imaging quantification of preoperative fat fractions within the rotator cuff muscles by using a two-point Dixon sequence may be a viable method for predicting postoperative retear. We demonstrated that the preoperative fat fractions in the supraspinatus muscle were significantly higher in patients with failed repair than in those with intact repair. Fatty degeneration of the rotator cuff muscles did not tend to progress in patients with intact repair at 1-year follow-up MR imaging, while it did tend to progress in patients with failed repair.

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