A Prospective, Quantitative Evaluation of Fatty Infiltration Before and After Rotator Cuff Repair

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Background: Current evaluation of muscle fatty infiltration has been limited by subjective classifications. Quantitative fat evaluation through magnetic resonance imaging (MRI) may allow for an improved longitudinal evaluation of the effect of surgical repair on the progression of fatty infiltration.

Hypotheses: We hypothesized that (1) patients with isolated full-thickness supraspinatus tendon tears would have less progression in fatty infiltration compared with patients with full-thickness tears of multiple tendons and (2) patients with eventual failed repair would have higher baseline levels of fatty infiltration.

Study Design: Cohort study; Level of evidence, 2.

Methods: Thirty-five patients with full-thickness rotator cuff tears were followed longitudinally. All patients received a shoulder MRI, including the iterative decomposition of echoes of asymmetric length (IDEAL) sequence for fat measurement, prior to surgical treatment and at 6 months after surgical repair. Fat fractions were recorded for all 4 rotator cuff muscles from measurements on 4 sagittal slices centered at the scapular-Y. Demographics and tear characteristics were recorded. Baseline and follow-up fat fractions were compared for patients with isolated supraspinatus tears versus multitendon tears and for patients with intact repairs versus failed repairs. Statistical significance was set at P < .05.

Results: The mean fat fractions were significantly higher at follow-up than at baseline for the supraspinatus (9.8% ± 7.0% vs 8.3% ± 5.7%; P = .025) and infraspinatus (7.4% ± 6.1% vs 5.7% ± 4.4%; P = .027) muscles. Patients with multitendon tears showed no significant change for any rotator cuff muscle after repair. Patients with isolated supraspinatus tears showed a significant progression in the supraspinatus fat fraction from baseline to follow-up (from 6.8% ± 4.9% to 8.6% ± 6.8%; P = .0083). Baseline supraspinatus fat fractions were significantly higher in patients with eventual failed repairs compared with those with intact repairs (11.7% ± 6.8% vs 7.1% ± 4.8%; P = .037).

Conclusion: Contrary to our initial hypothesis, patients with isolated supraspinatus tears showed a significant progression of fatty infiltration. Patients with eventual repair failure had higher baseline fat fractions in the supraspinatus.

Keywords: fatty infiltration; rotator cuff tears; quantitative imaging

Rotator cuff injuries are responsible for more than 4.5 million visits to physicians each year in the United States, and they can lead to pain and limitations in function. After tendon injury, the muscles of the rotator cuff undergo characteristic degenerative changes, including fatty infiltration and muscle atrophy. Advanced fatty infiltration has been shown to negatively affect outcomes after rotator cuff repair.

Multiple prior studies have attempted to determine the effects of surgical repair on the progression of fatty infiltration. Gerber et al reported that fatty infiltration progressed in all affected muscles after surgical repair of massive rotator cuff tears, although a successful repair limited the rate of progression. Gladstone et al also reported that fatty infiltration progressed, even with a successful repair. In contrast, Liem et al found no progression of fatty infiltration with intact repair of isolated supraspinatus tendon tears. Goutallier et al also showed regression of fatty...
infiltration in the setting of a successful repair. Tear size, baseline fatty infiltration, and repair integrity can all potentially contribute to the progression of muscle quality, although these relationships remain unclear with the current evidence.

The computed tomography–based Goutallier classification and the magnetic resonance imaging (MRI)–based modified Goutallier classification are commonly used to classify the severity of fatty infiltration.\textsuperscript{1,4} This scale has moderate reproducibility, with kappa values between 0.43 and 0.56 for interobserver and intraobserver variability, respectively.\textsuperscript{16} Recently, there has been increased interest in the quantitative assessment of fatty infiltration with chemical shift–based MRI.\textsuperscript{8,12,13} One method, the iterative decomposition of echoes of asymmetric length (IDEAL), has been shown to be both reproducible and to correlate with the Goutallier classification.\textsuperscript{12} By using this sequence, precise fat fraction measurements that represent the percentage of intramuscular fat can be determined within any defined region of interest. The accurate and continuous nature of this measurement may allow for improved evaluation of muscular changes over time, including after treatment for rotator cuff repair.

The purpose of this study was to evaluate the change in fatty infiltration after rotator cuff repair. We hypothesized that patients with isolated full-thickness supraspinatus tendon tears would have less progression in fatty infiltration compared with patients with full-thickness tears of 2 or more tendons. Additionally, we hypothesized that patients with eventual failed repair would have higher baseline levels of fatty infiltration.

METHODS

A total of 35 patients with full-thickness rotator cuff tears were recruited at an academic, tertiary-care sports medicine center. Inclusion criteria were age older than 18 years, a full-thickness rotator cuff, and plans for surgical repair. Exclusion criteria included an inability to obtain a pre- or postoperative MRI scan, a history of intrinsic muscular pathology, history of neural injury, or previous rotator cuff surgery to the affected shoulder. All procedures were approved by our institutional review board, and all patients provided written informed consent.

All patients completed preoperative MRI prior to surgical treatment and a follow-up imaging scan approximately 6 months after surgical repair. The endpoint of 6 months was chosen because most rotator cuff repair failures occur before this time point and because patients have completed their rehabilitation program by then.\textsuperscript{6} A standard clinical imaging sequence was obtained, including sagittal proton density–weighted images in addition to the sagittal IDEAL sequence for fat quantification. For IDEAL imaging, images were acquired and analyzed in the sagittal-oblique plane. The IDEAL algorithm with T2* correction and a 6-peak model for the fat spectrum was applied to a 3-dimensional fast gradient echo pulse sequence with 6 echoes. Parameters for this sequence included repetition time (TR) = 10.8 ms, bandwidth (BW) = 62.5 kHz, echo trail length (ETL) = 2, number of excitations (NEX) = 1, field of view (FOV) = 12 cm, alpha = 3, with a resolution of 0.33 × 0.33 × 4.0 mm\textsuperscript{3}.

Images were stored on a picture-archiving system, and image segmentation was performed with in-house, MATLAB-based (MathWorks) software as described previously.\textsuperscript{8,12} For segmentation, the scapular Y-view was identified on the proton density images and corresponding image on the IDEAL sequence, consisting of the acromion, coracoid process, and scapular body. This slice, along with 2 slices lateral and 1 slice medial, were segmented for each patient (Figure 1). Individual regions of interest were defined manually for the supraspinatus, infraspinatus, subscapularis, and teres minor muscles on each of the 4 image slices to define a volume of interest for each muscle. Regions of interest were selected within 1 to 2 mm of the outer border of the muscle to avoid partial-volume averaging from fat surrounding the muscle, and, in the case of severe muscle atrophy, perimuscular fat was not included in the region of interest. As per previous reports with these methods, the inferior border of the subscapularis region of interest was defined as 10 mm superior from the inferior tip of the scapula because of incomplete imaging of the lower subscapularis.
Tear size and retraction were measured on preoperative MRIs. At the time of surgery, the torn tendons were identified and used to divide patients according to whether they had isolated supraspinatus tears or multitendon tears. Repair integrity was evaluated on the postoperative scan and determined by a fellowship-trained musculoskeletal radiologist. A failed repair was defined as a tendon gap with fluid present on T2-weighted sequences (Sugaya type 4 or 5), in accordance with prior studies on postoperative imaging of rotator cuff repairs.12,17

Statistical analyses were performed with Stata software (StataCorp LP). Demographic data were compared between groups with unpaired t tests for continuous variables and Fisher exact tests for categorical variables. Fat fractions were compared with unpaired t tests for unmatched groups and paired t tests for longitudinal changes in the fat fraction. Proportion of fat change from baseline to follow-up was calculated as the follow-up fat fraction divided by the baseline fat fraction. These values were then compared between the tear size groups and failures by unpaired t tests.

An a priori power analysis was performed with data from previous studies to determine the appropriate sample size to detect significant changes in fat fraction values.8,12 A sample size of 15 patients per group would allow for the detection of 2.5% difference in fat fraction values to provide power level of 0.95 and alpha of 0.05. This difference was selected to allow for detection of changes within Goutallier grades based on our previous work.12

### RESULTS

The patient cohort (Table 1) included 17 female patients and 18 male patients, with an overall mean age of 61.5 ± 10.5 years. The mean time from baseline imaging to surgery was 55.5 ± 75.0 days, and the mean time from surgery to follow-up scan was 189.0 ± 24.3 days. There were 19 patients with isolated supraspinatus tears and 15 patients with multitendon tears (Table 2). The tear size and tendon retraction measurements were significantly larger in the multitendon tear group compared with the isolated supraspinatus tear group. One patient had an isolated subscapularis tear, which was excluded from the isolated supraspinatus versus multitendon analysis (but included in other analyses). There were 26 patients with an intact repair on follow-up imaging and 9 patients with a failed repair (Table 3). Tear size and retraction were significantly larger in the failed group as compared with the intact group.

Overall, the follow-up fat fractions were significantly higher than the baseline fat fractions for the supraspinatus (9.8% ± 7.0% vs 8.3% ± 5.7%; P = .025) and infraspinatus (7.4% ± 6.1% vs 5.7% ± 4.4%; P = .027) muscles (Figure 2). There was no significant difference in the fat fractions for the subscapularis (8.2% ± 4.5% vs 8.9% ± 6.5%; P = .48) or teres minor (9.9% ± 11.3% vs 9.4% ± 13.9%; P = .50) muscles.

Patients with isolated supraspinatus tears showed a significant progression in the supraspinatus fat fraction from baseline to follow-up (from 6.8% ± 4.9% to 8.6% ± 6.8%; P = .0083) (Figure 3). The infraspinatus fat fraction for patients with isolated supraspinatus tears also increased, although it did not reach statistical significance (from 5.3% ± 4.6% to 6.6% ± 6.6%; P = .074). There was no significant change in the fat fractions for the subscapularis (from 6.6% ± 3.8% to 6.6% ± 3.4%; P = .96) or teres minor (from 8.2% ± 15.5% to 8.4% ± 14.6%; P = .73) muscles. Patients with multitendon tears showed no significant change for supraspinatus (from 10.6% ± 6.0% to 11.9% ± 6.9%; P = .35), infraspinatus (from 6.4% ± 4.3% to 8.7% ± 5.4%; P = .13), subscapularis (from 12.0% ± 8.1% to 10.1% ± 5.2%; P = .43), or teres minor (from 10.0% ± 11.9% to 11.5% ± 16.9%; P = .32) between baseline and follow-up (Figure 4).

The baseline supraspinatus fat fractions were significantly higher in patients with eventual failed repairs as compared with those with intact repairs (11.7% ± 6.8% vs 7.1% ± 4.8%; P = .037) (Figure 5). The supraspinatus fat fraction trended higher in the failed group at follow-up compared with baseline, although it did not reach statistical significance (13.5% ± 8.5% vs 8.6% ± 6.1%; P = .070). Patients who had an intact repair showed a significant progression in fat fraction in the supraspinatus from baseline to follow-up (7.1% ± 4.8% vs 8.6% ± 6.1%; P = .019). There were no significant differences at either time point for the infraspinatus, subscapularis, or teres minor muscles.

### DISCUSSION

We have observed significant changes in fatty infiltration after rotator cuff repair. Notably, patients with isolated supraspinatus tears showed a significant progression in the intramuscular fat fraction. The magnitude of change was
similar for patients with larger cuff tears, although it did not reach statistical significance. Our first hypothesis was not supported by these results. The lack of significant progression in the multitendon tear group may be due to the higher variance in this group or because these patients had elevated baseline fat fractions with less potential for progression over time. Additionally, we observed higher baseline fat fractions in the supraspinatus for patients with eventual failed repairs at 6-month follow-up, consistent with one of our hypotheses.
Gladstone et al\(^3\) found that fatty infiltration progressed even in a series of 38 patients observed 1 year after rotator cuff repair, although they did find that fatty infiltration progressed in all patients after repair. Increase was observed in small, isolated supraspinatus infiltration. In a series of 220 patients treated with open repair using qualitative computed tomography–based classification. This group showed regression of fatty infiltration and 29\% retear rate of 70\% in patients with none or mild fatty infiltration. In small and medium tears.\(^{17}\) Gladstone et al\(^3\) reported a retear rate of 70\% in patients with moderate to severe fatty infiltration and 29\% in patients with none or mild fatty infiltration. In a series of 220 patients treated with open cuff repair, Goutallier et al\(^5\) reported an overall retear rate of 36\%, with a correlation between fatty infiltration stage and risk of repair failure. They found that having a Global Fatty Degeneration Index (average stage of all 4 muscles) greater than 2 was 100\% predictive of repair failure. One recent report also utilized quantitative fat imaging to evaluate progression of fatty infiltration after rotator cuff repair. Nozaki et al\(^13\) showed that patients with an eventual repair failure had higher baseline fat measurements in the supraspinatus. We observed a higher mean fat fraction at preoperative imaging for patients with an eventual repair failure compared with those with an intact repair. These patients did have, on average, larger tear sizes and greater amounts of retraction, but these results help reinforce muscle quality as an important predictor of surgical success. The mean fat fraction for patients with eventual failure (11\%), which would fall in the range of Goutallier stage 1 to 2, was lower than expected from previous studies. Going forward, quantitative fat measurements may be incorporated clinically to help surgeons and patients better understand the likelihood of a successful cuff repair.

Previous investigators have used qualitative MRI to evaluate the progression of fatty infiltration after rotator cuff repair, with mixed conclusions. Gerber et al\(^2\) demonstrated that fatty infiltration progressed in all patients after repair of massive rotator cuff tears, although they did find that an intact repair protected from more severe progression. In a series of 38 patients observed 1 year after rotator cuff repair, Gladstone et al\(^3\) found that fatty infiltration progressed even with a successful repair. On the other hand, Goutallier et al\(^5\) reviewed fatty infiltration for 57 patients after rotator cuff repair using qualitative computed tomography–based classification. This group showed regression of fatty infiltration in the supraspinatus for 6 of 14 patients with a successful repair and no improvement in fatty infiltration for the infraspinatus.\(^5\) Liem et al\(^9\) also showed that an intact repair was protective against progressive degenerative muscle changes. In our cohort, there was a small increase in fatty infiltration from baseline to follow-up. This slight increase was observed in small, isolated supraspinatus tears and also observed in patients with intact repairs. Rotator cuff repair failure is frequently encountered, with failure rates ranging from 13\% in small and medium tears to 44\% in large tears.\(^{17}\) Gladstone et al\(^3\) reported a retear rate of 70\% in patients with moderate to severe fatty infiltration and 29\% in patients with none or mild fatty infiltration. In a series of 220 patients treated with open repair, Goutallier et al\(^5\) reported an overall retear rate of 36\%, with a correlation between fatty infiltration stage and risk of repair failure. They found that having a Global Fatty Degeneration Index (average stage of all 4 muscles) greater than 2 was 100\% predictive of repair failure. One recent report also utilized quantitative fat imaging to evaluate progression of fatty infiltration after rotator cuff repair. Nozaki et al\(^13\) showed that patients with an eventual repair failure had higher baseline fat measurements in the supraspinatus. We observed a higher mean fat fraction at preoperative imaging for patients with an eventual repair failure compared with those with an intact repair. These patients did have, on average, larger tear sizes and greater amounts of retraction, but these results help reinforce muscle quality as an important predictor of surgical success. The mean fat fraction for patients with eventual failure (11\%), which would fall in the range of Goutallier stage 1 to 2, was lower than expected from previous studies. Going forward, quantitative fat measurements may be incorporated clinically to help surgeons and patients better understand the likelihood of a successful cuff repair.

This study has several strengths. First, the use of quantitative MRI allowed for the precise and reproducible measurement of intramuscular fat. Prior reported intra- and interobserver reliability measurements for methodology ranged from 0.84 to 0.92 for all muscles.\(^{12}\) This variability may be responsible for at least part of the differential conclusions observed in prior prospective studies of fatty infiltration. The method we used allows for the detection of small changes that would not be detectable with the qualitative Goutallier classification. Also, our methodology used 4 slices of each muscle. While the segmented area may vary slightly between pre- and postoperative scans, this volumetric measurement should allow for a more robust measurement of the muscle.

Our results should be interpreted with an understanding of some weaknesses. First, we have evaluated only patients treated surgically and cannot comment on the expected changes in fatty infiltration over this time frame. Future studies should evaluate muscle changes with quantitative MRI in patients with nonoperative management. Slightly different regions of the muscle may have been measured before and after surgery, especially in the setting of retracted muscle being reduced back to a more anatomic position. Regional variation in intramuscular fat has been reported in an animal model, with higher levels of fatty infiltration closer to the myotendinous junction.\(^{10}\) Additionally, immediate postoperative imaging has shown changes in muscle appearance after rotator cuff repair.\(^7\) Finally, patients with eventual failed repairs did have larger baseline tear sizes and measurements of retraction. Future studies with larger patient cohorts can help clarify the relative contributions of each factor with multivariate modeling, although this is not reliable in the current group with limited patient numbers.

**CONCLUSION**

We applied quantitative fat MRI to patients with rotator cuff injuries and observed significant changes after surgical...
treatment. Additionally, increased fat fractions in the supraspinatus were observed in patients with eventual repair failure. This methodology can be applied in future studies to better clarify the role of muscle quality on surgical outcomes and as a marker of efficacy for treatments directed toward improving muscle quality.

REFERENCES

1. Fuchs B, Weishaupt D, Zanetti M, Hodler J, Gerber C. Fatty degeneration of the muscles of the rotator cuff: Assessment by computed tomography versus magnetic resonance imaging. *J Shoulder Elbow Surg*. 1999;8:599-605.

2. Gerber C, Fuchs B, Hodler J. The results of repair of massive tears of the rotator cuff. *J Bone Joint Surg Am*. 2000;82:505-515.

3. Gladstone JN, Bishop JY, Lo IKY, Flatow EL. Fatty infiltration and atrophy of the rotator cuff do not improve after rotator cuff repair and correlate with poor functional outcome. *Am J Sports Med*. 2007;35:719-728.

4. Goutallier D, Postel J-M, Bernageau J, Lavau L, Voisin M-C. Fatty muscle degeneration in cuff ruptures: pre- and postoperative evaluation by CT scan. *Clin Orthop Relat Res*. 1994;304:78-83.

5. Goutallier D, Postel J-M, Gleyze P, Leguilloux P, Van Driessche S. Influence of cuff muscle fatty degeneration on anatomic and functional outcomes after simple suture of full-thickness tears. *J Shoulder Elbow Surg*. 2003;12:550-554.

6. Iannotti JP, Deutsch A, Green A, et al. Time to failure after rotator cuff repair: a prospective imaging study. *J Bone Joint Surg Am*. 2013;95:965-971.

7. Jo CH, Shin JS. Changes in appearance of fatty infiltration and muscle atrophy of rotator cuff muscles on magnetic resonance imaging after rotator cuff repair: establishing new time-zero traits. *Arthroscopy*. 2013;29:449-458.

8. Lee S, Lucas RM, Lansdown DA, et al. Magnetic resonance rotator cuff fat fraction and its relationship with tendon tear severity and subject characteristics. *J Shoulder Elbow Surg*. 2015;24:1442-1451.

9. Liem D, Lichtenberg S, Magosch P, Habermeyer P. Magnetic resonance imaging of arthroscopic supraspinatus tendon repair. *J Bone Joint Surg Am*. 2007;89:1770-1776.

10. Melis B, Nemoz C, Walch G. Muscle fatty infiltration in rotator cuff tears: descriptive analysis of 1688 cases. *Orthop Traumatol Surg Res*. 2009;95:319-324.

11. Melis B, Wall B, Walch G. Natural history of infraspinatus fatty infiltration in rotator cuff tears. *J Shoulder Elbow Surg*. 2010;19:757-763.

12. Nardo L, Karampinos DC, Lansdown DA, et al. Quantitative assessment of fat infiltration in the rotator cuff muscles using water-fat MRI. *J Magn Reson Imaging*. 2014;39:1178-1185.

13. Nozaki T, Tasaki A, Horiuchi S, et al. 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. *Radiology*. 2016;280:500-509.

14. Oh LS, Wolf BR, Hall MP, Levy BA, Marx RG. Indications for rotator cuff repair: a systematic review. *Clin Orthop Relat Res*. 2007;455:52-63.

15. Rubino LJ, Stills HF Jr, Sprott DC, Crosby LA. Fatty infiltration of the torn rotator cuff worsens over time in a rabbit model. *Arthroscopy*. 2007;23:717-722.

16. Slabaugh MA, Friel NA, Karas V, Romeo AA, Verma NN, Cole BJ. Interobserver and intraobserver reliability of the Goutallier classification using magnetic resonance imaging; proposal of a simplified classification system to increase reliability. *Am J Sports Med*. 2012;40:1728-1734.

17. Sugaya H, Maeda K, Matsuki K, Morishita J. Functional and structural outcome after arthroscopic full-thickness rotator cuff repair: single-row versus dual-row fixation. *Arthroscopy*. 2005;21:1307-1316.

18. Sugaya H, Maeda K, Matsuki K, Morishishi J. Repair integrity and functional outcome after arthroscopic double-row rotator cuff repair. *J Bone Joint Surg Am*. 2007;89:953-960.