



Preoperative IDEAL (Iterative Decomposition of Echoes of Asymmetrical Length) magnetic resonance imaging rotator cuff muscle fat fractions are associated with rotator cuff repair outcomes

Drew A. Lansdown, MD^{a,*}, Cyrus Morrison^a, Musa B. Zaid, MD^a, Rina Patel, MD^b, Alan L. Zhang, MD^a, Christina R. Allen, MD^a, Brian T. Feeley, MD^a, C. Benjamin Ma, MD^a

^aDepartment of Orthopedic Surgery, Sports Medicine & Shoulder Surgery, University of California, San Francisco, San Francisco, CA, USA

^bDepartment of Radiology & Biomedical Imaging, University of California, San Francisco, San Francisco, CA, USA

Background and hypothesis: IDEAL (Iterative Decomposition of Echoes of Asymmetrical Length) imaging is a magnetic resonance imaging sequence that precisely measures rotator cuff muscle fatty infiltration. The influence of lower levels of fatty infiltration on outcomes after rotator cuff repair remains unclear. We hypothesized that increased preoperative fat fractions would be associated with inferior clinical outcomes after rotator cuff repair.

Methods: We retrospectively identified patients who underwent arthroscopic rotator cuff repair with preoperative IDEAL imaging. Patients completed the Patient-Reported Outcomes Measurement Information System (PROMIS) Upper Extremity computer adaptive survey at a minimum of 2 years after repair. Muscle segmentation was performed on 4 consecutive slices. Correlations between intramuscular fat fractions and PROMIS scores were determined. Patients were grouped by PROMIS scores of 50 or greater and scores lower than 50 for comparison of fat fractions. Multivariate linear regression was performed to model PROMIS scores as a function of demographic characteristics, tear size, and fat fractions. Significance was defined as $P < .05$.

Results: Eighty patients were included (mean follow-up, 42.5 ± 10.7 months). Postoperative PROMIS scores were significantly inversely correlated with the infraspinatus ($\rho = -0.25$, $P = .02$) and subscapularis ($\rho = -0.29$, $P = .009$) fat fractions. The infraspinatus ($7.2\% \pm 4.9\%$ vs. $5.2\% \pm 3.0\%$, $P = .046$) and subscapularis ($10.4\% \pm 5.1\%$ vs. $8.2\% \pm 5.0\%$, $P = .001$) fat fractions were significantly higher for patients with low PROMIS scores vs. those with PROMIS scores of 50 or greater. In multivariate modeling, the infraspinatus fat fraction ($\beta = -0.68$, $P = .029$) was the only significant independent predictor of postoperative PROMIS score.

Conclusion: Intramuscular fat as determined by quantitative magnetic resonance imaging is an important factor in postoperative outcomes even in patients with lower levels of preoperative fatty infiltration.

This study was approved by the University of California, San Francisco Committee on Human Research (no. 13-12250).

*Reprint requests: Drew A. Lansdown, MD, 1500 Owens St, Ste 170, San Francisco, CA 94158, USA.

E-mail address: Drew.lansdown@ucsf.edu (D.A. Lansdown).

Level of evidence: Level II; Retrospective Design; Prognosis Study

© 2019 Journal of Shoulder and Elbow Surgery Board of Trustees. All rights reserved.

Keywords: Rotator cuff repair outcomes; fatty infiltration; quantitative imaging; muscle quality; infraspinatus; IDEAL MRI

Fatty infiltration occurs in the rotator cuff muscles following tendon injury. Severe fatty infiltration negatively impacts outcomes after surgical repair and develops over the course of 3 to 5 years.^{18,19} These degenerative changes do not appear to be reversible, even with surgical repair of the torn tendon^{5,7} and may lead to decreased strength owing to loss of contractile force.^{11,26}

The Goutallier classification is most commonly used in the clinical setting to grade the severity of fatty infiltration.⁸ First described using computed tomography, this classification system was validated by Fuchs et al⁴ for magnetic resonance imaging (MRI). The semiquantitative scale, however, is limited by its intrauser and interuser reproducibility, which results in difficulty in understanding the complete influence that muscle quality has on postoperative outcomes.^{14,25} Nevertheless, the Goutallier classification is often used for surgical decision making given the poor outcomes observed in patients with advanced fatty infiltration.^{7,9,13}

Various quantitative MRI sequences have been applied recently to evaluate rotator cuff fatty infiltration and can precisely measure intramuscular fat.^{1,6,10,16,21} The IDEAL (Iterative Decomposition of Echoes of Asymmetrical Length) sequence is a chemical shift–based method for fat and water separation.²³ The fat fractions measured from this sequence have been correlated with the Goutallier classification and related to tear size and tendon retraction.^{12,20} It remains unclear, however, how these measurements relate to patient-reported outcomes after rotator cuff repair.

The purpose of this study was to investigate the relationship between preoperative fat fraction measurements and postoperative outcomes after rotator cuff repair. We hypothesized that increased preoperative fat fractions would be associated with inferior clinical outcomes.

Methods

A retrospective evaluation was performed using Current Procedural Terminology codes to identify patients who had undergone rotator cuff repair by 1 of 4 fellowship-trained sports medicine surgeons between August 2012 and September 2016. During this time frame, the IDEAL sequence was routinely part of the clinical shoulder MRI protocol at our institution. Inclusion criteria were rotator cuff repair, a preoperative MRI scan within 6 months of surgical treatment with the IDEAL sequence added, and adequate imaging quality to evaluate the rotator cuff musculature on sagittal-oblique images. Exclusion criteria were revision surgery and incomplete preoperative imaging. There were 573 rotator cuff repairs performed in this time frame. A preoperative MRI scan with the IDEAL sequence was available for 106 patients.

In general, patients underwent shoulder arthroscopy in the beach-chair position. The rotator cuff was repaired with a single-row or transosseous-equivalent construct based on the treating surgeon's determination of appropriate fixation. Patients were immobilized in an abduction sling for 6 weeks after surgery and began physical therapy with a standardized rehabilitation protocol with progression of active range of motion at 6 weeks after surgery, light strengthening at 3 month after surgery, and return to full activities generally at 6 months after surgery.

Patients were contacted postoperatively for participation in this study at a minimum of 2 years after surgical repair. After providing documented informed consent, patients completed the Patient-Reported Outcomes Measurement Information System (PROMIS) Upper Extremity (UE) survey. The PROMIS-UE survey is a validated, computer adaptive test that allows for the efficient evaluation of patient outcomes related to upper-extremity function.²² The population average for this score is 50 with a standard deviation of 10.²

The electronic medical record was reviewed to collect patient demographic characteristics, including age, sex, and body mass index (BMI). Preoperative MRI scans were evaluated by a fellowship-trained musculoskeletal radiologist (R.P.) to determine dimensions of full-thickness tear involvement and tendon retraction.

The preoperative MRI scan was completed on a standard 3-T clinical scanner (MR 750; GE Healthcare; Milwaukee, WI, USA) with an 8-channel shoulder surface coil (Clinical MR Solutions, Brookfield, WI, USA). Standard clinical images were acquired, including coronal-oblique T1 and T2 fat saturation, axial-oblique proton density and T2 fat saturation, and sagittal-oblique fat-suppressed, T2 fast-spin echo sequences and proton density–weighted fast-spin echo sequences. The IDEAL scan with T2* correction was added to this protocol in the sagittal-oblique orientation (slice thickness, 4 mm; field of view, 12 cm; in-plane resolution, 0.468 × 0.468 mm) similarly to a prior published protocol for rotator cuff imaging, from which an IDEAL fat fraction map was reconstructed.^{11,12,20}

Fat fraction measurements were made by 1 of 3 trained observers (D.A.L., C.M. and M.B.Z.) using previously validated methodology (Fig. 1).^{11,12,20} All final segmentations were reviewed by 1 observer (D.A.L.) to ensure consistency. Reviewers were blinded to the patient-reported outcome scores. Fat fractions were measured through manual definition of the rotator cuff muscles on 4 consecutive slices. The first slice was selected where the scapular Y was visible (coracoid, acromion, and scapular body), with 1 slice medial and 2 slices lateral to this. The rotator cuff muscle regions of interest were segmented on the IDEAL images using the proton density scans for anatomic reference. For the subscapularis, the inferior aspect of the muscle was excluded as in prior studies because of field inhomogeneities in this region.

Statistical analyses were performed with Stata software (version 14; StataCorp, Austin, TX, USA). Spearman rank correlation tests were used to investigate the relationship between fat fractions for the rotator cuff muscles and the PROMIS-UE scores.

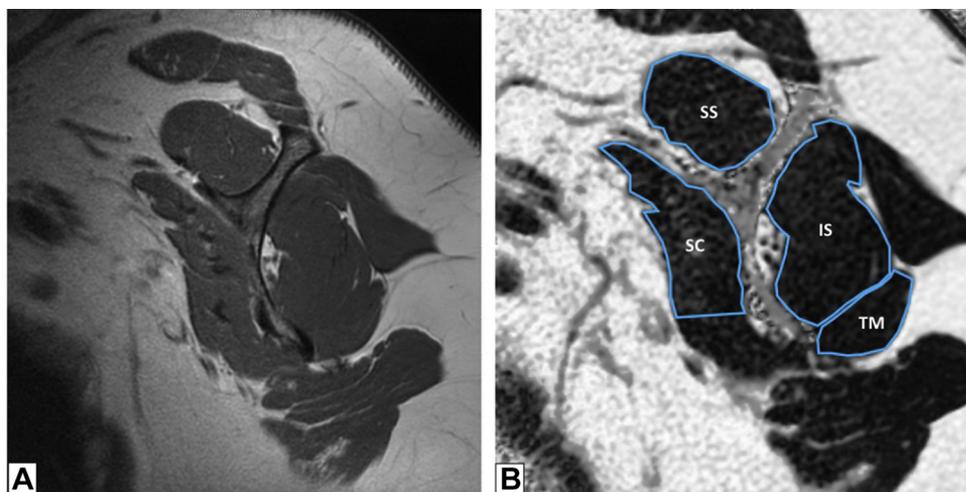


Figure 1 The sagittal-oblique proton density sequence (A) and IDEAL (Iterative Decomposition of Echoes of Asymmetrical Length) sequence (B) are shown with segmentations drawn for the supraspinatus (SS), infraspinatus (IS), subscapularis (SC), and teres minor (TM). The fat fractions for this patient were 8.7% for the SS, 7.5% for the IS, 10.9% for the SC, and 3.6% for the TM. Muscle segmentation lines are drawn larger for representation purposes.

Patients were then analyzed in 2 groups based on their post-operative PROMIS-UE scores, separated into those with scores of 50 or greater and those with scores lower than 50 because the population average is expected to be 50. Shapiro-Wilk tests were used to check normality of the fat fraction measurements. Given non-normal distributions, Mann-Whitney *U* tests were used to compare fat fractions between patients with PROMIS-UE scores of 50 or greater and those with scores lower than 50. Potential empirical cut points were derived using receiver operating characteristic (ROC) curve analysis and the methods described by Liu¹⁵ to determine the ability of preoperative fat fractions to appropriately classify patients based on PROMIS-UE scores of 50 or greater vs. scores lower than 50. Finally, multivariate linear regression modeling was performed with PROMIS-UE scores as the dependent variable and patient age, sex, BMI, muscle fat fractions, and preoperative tear size as independent predictor variables. Significance was defined as $P < .05$.

Results

A total of 80 patients (75% follow-up rate) completed the PROMIS-UE survey postoperatively and had available preoperative MRI scans with the IDEAL sequence. There were 32 female and 48 male patients. Demographic characteristics are displayed in Table I. The mean rotator cuff tear size was 16.3 ± 14.1 mm. There were 66 full-thickness supraspinatus tears, 3 full-thickness infraspinatus tears, and 44 subscapularis tears. The mean preoperative fat fractions were $8.5\% \pm 5.4\%$ for the supraspinatus, $6.0\% \pm 4.0\%$ for the infraspinatus, $9.0\% \pm 5.1\%$ for the subscapularis, and $6.6\% \pm 6.0\%$ for the teres minor. The mean follow-up period was 42.5 ± 10.7 months. The mean postoperative PROMIS-UE score was 50.3 ± 7.3 . There were 31 patients with PROMIS-UE scores lower than 50 and 49 patients with scores of 50 or greater.

Postoperative PROMIS-UE scores were significantly correlated with the infraspinatus fat fraction ($\rho = -0.25$,

$P = .02$) and subscapularis fat fraction ($\rho = -0.29$, $P = .009$) (Table II). Of the demographic variables, only BMI showed a significant correlation with postoperative PROMIS-UE scores ($\rho = -0.23$, $P = .044$).

The infraspinatus fat fraction was significantly higher for patients with low PROMIS-UE scores relative to those with PROMIS-UE of 50 or greater ($7.2\% \pm 4.9\%$ vs. $5.2\% \pm 3.0\%$, $P = .046$) (Fig. 2). The subscapularis fat fraction was also significantly higher for patients with low PROMIS-UE scores relative to those with PROMIS-UE scores of 50 or greater ($10.4\% \pm 5.1\%$ vs. $8.2\% \pm 5.0\%$, $P = .001$). There were no significant differences between these groups regarding age, sex, BMI, tear size, or retraction (Table III).

ROC curve analysis found the greatest area under the curve (AUC) for the subscapularis fat fraction in discriminating low vs. high PROMIS-UE scores (Fig. 3). The optimal cut point was 6.6% with a sensitivity of 0.84, specificity of 0.53, and AUC of 0.68. The optimal cut point for the infraspinatus fat fraction was 4.6% (AUC, 0.63) with a sensitivity of 0.59 and specificity of 0.68. In controlling for age, BMI, sex, total tear size, and rotator cuff muscle quality, multivariate linear regression modeling identified the infraspinatus fat fraction ($\beta = -0.68$, $P = .029$) as the only significant independent predictor of postoperative PROMIS-UE scores.

Discussion

Significant relationships were found between preoperative infraspinatus and subscapularis muscle quality and PROMIS-UE scores following rotator cuff repair. The infraspinatus fat fraction was the only significant predictor of postoperative outcomes when accounting for patient demographic variables and rotator cuff tear size. These results highlight the value of precise measurement of fatty

Table I Patient demographic characteristics

Variable names	Mean	SD
Age, yr	62.3	7.5
BMI, kg/m ²	26.7	4.9
Tear size, mm	16.3	14.1
Retraction, mm	15.9	14.5
Supraspinatus fat fraction, %	8.53	5.34
Infraspinatus fat fraction, %	5.99	3.96
Subscapularis fat fraction, %	9.04	5.14
Teres minor fat fraction, %	6.55	6.03
Postoperative PROMIS-UE score	51.29	7.33

SD, standard deviation; BMI, body mass index; PROMIS-UE, Patient-Reported Outcomes Measurement Information System Upper Extremity.

Table II Correlations between rotator cuff fat fractions, demographic variables, and tear characteristics and postoperative PROMIS-UE scores

	Spearman ρ	P value
Supraspinatus fat fraction	-0.075	.51
Infraspinatus fat fraction	-0.25	.024 *
Subscapularis fat fraction	-0.29	.0092 *
Teres minor fat fraction	0.11	.31
Tear size	-0.14	.21
Retraction	-0.15	.18
Age	0.014	.9
Body mass index	-0.23	.044 *

PROMIS-UE, Patient-Reported Outcomes Measurement Information System Upper Extremity.

* Statistically significant.

infiltration and the importance of even small increases in intramuscular fat regarding eventual outcomes after rotator cuff repair.

The significance of advanced fatty infiltration regarding outcomes and retear rates after rotator cuff repair has been reported in prior clinical studies. Liem et al¹³ reported on postsurgical outcomes of 53 patients with supraspinatus tears, finding that Goutallier grade 2 was a predictor of retear. Similarly, Goutallier et al⁹ identified an average Goutallier grade of 2 or higher as 100% predictive of retear after open repair of a full-thickness rotator cuff tear. Gladstone et al⁷ identified infraspinatus muscle quality as strongly associated with functional outcomes after rotator cuff repair, with supraspinatus muscle quality also influencing final outcomes. This study analyzed patients with a modified Goutallier classification. Lansdown et al¹¹ demonstrated that elevated preoperative IDEAL measurements are associated with an increased risk of MRI-based retear at 6 months after surgery. Importantly, the infraspinatus fat fraction in our study was the only variable in the multivariate regression model that was a significant predictor of the postoperative PROMIS-UE score, which is consistent with prior reports.

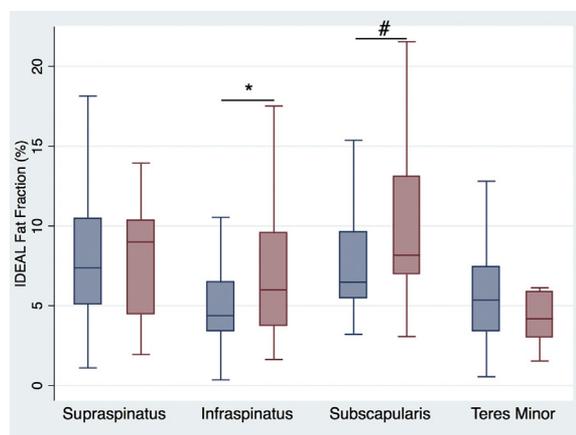


Figure 2 Box plots for the preoperative fat fractions for the supraspinatus, infraspinatus, subscapularis, and teres minor are shown for patients with Patient-Reported Outcomes Measurement Information System Upper Extremity scores lower than 50 (n = 31) and scores of 50 or greater (n = 49) at 2 years postoperatively. Each box represents the interquartile range with whiskers extending to 1.5 times the interquartile range. The line within the box represents the median of the measurement. *P = .046 and #P = .001 by Mann-Whitney U tests. IDEAL, Iterative Decomposition of Echoes of Asymmetrical Length.

Quantitative MRI allows for the precise determination of fat content within the rotator cuff muscles. The IDEAL sequence was selected for use in this study because it provides excellent definition between fat and water and is readily available in clinical practice. The methodology has been previously validated; the fat fractions correlate with the Goutallier classification and with measurements of rotator cuff tear size and tendon retraction.^{12,20} The mean values for the infraspinatus fat fraction in patients with PROMIS scores above or below 50, for instance, would both fall in the range of Goutallier grade 1 to 2 (Fig. 1, B).²⁰

The ROC curve analysis in this study could not identify fat fraction cut points that can predict outcomes with an adequate sensitivity, specificity, or AUC to use routinely in clinical practice. The subscapularis showed the best diagnostic performance but with a specificity of just 53% for predicting patients with PROMIS-UE scores below 50. This finding is also supported by prior reports, as good clinical outcomes may still be achieved with rotator cuff repair in patients with advanced fatty infiltration.³ A strict cutoff for the purposes of recommending rotator cuff repair with expected satisfactory outcomes could not be determined with the results from this study. Although muscle quality is clearly an important factor in postoperative outcomes, it is not the only determinant. We did control for tear size and patient age in the multivariate regression analysis; however, other patient-specific factors will undoubtedly influence eventual outcomes.^{17,24} The preoperative fat fractions can, however, be used in counseling patients regarding expected outcomes and consideration of alternative treatment

Table III Comparisons of demographic variables, tear characteristics, and rotator cuff fat fractions between patients with PROMIS-UE scores of 50 or greater and those with PROMIS-UE scores lower than 50

	PROMIS-UE score \geq 50 (n = 49)		PROMIS-UE score < 50 (n = 31)		P value
	Mean or n (%)	SD	Mean or n (%)	SD	
Age, yr	62.2	6.95	62.3	8.5	.81
BMI, kg/m ²	26	4.4	27.8	5.4	.11
Total tear size, mm	15.2	13.5	17.8	15.2	.51
Maximum retraction, mm	14.8	12.8	17.7	16.9	.52
Sex					
Female	19 (39)		13 (42)		.82
Male	30 (61)		18 (58)		
Supraspinatus fat fraction, %	8.72	5.71	8.24	4.78	.84
Infraspinatus fat fraction, %	5.21	3.02	7.24	4.92	.046*
Subscapularis fat fraction, %	8.17	5.02	10.41	5.11	.001*
Teres minor fat fraction, %	6.76	6.41	6.23	5.49	.24

PROMIS-UE, Patient-Reported Outcomes Measurement Information System Upper Extremity; SD, standard deviation; BMI, body mass index. P values are from Mann-Whitney U tests for all characteristics except BMI (Student t test) and the sex distribution (Fisher exact test).

* Statistically significant.

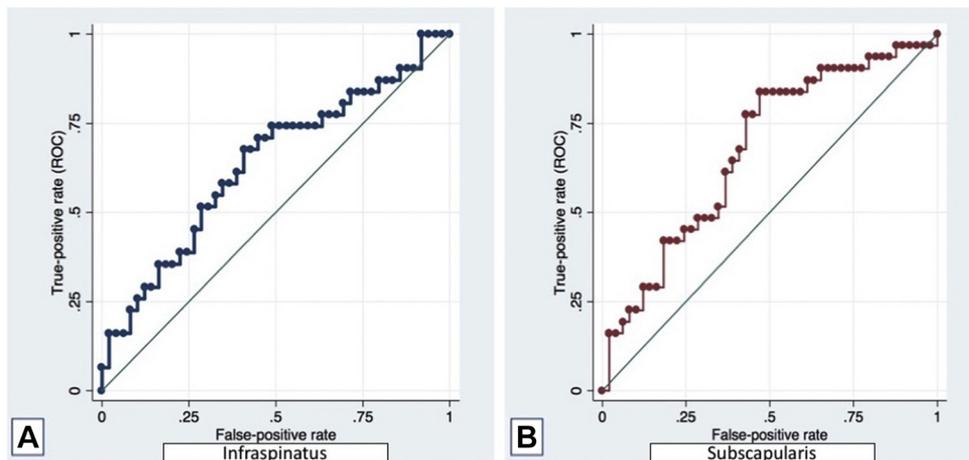


Figure 3 Receiver operating characteristic (ROC) curves are displayed for use of the fat fraction from the infraspinatus (A) and subscapularis (B) to distinguish patients with above- and below-average Patient-Reported Outcomes Measurement Information System Upper Extremity scores. The area under the curve is 0.68 for the subscapularis fat fraction and 0.63 for the infraspinatus fat fraction.

options, in addition to being an important tool for future research on rotator cuff repairs.

This study should be interpreted with an understanding of its limitations. First, patients were contacted retrospectively, and there were no preoperative measures of patient function. This group of patients also does not comprise all patients treated with rotator cuff repair. Patients were selected for inclusion if their preoperative scan included IDEAL imaging, and we would not anticipate that this would introduce selection bias. We also did not perform postoperative imaging, so we cannot evaluate for potential rotator cuff retears or postoperative progression of fatty infiltration. Outcomes are certainly influenced by multiple factors that were not controlled for in this study, including but not limited to postoperative compliance, participation in rehabilitation, and systemic medical conditions.

Conclusion

Intramuscular fat is an important factor in postoperative outcomes even in patients with lower levels of preoperative fatty infiltration. Quantitative MRI offers improved determination of muscle quality that relates to eventual postoperative outcomes.

Acknowledgments

The authors acknowledge Mya Sandi Aung and Kristina Borak for their assistance as research coordinators in data collection.

Disclaimer

Drew A. Lansdown receives fellowship-related educational and research support from Arthrex and Smith & Nephew.

Alan L. Zhang receives personal fees from Stryker.

Brian T. Feeley reports research grants from Zimmer Biomet. He is an associate editor for the *Journal of Shoulder and Elbow Surgery* and receives funding from the National Institutes of Health.

C. Benjamin Ma reports research grants from Zimmer Biomet, grants from Anika, personal fees from ConMed Linvatec, grants and personal fees from Histogenics, personal fees from Medacta, grants from Samumed, personal fees from SLACK, personal fees from Stryker, and grants from Zimmer outside the submitted work.

The other authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

References

- Agten CA, Roskopf AB, Gerber C, Pfirrmann CW. Quantification of early fatty infiltration of the rotator cuff muscles: comparison of multi-echo Dixon with single-voxel MR spectroscopy. *Eur Radiol* 2016;26:3719-27. <https://doi.org/10.1007/s00330-015-4144-y>
- Brodke DJ, Saltzman CL, Brodke DS. PROMIS for orthopaedic outcomes measurement. *J Am Acad Orthop Surg* 2016;24:744-9. <https://doi.org/10.5435/JAAOS-D-15-00404>
- Burkhart SS, Barth JR, Richards DP, Zlatkin MB, Larsen M. Arthroscopic repair of massive rotator cuff tears with stage 3 and 4 fatty degeneration. *Arthroscopy* 2007;23:347-54. <https://doi.org/10.1016/j.arthro.2006.12.012>
- 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.
- Gerber C, Fuchs B, Hodler J. The results of repair of massive tears of the rotator cuff. *J Bone Joint Surg Am* 2000;82:505-15.
- Giambini H, Hatta T, Gorny KR, Widholm P, Karlsson A, Leinhard OD, et al. Intramuscular fat infiltration evaluated by magnetic resonance imaging predicts the extensibility of the supraspinatus muscle. *Muscle Nerve* 2018;57:129-35. <https://doi.org/10.1002/mus.25673>
- 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;35:719-28. <https://doi.org/10.1177/0363546506297539>
- 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.
- 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;12:550-4. [https://doi.org/10.1016/S1058-2746\(03\)00211-8](https://doi.org/10.1016/S1058-2746(03)00211-8)
- Horiuchi S, Nozaki T, Tasaki A, Yamakawa A, Kaneko Y, Hara T, et al. Reliability of MR quantification of rotator cuff muscle fatty degeneration using a 2-point Dixon technique in comparison with the Goutallier classification: validation study by multiple readers. *Acad Radiol* 2017;24:1343-51. <https://doi.org/10.1016/j.acra.2017.03.026>
- Lansdown DA, Lee S, Sam C, Krug R, Feeley BT, Ma CB. A prospective, quantitative evaluation of fatty infiltration before and after rotator cuff repair. *Orthop J Sports Med* 2017;5. <https://doi.org/10.1177/2325967117718537>. 2325967117718537.
- Lee S, Lucas RM, Lansdown DA, Nardo L, Lai A, Link TM, et al. Magnetic resonance rotator cuff fat fraction and its relationship with tendon tear severity and subject characteristics. *J Shoulder Elbow Surg* 2015;24:1442-51. <https://doi.org/10.1016/j.jse.2015.01.013>
- Liem D, Lichtenberg S, Magosch P, Habermeyer P. Magnetic resonance imaging of arthroscopic supraspinatus tendon repair. *J Bone Joint Surg Am* 2007;89:1770-6. <https://doi.org/10.2106/JBJS.F.00749>
- Lippe J, Spang JT, Leger RR, Arciero RA, Mazzocca AD, Shea KP. Inter-rater agreement of the Goutallier, Patte, and Warner classification scores using preoperative magnetic resonance imaging in patients with rotator cuff tears. *Arthroscopy* 2012;28:154-9. <https://doi.org/10.1016/j.arthro.2011.07.016>
- Liu X. Classification accuracy and cut point selection. *Stat Med* 2012;31:2676-86. <https://doi.org/10.1002/sim.4509>
- Matsumura N, Oguro S, Okuda S, Jinzaki M, Matsumoto M, Nakamura M, et al. Quantitative assessment of fatty infiltration and muscle volume of the rotator cuff muscles using 3-dimensional 2-point Dixon magnetic resonance imaging. *J Shoulder Elbow Surg* 2017;26:e309-18. <https://doi.org/10.1016/j.jse.2017.03.019>
- McElvany MD, McGoldrick E, Gee AO, Neradilek MB, Matsen FA 3rd. Rotator cuff repair: published evidence on factors associated with repair integrity and clinical outcome. *Am J Sports Med* 2015;43:491-500. <https://doi.org/10.1177/0363546514529644>
- Melis B, Nemoz C, Walch G. Muscle fatty infiltration in rotator cuff tears: descriptive analysis of 1688 cases. *Orthop Traumatol Surg Res* 2009;95:319-24. <https://doi.org/10.1016/j.otsr.2009.05.001>
- Melis B, Wall B, Walch G. Natural history of infraspinatus fatty infiltration in rotator cuff tears. *J Shoulder Elbow Surg* 2010;19:757-63. <https://doi.org/10.1016/j.jse.2009.12.002>
- Nardo L, Karampinos DC, Lansdown DA, Carballido-Gamio J, Lee S, Maroldi R, et al. Quantitative assessment of fat infiltration in the rotator cuff muscles using water-fat MRI. *J Magn Reson Imaging* 2014;39:1178-85. <https://doi.org/10.1002/jmri.24278>
- Nozaki T, Tasaki A, Horiuchi S, Ochi J, Starkey J, Hara T, 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;280:500-9. <https://doi.org/10.1148/radiol.2016151789>
- Patterson BM, Orvets ND, Aleem AW, Keener JD, Calfee RP, Nixon DC, et al. Correlation of Patient-Reported Outcomes Measurement Information System (PROMIS) scores with legacy patient-reported outcome scores in patients undergoing rotator cuff repair. *J Shoulder Elbow Surg* 2018;27:S17-23. <https://doi.org/10.1016/j.jse.2018.03.023>
- Reeder SB, Pineda AR, Wen Z, Shimakawa A, Yu H, Brittain JH, et al. Iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL): application with fast spin-echo imaging. *Magn Reson Med* 2005;54:636-44. <https://doi.org/10.1002/mrm.20624>
- Saccomanno MF, Sircana G, Cazzato G, Donati F, Randelli P, Milano G. Prognostic factors influencing the outcome of rotator cuff repair: a systematic review. *Knee Surg Sports Traumatol Arthrosc* 2016;24:3809-19. <https://doi.org/10.1007/s00167-015-3700-y>
- 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;40:1728-34. <https://doi.org/10.1177/0363546512452714>
- Valencia AP, Lai JK, Iyer SR, Mistretta KL, Spangenburg EE, Davis DL, et al. Fatty infiltration is a prognostic marker of muscle function after rotator cuff tear. *Am J Sports Med* 2018;46:2161-9. <https://doi.org/10.1177/0363546518769267>