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Agreement between intraoperative and magnetic resonance imaging assessments of rotator cuff pathology and 2 magnetic resonance imaging-based assessments of supraspinatus muscle atrophy

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A R T I C L E I N F O

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Inter-rater agreement
Tear characteristics
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Warner classification
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Level of Evidence: Level III; Diagnostic Study

Background: Magnetic resonance imaging (MRI)-based rotator cuff assessment is often qualitative and subjective; few studies have tried to validate such preoperative assessments. This study investigates relationships of preoperative MRI assessments made by conventional approaches to intraoperative findings of tear type, location, and size or MRI-assessed muscle occupation ratio.

Methods: Intraoperatively, surgeons assessed tear type, location, anterior-posterior (AP) width, and medial-lateral length in 102 rotator cuff repair patients. Two musculoskeletal radiologists independently assessed the preoperative MRI scans for these same parameters and supraspinatus muscle atrophy by both Warner classification and quantitative occupation ratio. Exact agreement proportions, kappa statistics, and correlation coefficients were used to quantify agreement relationships.

Results: Agreement between MRI readers' and surgeons' observations of tear status averaged 93% with $\kappa = 0.38$, and that of tear location averaged 77% with $\kappa = 0.50$. Concordance correlations of MRI and intraoperative measures of anterior-posterior and medial-lateral tear length averaged 0.59 and 0.56 across readers, respectively. Despite excellent interrater agreement on Warner classification (exact agreement proportion 0.91) and occupation ratio (concordance correlation 0.93) separately, correlations between these 2 measures were −0.54 and −0.64 for the 2 readers, respectively. Patients with Warner grade 0 had occupation ratios ranging from 0.5 to 1.5.

Conclusion: Correlations of preoperative MRI tear dimensions and muscle atrophy assessed by conventional approaches with intraoperatively measured tear dimensions and quantitative occupation ratio, respectively, were only fair. Since tear size and muscle atrophy are known strong predictors of outcomes following rotator cuff repair that may influence treatment decisions, surgeons need to be aware of the limitations of MRI methods. Continued development and validation of quantitative preoperative imaging methods to accurately assess these parameters are needed to improve surgical planning and prognosis.

Magnetic resonance imaging (MRI) is considered the standard of care modality for rotator cuff imaging, with excellent sensitivity and specificity for diagnosing full-thickness rotator cuff tears.[4] MRI assessment of rotator cuff tear type (partial- vs. full-thickness tear), size, and retraction, as well as the presence of muscle atrophy and fatty infiltration, plays an important role in diagnosis, treatment,

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surgical decision-making, and prognosis. For example, these tear characteristics are used to determine reparability and surgical approach and are of significant prognostic value. Accurate interpretation of preoperative shoulder MRI is therefore critical to clinical care.

Several studies have shown varying degrees of interrater agreement among radiologists in assessing rotator cuff parameters from MRI. Interreader agreement rates are generally acceptable for tear size and type,[10,19] but subjective MRI assessments of muscle atrophy and fatty infiltration using Warner and Goutallier scales have shown only fair and moderate inter-reader reliability, respectively.[14] We have recently reported on the interrater agreement between 2 musculoskeletal radiologists in making MRI assessments of the rotator cuff preoperatively and during the first postoperative year following the rotator cuff repair (RCR) in 42 patients.[15] Despite reasonable inter-reader reliability on most assessments, mutually exclusive and potentially clinically consequential disagreements in preoperatively classifying tear integrity (eg, a tear is classified as intact by one reader and torn by the other) did occasionally occur. Collectively, these studies demonstrate the degree of ambiguity in MRI evaluation of rotator cuff tear pathology and a need for continued refinement and validation of MRI-based assessments.

The few studies attempting to validate the accuracy of preoperative MRI assessments relative to intraoperative findings reported varying degrees of agreement, ranging from no agreement for tear type,[5] 63%-80% for tear dimensions,[21] and 91%-98% for tear shape.[3,5] Furthermore, the conventional approaches to MRI-based rotator cuff *muscle* assessment are qualitative classifications that cannot be validated via intraoperative observation, so alternate validation methods are needed. For example, the Warner classification of muscle atrophy subjectively considers the contour of the supraspinatus muscle relative to the fossa.[23] While MRI-based measurement of the actual muscle and fossa cross-sectional areas (CSAs) has been used to quantitatively assess muscle atrophy in select research studies,[9,11,13,18,22,25] the use of a measured "occupation ratio" as a means to validate the standard Warner grading has not been fully explored.

Hence, the objective of the current study is to validate preoperative MRI assessments made by conventional approaches with direct intraoperative observation of tear type, location, and size or MRI-assessed muscle occupation ratio. We then discuss the implications of our findings for interpretation of MRI-derived preoperative rotator cuff tear pathology and clinical decision-making.

Methods

Study design

This study was performed on a convenience cohort of 102 patients prospectively enrolled in an institutional review board-approved study of the clinical course of patients after primary RCR at our institution between 2016 and 2020 (https://clinicaltrials.gov/ct2/show/NCT02716441). Patients with 1- to 5-cm tears of the supraspinatus and/or infraspinatus tendons that were fully reparable by a double-row or equivalent technique using *nonmetallic* anchors (type and manufacturer at the discretion of the surgeon) were included. Exclusion criteria were partial-thickness tears of the supraspinatus and/or infraspinatus tendons that were not débrided to full thickness at surgery, subscapularis tendon or labral tear requiring repair, advanced muscle fatty atrophy or glenohumeral arthritis, or revision surgery. Each patient had a preoperative shoulder MRI obtained within 3 months of surgery (median 33 days, range 7-107 days), and patients underwent arthroscopic RCR by 1 of 8 fellowship-trained shoulder surgeons. Intraoperatively, the surgeons assessed tear classification, location, and size using a standardized protocol. The preoperative MRIs were deidentified and independently reviewed for the same parameters by 2 fellowship-trained musculoskeletal radiologists with 33 and 16 years of experience, respectively. Interrater agreement of the assessments of preoperative and postoperative MRIs from 42 of these 102 patients was previously reported[15] and is computed and reported herein for all 102 preoperative cases because interobserver variation is an inherent component of discrepancies between MRI and intraoperative assessments. Correlations between preoperative MRI-based and intraoperative assessments, and between 2 MRI-based methods of assessing preoperative supraspinatus muscle CSA, are described.

Preoperative magnetic resonance imaging

All MRI studies were obtained using a dedicated shoulder coil at 1.5T or 3T. Fifty (49%) MRIs were obtained at our institution at 1.5T (Aera, Symphony, Avanto, or Espree; Siemens Medical Solutions, Malvern, PA, USA). Fifty-two (51%) preexisting preoperative shoulder MRIs from outside centers (31 performed at 1.5T, 20 at 3T, and 1 at 1.0T) were also accepted into the study after screening for adequate quality and completeness for making MRI assessments; patients with outside MRIs deemed of inadequate quality had repeat preoperative imaging at our institution. Patients were imaged under the routine clinical conditions of lying supine with their arm at the side, with hand on the thigh and thumb facing upward. All MRIs included oblique coronal and sagittal intermediate-weighted (echo time [TE] 36-38 ms, repetition time [TR] 2340-3400 ms) images with fat suppression, oblique coronal T2-weighted images without fat suppression (T2W, TE 60-65 ms, TR 2040-3200 ms), and sagittal T1-weighted (T1W, TE 10-14 ms, TR 526-907 ms) images without fat suppression. Field of view was 12 cm with a 3- to 4-mm slice thickness, interslice gap of 15%-20%, and in-plane resolution of 0.23×0.23 mm. Sagittal images were prescribed to include at least 1 image medial to the spinoglenoid notch for muscle grading. Four (5%) studies lacked a coronal non−fat-suppressed T2W sequence, and 2 (2%) had sagittal T1W sequences that extended to the spinoglenoid but not to the medial notch. However, in each instance, all were considered to be of adequate quality for analysis with no patients requiring repeat imaging.

Intraoperative evaluation

All surgical procedures were performed with the patient under general anesthesia in either the beach-chair (n = 79) position with the arm at the side of the body or the lateral decubitus (n = 23) position with the arm in mid-abduction under traction.

Tear classification, dimensions, and location

During surgery, the rotator cuff was examined by the operating surgeon from both the articular and the bursal sides. Tears were classified as partial or full thickness. Tear dimensions and location were assessed after all preparatory débridement and immediately prior to repair. Tear dimensions were estimated using an arthroscopic straight-hook surgical probe with 5-mm calibrated markings (ConMed Corp., Largo, FL, USA). The anterior-posterior (AP) tear width was measured between the anterior and posterior tear margins across the middle of the footprint of the greater tuberosity (Fig. 1, *A*). The medial-lateral (ML) tear length was measured from the most medial aspect of the torn tendon stump to the lateral edge of the footprint (Fig. 1, *B*). Surgeons also noted whether they considered the tear to involve the supraspinatus, infraspinatus, or both tendons.

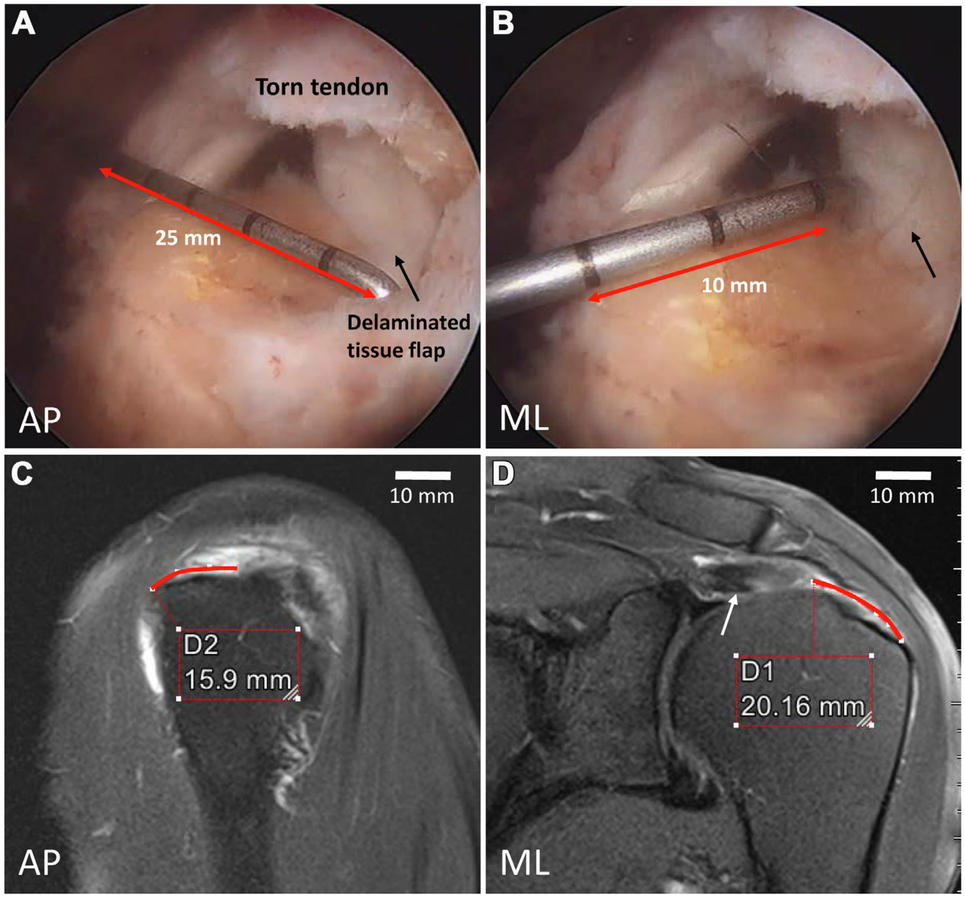

Figure 1 Examples of operative and MRI measurements to demonstrate the 2 measurement techniques in the same patient. An arthroscopic straight-hook surgical probe with 5-mm calibrated markings was used for measuring (**A**) AP and (**B**) ML tear dimensions intraoperatively (after débridement). On preoperative MRI, the PACS software was used for (**C**) AP and (**D**) ML measurements. *MRI*, magnetic resonance imaging; *AP*, anterior-posterior; *ML*, medial-lateral; *PACS*, picture-archiving and communication system (TeraRecon, Inc. Durham, NC,USA).

MRI evaluation

As described previously,[15] reading rules for all MRI assessments were prospectively defined and refined on a separate image set by the 2 radiologist readers prior to the start of reading the study images, and the rule book was available to these readers during independent scoring of each MRI. Preoperative MRI studies from all patients who met intraoperative inclusion criteria were reviewed independently, in random order, on a commercial picture-archiving and communication system (PACS, AquariusNET viewer software v4.4; TeraRecon, Inc., Durham, NC, USA). All quantitative measurements were performed using the PACS software and recorded in a standardized Research Electronic Data Capture (REDCap) database.

Tear classification

Preoperative rotator cuff integrity was assessed from coronal T2W non–fat-suppressed and sagittal intermediate-weighted fat-suppressed images using the Sugaya classification,[20] described for postoperative assessment of retears but used to classify preoperative tears in this study: 1, sufficient thickness with homogenously low intensity; 2, sufficient thickness with partial high-intensity area; 3, less than half with normal thickness but no discontinuity; 4, minor discontinuity on only 1 or 2 slices on both oblique coronal and sagittal images; 5, major discontinuity on >2 slices on both oblique coronal and sagittal images. Using this scoring classification, Sugaya 1 and 2 imply absence of a tear, Sugaya 3 a partial thickness tear, Sugaya 4 a small full thickness tear, and Sugaya 5 a medium-large full-thickness tear. For comparison to an intraoperative tear status, the Sugaya scores were trichotomized by combining 1 and 2 as “intact” and 4 and 5 as “full-thickness tear.”

Tear dimensions

Tear dimensions were measured for studies with a Sugaya grade of 4 or 5. AP tear width was determined as the curvilinear distance along the contour of the humeral head between the anterior and posterior tear margins at the midpoint of tendon thickness (Fig. 1, *C*). AP tear width was measured on the sagittal slice at the midportion of the footprint’s ML dimension when the tear was at the footprint. For tears medial to the footprint, the most lateral sagittal slice demonstrating the tear was selected for AP tear width measurement. ML tear length was determined as the curvilinear distance from the lateral edge of the footprint to the lateral edge of the tendon stump at the midpoint of the tendon thickness using the coronal slice where ML tear length appeared maximal (Fig. 1, *D*).

Tear location

Tear location was assessed for studies with a Sugaya grade of 3, 4, or 5. The readers indicated the anatomic location of the tear as anterior supraspinatus, posterior supraspinatus, anterior infraspinatus, and/or the posterior infraspinatus using their clinical judgment. The readers also noted whether the lateral (at the footprint) or medial (mid-substance) location was involved. The MR tear locations were combined into supraspinatus, infraspinatus, or both tendons to match the intraoperative observation categories.

Supraspinatus muscle atrophy and occupation ratio

Supraspinatus atrophy was evaluated for the oblique sagittal T1W non–fat-suppressed acquisition using the slice immediately medial to the spinoglenoid notch, the standard location used for the Warner and Goutallier scales. Muscle atrophy was judged only on MRI, since atrophy of the rotator cuff musculature cannot be assessed intraoperatively. The atrophy was graded by the Warner classification with the aid of a so-called "tangent line"[13,25] drawn between the superior borders of the scapular spine and coracoid process, as 0, none (muscle convex above the line); 1, mild (muscle even with the line); 2, moderate (muscle is below the line but ≥50% of the height of the supraspinatus fossa); and 3, severe (muscle is below the line and <50% of the fossa height).[23] Each radiologist also manually outlined the supraspinatus muscle and supraspinatus fossa, where the superior border of the fossa was defined by the tangent line[25] to allow direct comparison to Warner classification. CSAs of the outlined regions were automatically calculated by using the PACS software. Occupation ratio was then calculated as the supraspinatus muscle CSA divided by the supraspinatus fossa CSA.[25] Based on the graphical depiction of Warner's classifications[23] and our use of the tangent line to measure occupation ratio, we infer that grade 0 (none) should correspond to occupation ratios >1, grade 1 (mild) to 0.9-1, grade 2 (moderate) to 0.5-0.9, and grade 3 (severe) to occupation ratios <0.5. While estimation of muscle fat infiltration was performed with the qualitative Goutallier grading system,[7] there is no correlative operative assessment, and validation of this grading requires a quantitative image measurement such as Dixon MRI fat fraction analysis which was not acquired for the parent study of this convenience cohort.

Statistical analysis

For categorical variables, interreader agreement and agreement between intraoperative and MRI assessments were evaluated by the raw exact agreement proportion and the chance-corrected simple (Cohen) kappa statistic. Concordance correlation coefficients were used to assess inter-reader agreement and MRI-intraoperative agreement on continuous variables. Intraoperative and MRI measurements of tear dimensions were categorized by whether the difference between the MRI and intraoperative measurement was (1) >5 mm, (2) within a 5-mm range, and (3) <−5 mm. Characteristics of the sample, and of each MRI reader's results, were described by frequency distributions of proportions for categorical variables and either mean ± standard deviation for reasonably symmetrically distributed measurements or median (interquartile range) for markedly skewed continuous measurements. Measures of agreement or correlation are presented as means with associated 95% confidence intervals. In addition, scatterplots were used to visually portray MRI-intraoperative agreement for the continuous measurements of tear dimension, and Bland-Altman plots were used to qualitatively assess dependence of intermethod differences on the magnitudes of tear dimensions. Finally, Spearman's rank correlation coefficient was used to assess agreement between the 2 MRI-based assessments of supraspinatus muscle atrophy by Warner classification and occupation ratio. Kappa statistics were described by ranges as almost perfect, 0.81-1.00; substantial, 0.61-0.80; moderate, 0.41-0.60; fair, 0.21-0.40; slight, 0.00-0.20; and poor, <0.00,[12] and concordance correlation coefficients and Spearman correlation coefficients by ranges of excellent, 0.75-1.00; good, 0.60-0.74; fair, 0.40-0.59; and poor, <0.40.[2]

Table I
Baseline demographics of patients who underwent RCR.

Characteristics for 102 patients	
Age (yr)	58 ± 9
Sex	
Male	56 (55%)
Female	46 (45%)
Body Mass Index	30 ± 6
Race	
White	89 (87%)
Black or African American	11 (11%)
Other	2 (2%)
Laterality	
Right	71 (70%)
Left	31 (30%)

RCR, rotator cuff repair; *SD*, standard deviation.
Statistics are presented as frequency (%) or mean ± SD.

Results

Patient demographics and rotator cuff characteristics

Demographics are summarized in Table I. The average age and Body Mass Index were 58.2 years and 30.2, respectively. Of all in the cohort, 54.9% were male, 87.3% were white, and 69.6% were right-hand-dominant. Preoperative (MRI) and intraoperative (surgeon) rotator cuff tendon and muscle assessments are summarized in Table II.

MRI inter-reader agreement

The raw agreement between the radiologist readers was 87%-95%, with chance-corrected κ ranging from 0.48 to 0.70, for categorical assessment of tear location, tear status, and muscle atrophy (Table III). Their concordance correlation ranged from 0.85 to 0.98 for continuous measurements of AP tear width, ML tear length, supraspinatus CSA, fossa CSA, and occupation ratio (Table III).

Tear classification

Surgeons considered 95 of 102 (93%) of the tears to be of full thickness and 7 of 102 (7%) to be of partial thickness at the time of surgery (Table II). Raw agreement in assessing preoperative tear status as "intact," "partially torn," or "full-thickness tear" was 94%, κ = 0.37, and 92%, κ = 0.39, between the MRI readers and the surgeon observations, respectively, (Table IV). Most discrepancies occurred when assessing the 7 tears intraoperatively confirmed as high-grade partial-thickness. Of these, reader A considered 2 partial- and 5 full-thickness tears (3 articular-sided, 2 bursal-sided) while reader B considered 2 intact, 2 partial-, and 3 full-thickness tears (2 articular-sided, 1 bursal-sided) (Fig. 2); both readers considered the same partial-thickness tear as full-thickness tears 3 times. Of the 95 tears intraoperatively assessed as full thickness, both MRI readers considered one and the same case of a small (1 cm) tear as partial thickness, shown in Fig. 2, case 1.

Tear location

Surgeons considered 63 of the 102 (61.8%) tears to be in the supraspinatus tendon only and 39 of 102 (38.2%) to involve both tendons (Table II). MRI readers classified modestly more tears as supraspinatus only (65.7% and 74%, respectively) and

Table II
Assessments of rotator cuff pathology of patients by MRI readers (preoperatively) and surgeon (intraoperatively).

Assessment	Categories	Intraoperative (surgeon)	MRI (reader A)	MRI (reader B)
Tear classification [a]	Intact	0 (0%)	0 (0%)	2 (2%)
	Partial-thickness tear	7 (7%)	3 (3%)	5 (5%)
	Full-thickness tear	95 (93%)	99 (97 %)	95 (93%)
Tear location [a]	Supraspinatus	63 (62%)	67 (66%)	74 (74%)
	Infraspinatus	0 (0%)	2 (2%)	0 (0%)
	Both tendons	39 (38%)	33 (32%)	26 (26%)
AP tear width (cm) [b]		2.2 ± 0.9 (n = 102)	2.2 ± 1.1 (n = 99)*	2.3 ± 1.2 (n = 95)*
ML tear length (cm) [b]		1.2 ± 0.6 (n = 102)	2.4 ± 1.2 (n = 99)*	2.5 ± 1.2 (n = 95)*
Supraspinatus muscle atrophy (Warner classification)[a]	0	n/a	90 (88%)	84 (82%)
	1		5 (5%)	11 (11%)
	2		7 (7%)	7 (7%)
	3		0 (0%)	0 (0%)
Supraspinatus muscle occupation ratio [b]	—	n/a	0.89 ± 0.26	0.89 ± 0.25

MRI, magnetic resonance imaging; *AP*, anterior-posterior; *ML*, medial-lateral; *n/a*, not applicable; *SD*, standard deviation.
Statistics presented as (a) counts (frequency) or (b) mean ± SD.
*The sample size for tear length was <102 and differed between the 2 readers because lengths were only measured in cases where each considered the tear to be full-thickness.

Table III
Agreement statistics (mean, 95% CI) of MRI parameters assessed between 2 readers.

Assessment	Statistic	Agreement
Tear classification (Sugaya, trichotomized)	Exact agreement	0.95 (0.89, 0.98)
	Simple κ	0.48 (0.14, 0.82)
Tear location (supraspinatus, infraspinatus, both tendons)	Exact agreement	0.87 (0.79, 0.93)
	Simple κ	0.70 (0.55, 0.85)
AP tear width	CCC	0.87 (0.81, 0.91)
ML tear length	CCC	0.85 (0.79, 0.90)
Supraspinatus muscle atrophy (Warner)	Exact agreement	0.91 (0.84, 0.96)
	Simple κ	0.66 (0.48, 0.85)
Supraspinatus muscle CSA	CCC	0.98 (0.96, 0.98)
Supraspinatus fossa CSA	CCC	0.94 (0.92, 0.96)
Supraspinatus muscle occupation ratio	CCC	0.93 (0.89, 0.95)

CI, confidence interval; *MRI*, magnetic resonance imaging; *AP*, anterior-posterior; *CCC*, concordance correlation coefficients; *ML*, medial-lateral; *CSA*, cross-sectional area.

Table IV
Agreement statistics (mean, 95% CI) of standard MRI assessments with intraoperative assessments.

Assessment	Statistic	Agreement reader A	Agreement reader B
Tear classification (reader A, n = 102)	Exact agreement	0.94 (0.99, 0.98)	0.92 (0.85, 0.97)
(reader B, n = 102)	Simple κ	0.37 (−0.01, 0.76)	0.39 (0.11, 0.67)
Tear location (reader A, n = 102)	Exact agreement	0.73 (0.63, 0.81)	0.81 (0.72, 0.88)
(reader B, n = 100)*	Simple κ	0.42 (0.24, 0.59)	0.58 (0.41, 0.74)
AP tear width[†] (reader A, n = 99) (reader B, n = 95)	CCC	0.55 (0.40, 0.68)	0.63 (0.49, 0.74)
ML tear length[†] (reader A, n = 99) (reader B, n = 95)	CCC	0.57 (0.42, 0.69)	0.56 (0.41, 0.69)

CI, confidence interval; *MRI*, magnetic resonance imaging; *AP*, anterior-posterior; *CCC*, concordance correlation coefficients; *ML*, medial-lateral.
*The sample size for tear location differed between the 2 readers because 2 of the 102 cases were assessed as no tear (Sugaya 2) by reader B, and therefore, no tear location was recorded.
†The sample size for tear length was <102 and differed between the 2 readers because lengths were only measured in cases that each considered the tear to be full-thickness.

correspondingly fewer as involving both tendons (Table II). In describing preoperative tear location as "supraspinatus," "infraspinatus," or "both tendons," the exact agreement was 73%, κ = 0.42, and 81%, κ = 0.58, between the respective readers and surgeon observation (Table IV).

Tear dimensions

AP tear width measured intraoperatively averaged 2.2 ± 0.91 cm across the cohort, which was similar to the mean AP tear width measured from preoperative MRI of 2.2 ± 1.06 cm (reader A) and 2.3 ± 1.2 cm (reader B) (Table II). Concordance correlations of intraoperative and MRI measures of AP tear width averaged 0.59 across MRI readers (Table IV). MRI measurements were within 5 mm of intraoperative measures of AP tear width approximately half the time, with overestimation and underestimation >5 mm approximately evenly distributed among the other half of cases for both readers (Table V). Differences between the 2 modes of measurement did not appear to be dependent on the AP size of the tear (Supplementary Figure S1).

ML tear length measured intraoperatively averaged 1.2 ± 0.6 cm across the cohort, which was approximately half the mean values of ML tear length measured from preoperative MRI of 2.4 ± 1.2 cm (reader A) and 2.5 ± 1.2 cm (reader B) (Table II). On a case-by-case

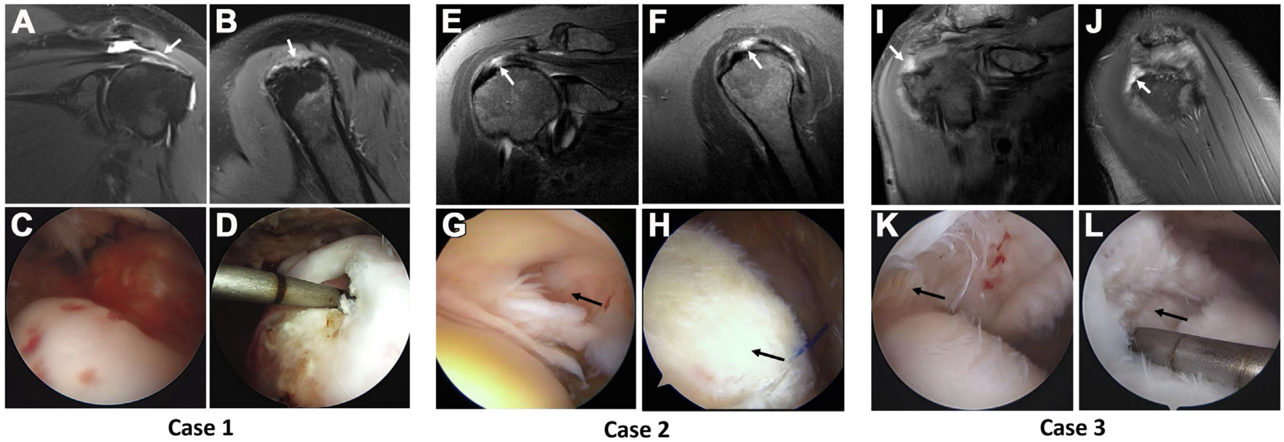

Figure 2 Examples of discrepant MRI and intraoperative tear grades. Case 1 (**A-D**): Both MRI readers independently graded this intraoperatively confirmed full-thickness tear as partial thickness. Coronal (**A**) and sagittal (**B**) MR images show severe thinning of the supraspinatus (*arrows*) but no apparent fluid gap to indicate a full-thickness tear. Arthroscopic photos from the articular (**C**) and bursal (**D**) views show the full-thickness tear. Case 2 (**E-H**): Both MRI readers independently graded this intraoperatively confirmed partial-thickness (articular-sided) tear as a full-thickness tear on MRI. Coronal (**E**) and sagittal (**F**) MR images demonstrate focal fluid-like signal (*arrows*), widest on the bursal side, crossing the thickness of the supraspinatus tendon. Arthroscopic photographs from the articular (**G**) and bursal (**H**) views show only a partial-thickness articular-sided tear was present (*arrows* indicate intact bursal fibers). Case 3 (**I-L**): Another intraoperatively confirmed partial-thickness (bursal-sided) tear that both readers independently graded as a full-thickness tear on MRI. Coronal (**I**) and sagittal (**J**) MR images demonstrate focal fluid-like signal crossing the full thickness of the supraspinatus tendon (*arrows*). Arthroscopic photographs from the articular (**K**) and bursal (**L**) views show only a partial-thickness bursal-sided tear (*arrows* indicate intact articular fibers). *MRI*, magnetic resonance imaging.

Table V
Correspondence between measurements of tear dimensions by MRI readers (preoperatively) and surgeon (intraoperatively).

MRI measurement vs. Surgeon measurement	AP tear width		ML tear length	
	Reader A (n = 94)*	Reader B (n = 92)*	Reader A (n = 94)*	Reader B (n = 92)*
Overestimated by >5 mm				
n (%)	24 (25.5%)	29 (31.5%)	70 (74.5%)	68 (73.9%)
95% CI	17.1-35.6%	22.2-42.0%	64.4-82.9%	63.7-82.5%
Within 5 mm				
n (%)	46 (49.0%)	46 (50.0%)	24 (25.5%)	24 (26.1%)
95% CI	38.5-59.5%	39.4-60.6%	17.1-35.6%	17.5-36.3%
Underestimated by >5 mm				
n (%)	24 (25.5%)	17 (18.5%)	0 (0%)	0 (0%)
95% CI	17.1-35.6%	11.1-27.9%	–	–

MRI, magnetic resonance imaging; *AP*, anterior-posterior; *ML*, medial-lateral; *CI*, confidence interval.
*Among 95 full-thickness tear cases identified intraoperatively, 94 cases were assessed as full-thickness tear by reader A, and 92 cases were assessed as full-thickness tear by reader B.

basis, MRI reader measurements were within 5 mm of intraoperative measures of ML tear length only about 25% of the time (Table V). Both readers overestimated the intraoperatively measured ML tear length by more than 5 mm in about 75% of cases (Table V). The correlation between intraoperative and MRI measures of ML tear length averaged 0.56 (Table IV). Differences between MRI and surgical measurements for ML tear length increased as ML tear length increased (Supplementary Figure S2).

Muscle atrophy and occupation ratio

Both readers graded supraspinatus muscle atrophy according to the Warner classification as grade 0 or 1 ("none" or "minimal") in 95 of the 102 (93%) patients preoperatively (Table II). Across the cohort, the quantitative supraspinatus muscle occupation ratio ranged from 0.36 to 1.51 (reader A) and 0.35 to 1.50 (reader B) (Fig. 3) and averaged 0.89 for both readers (Table II). The measured occupation ratios ranged from 0.5 to 1.5 for Warner grade 0, 0.5-0.7 for grade 1, and 0.4-0.7 for grade 2 (Fig. 4), with over 60% of patients given a Warner grade of 0 by either reader having a measured occupation ratio <1 (Fig. 3). The Spearman correlations between the Warner classification and occupation ratio were −0.54 (−0.66, −0.38) and −0.64 (−0.74, −0.51) for the 2 readers, respectively.

Discussion

We assessed the relationships of preoperative MRI assessments made by conventional approaches to intraoperative findings of tear type, location, and size or MRI-assessed muscle occupation ratio for 102 RCR patients. Following on and consistent with our prior report on the first 42 patients of this cohort,[15] MRI readers showed excellent raw agreement (87%-95%) or concordance (0.85-0.98) for all preoperative MRI rotator cuff assessments. MRI assessment of tear type and location also agreed substantially with intraoperative observation. In contrast, the correlations of preoperative MRI and intraoperatively measured tear dimensions and of muscle atrophy assessed by Warner classification with the measured occupation ratio were only fair.

The high overall agreement between MRI and intraoperative assessments of tear status is consistent with many prior studies which have reported high accuracy of MRI for the detection of rotator cuff tears.[4,21] Our findings are also consistent with prior reports showing that MRI accuracy decreases for diagnosing partial-thickness tears[21] and confirm the well-appreciated challenge of interpreting abnormal MRI signal intensity in the absence of a clear defect. It has been suggested that tendinopathy alone produces abnormal signal intensity, which, if extending to both cuff surfaces,

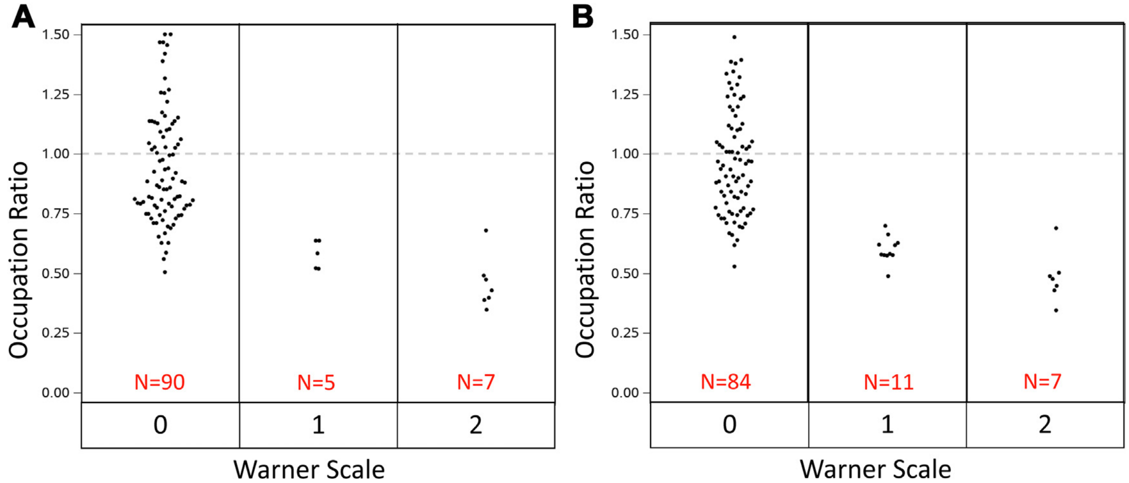

Figure 3 Warner classification vs. occupation ratio from preoperative MRIs assessed by 2 independent radiologist readers (**A**) Reader A and (**B**) Reader B. Across the cohort, both readers classified supraspinatus muscle atrophy as grade 0 or 1 ("none" or "minimal") in 95 of 102 (93%), and supraspinatus muscle occupation ratio ranged from 0.36 to 1.51 (reader A) and 0.35 to 1.50 (reader B). *MRI*, magnetic resonance imaging.

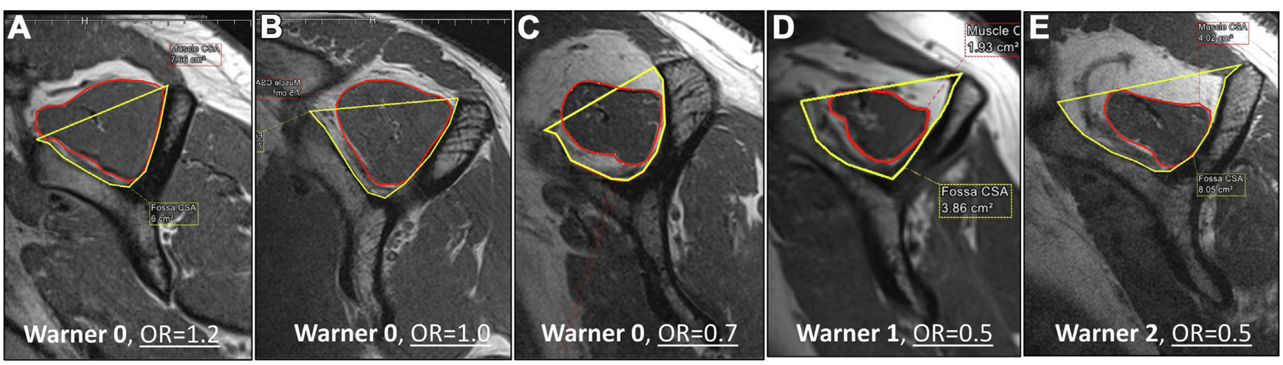

Figure 4 Examples showing the range of variation between Warner classification and measured occupation ratios. (**A-C**) Occupation ratios (OR) for 3 patients assigned Warner grade 0 (no atrophy) varied from 1.2 (no atrophy, **A**) to 0.7 (moderate atrophy, **C**). (**C-E**) Three patients with low occupation ratios of 0.5-0.7 (moderate atrophy) had Warner classifications in the range of 0 (none, **C**), 1 (mild, **D**), and 2 (moderate, **E**) atrophy.

may simulate a full-thickness tear.[21] Furthermore, small full-thickness tears depending on their shape and/or location may not readily show as a defect. Collectively, these findings demonstrate the inherent strengths and limitations of MRI for diagnosis of rotator cuff tear.

In this study, MRI readers agreed exactly with intraoperative observation of tear location 73%-81% of time. MRI readers classified modestly more tears as supraspinatus only and correspondingly fewer as involving both tendons than intraoperative observation. This difference may represent the challenge of interpreting the posterior edge of a supraspinatus tear that extends adjacent to the anterior infraspinatus insertion, as there is a blending of the tendon fibers at this junction. Determining where one tendon ends and the other begins can be difficult to judge on both MRI and arthroscopic observation. The obliquity of the rotator cuff insertion in this transition area also makes the exact posterior extent of the tear difficult to interpret with imaging or direct observation.

Despite excellent agreement with each other in measurement of AP tear width and ML tear length, MRI readers' measurements did not match well with intraoperative measurements and were within 5 mm of the intraoperatively measured AP tear width and ML tear length in only about 50% and 25% of cases, respectively. Since tear size measurements on MRI are done preoperatively, that is, *before the tear is débrided*, MRI-measured tear size should be smaller than the same tear measured intraoperatively after débridement, a finding which has been reported by others.[1,5] Yet, in this study, MRI-measured AP and ML tear dimensions *overestimated* the intraoperative tear size by more than 5 mm in approximately 25% and 75% of cases, respectively, and in no instance did the MRI measurement *underestimate* the intraoperative ML tear length measurement by more than 5 mm. Challenges of interpreting abnormal MRI signal intensity at the torn tendon edge may explain some of the discrepancies. In addition, depending on the shape of the tendon defect, AP tear dimension may vary with sagittal MR slice selection or the positioning of the probe at surgery.

In contrast with our results, Teefey et al reported that MRI predicted AP tear width within 5 mm in 80% of tears (overestimated 7% and underestimated 13%) and predicted ML tear length within 5 mm in 63% of tears (overestimated 24% and underestimated 13%).[21] The lower MRI-intraoperative correspondence in our study, particularly for ML tear length, can likely be explained in part by methodologies that would preferentially increase the MRI-measured tear dimensions in the current study. First, our MRI readers made curvilinear measurements around the humeral head, whereas the prior study made linear MRI measurements, while surgeons in both studies used a rigid (linear) probe for intraoperative measurements. Our finding that differences between MRI and surgical measurements of ML tear length increased as ML tear length increased (Supplementary Figure S2) supports the conclusion that curvilinear MRI measurement primarily accounts for the consistent bias toward overestimation of ML tear length in this study. In addition, we measured MRI ML tear length from the lateral edge of the rotator cuff footprint, and the prior study measured ML tear length from the lateral edge of the articular surface, that is, the medial edge of the footprint.

Differences in shoulder position during surgery (lateral decubitus or beach chair) and MR imaging (supine) could also introduce differences between MRI and intraoperative measured tear lengths. This study was not designed to quantify this effect, nor were there enough cases in the lateral decubitus position to rigorously test for measurement differences between surgical positions, but our findings do reflect the measurement variation encountered in routine clinical conditions. It is also important to acknowledge that MR measurement accuracy is dependent on the linearity of the imaging gradient local to the object measured and thus impacted by patient positioning and size. Although such confounding was minimized by employing standard clinical protocols that image patients in the same position and as close to the isocenter as possible, some distortion in MRI measurements is inevitable, and again, our methodology replicates clinical reality. In summary, MRI offers the ability to make curvilinear measurements, potentially at multiple locations across the length and width of the tear, to identify the *lateral* edge of the tendon footprint on the humeral head accurately and consistently, and to control shoulder position. Since tear length is a known strong predictor of outcomes following RCR, future work should continue to improve MRI-based assessments of tear size that are validated with intraoperative findings, potentially using standardized arm positions and machine learning algorithms.

Muscle atrophy is most conventionally assessed by categorical classification such as the Warner scale. However, these categorical MRI assessments are subjective, and the reported intrarater and interrater reliabilities have been fair at best.[10,14,19,24] Some groups have recently reported direct measurement of supraspinatus muscle CSA,[16] or the "occupation ratio" of the supraspinatus in its fossa,[9,11,13,18,22,25] as a means to quantify muscle atrophy more precisely and accurately. Most prior studies reporting occupation ratio defined the supraspinatus fossa as the space occupied by the full muscle volume, which requires estimation of the superior boundary of the once healthy muscle. In our study, we defined the superior border of the fossa by the tangent line,[25] in order to allow direct comparison to the Warner classification which uses the tangent line to assign a score. Despite excellent agreement among the MRI readers for Warner classification and CSA measurements separately, correlation between Warner classification and occupation ratio of supraspinatus atrophy was only fair on average. It is apparent that discrepancies between the 2 modes of assessment arise due to the simplified definition of the Warner scale, which considers only whether the convexity of the muscle extends beyond the tangent line and is insensitive to multidimensional atrophic changes (Fig. 4). We conclude therefore that the occupation ratio is a more sensitive and accurate measure of supraspinatus muscle atrophy than the Warner classification or the simple "tangent sign" classification used by others.[13,25] However, in its current application, occupation ratio relies on manual tracing of a single muscle cross-section and is limited to the supraspinatus muscle with its well-defined fossa. Future development of automated muscle segmentation algorithms[17] applied to 3D muscle volumes,[8] using quantitative MRI such as Dixon to measure fat fraction[6] and acquisition of age and gender normative data on muscle volumes[25] and fat fractions, would greatly enhance accurate assessment of shoulder muscle pathology.

The strength of this study is the prospective and independent evaluation of preoperative MRI assessments of the rotator cuff by 2 musculoskeletal radiologists and the correlation of these evaluations with intraoperative assessments by the operating surgeon who was blinded to the MRI findings or alternate quantitative MRI measurements. However, this study was limited by the highly controlled research environment and the known selection bias of including only patients in a convenience cohort indicated for RCR surgery which may have unconsciously influenced the MRI readers. Furthermore, patients in the cohort used by this research study were included only if they had no advanced muscle atrophy or fatty infiltration grades and had a 1- to 5-cm tear that was fully reparable by a double-row or equivalent technique at surgery. Hence, our findings may not be generalizable to settings of a more diverse or severe tendon or muscle pathology.

Conclusion

Preoperative MRI assessment of tear type and location agreed substantially with intraoperative observation, consistent with prior literature. Discrepancies were most common in the setting of intraoperatively confirmed high-grade partial-thickness tears. However, in variance with the literature, the correlations of MRI and intraoperatively measured tear dimensions were only fair with MRI often overestimating the tear size. Additionally, the correlation between muscle atrophy assessed by the conventional Warner scale and an alternate, quantitative, occupation ratio method was only fair. These results were despite the very high interrater agreement for the MRI assessments. Since tear size and shoulder muscle atrophy are known strong predictors of outcomes following RCR, surgeons should be aware of the limitations of MRI methods when determining a patient's treatment plan based on these radiologic assessments alone. Continued development and intraoperative validation of quantitative preoperative imaging methods to accurately assess these parameters would likely improve surgical planning and prognosis.

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Supplementary Data

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