Association Between Rotator Cuff Tears and Superior Migration of the Humeral Head

An MRI-Based Anatomic Study

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Background: Superior humeral migration has been established as a component of rotator cuff disease, as it disrupts normal glenohumeral kinematics. Decreased acromiohumeral interval (AHI) as measured on radiographs has been used to indicate rotator cuff tendinopathy. Currently, the data are mixed regarding the specific rotator cuff pathology that contributes the most to humeral head migration.

Purpose: To determine the relationship between severity of rotator cuff tears (RCTs) and AHI via a large sample of magnetic resonance imaging (MRI) shoulder examinations.

Study Design: Cohort study; Level of evidence, 3.

Methods: A search was performed for 3-T shoulder MRI performed in adults for any indication between January 2010 and June 2019 at a single institution. Three orthopaedic surgeons and 1 musculoskeletal radiologist measured AHI on 2 separate occasions for patients who met the inclusion criteria. Rotator cuff pathologies were recorded from imaging reports made by fellowship-trained musculoskeletal radiologists.

Results: A total of 257 patients (mean age, 52 years) met the inclusion criteria. Of these, 199 (77%) had at least 1 RCT, involving the supraspinatus in 174 (67.7%), infraspinatus in 119 (46.3%), subscapularis in 80 (31.1%), and teres minor in 3 (0.1%). Full-thickness tears of the supraspinatus, infraspinatus, or subscapularis tendon were associated with significantly decreased AHI (7.1, 5.3, and 6.8 mm, respectively) compared with other tear severities ($P < .001$). Having a larger number of RCTs was also associated with decreased AHI ($\rho = -0.157$; $P = .012$). Isolated infraspinatus tears had the lowest AHI (7.7 mm), which was significantly lower than isolated supraspinatus tears (8.9 mm; $P = .047$).

Conclusion: Although various types of RCTs have been associated with superior humeral head migration, this study demonstrated a significant correlation between a complete RCT and superior humeral migration. Tears of the infraspinatus tendon seemed to have the greatest effect on maintaining the native position of the humeral head. Further studies are needed to determine whether early repair of these tears can slow the progression of rotator cuff disease.

Keywords: MRI; rotator cuff tear; rotator cuff arthropathy; Hamada classification; shoulder; acromiohumeral interval; superior migration; rotator cuff repair; shoulder arthroplasty; superior capsular reconstruction

Superior migration of the humeral head has been established as a characteristic finding of rotator cuff tear–associated glenohumeral arthropathy.[11] This migration has significant clinical relevance, as it disrupts normal glenohumeral kinematics and is associated with more advanced disease.[2,5,13] The acromiohumeral interval (AHI) was traditionally used as an indicator for rotator cuff tears before widespread use of magnetic resonance imaging (MRI). In 1962, Golding[4] initially reported a normal AHI range from 6 to 14 mm in 150 patients without rotator cuff pathology. Weiner and Macnab[12] then suggested that supraspinatus deficiency was the root cause of superior migration of the humeral head because there was no inferior force to counteract the superior pull of the deltoid.

Hamada and colleagues[6] proposed a classification that was essentially an order of progression of the findings associated with rotator cuff arthropathy (RCA). It was based primarily on the AHI, a measurement made using radiographs and validated in 65 surgically confirmed rotator cuff tears. They proposed that rotator cuff deficiency

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leads to superior humeral migration, as well as increased stress on the long head of the biceps tendon to stabilize the superior pull of the deltoid. Subsequent rupture of the long head of the biceps tendon leads to further superior migration and eventually acetabularization of the acromion in the more severe grades of the Hamada classification.[6]

The data are mixed as to which specific rotator cuff tendon deficit contributes the most to humeral head migration.[2,3,5,9-11] These previous studies were largely performed using cadavers,[5,11] radiographs,[6] or ultrasound,[7] and studies that used MRI were limited by small sample sizes.[2] There remains a void in the literature for larger-scale advanced imaging studies that analyze the specific relationship between superior humeral migration and rotator cuff pathology, limiting our understanding of glenohumeral kinematics.

To date, studies that have tried to determine contributors of humeral head migration have been based on plain radiographs or ultrasound, which are much more limited in their dimensionality and resolution. In this study, we aimed to analyze a large sample size of high-resolution 3-T MRI scans to evaluate whether the AHI varies based on the presence of rotator cuff tear, types of tears, number of tears, and severity of the tear. Our purposes included identifying differences in average migration based on the presence and severity of rotator cuff tears and examining whether there is a linear relationship for increasing severity of tear or number of tears.

METHODS

This was a cross-sectional observational analysis of patients who underwent high-resolution 3-T shoulder MRI at a single institution between January 2010 and June 2019. The institutional review board at our institution approved this retrospective review of electronic medical records and MRI examinations. Our institutional imaging database was queried for all shoulder MRI studies obtained for any indication during the study period. From these MRI scans, a subset of high-resolution 3-T studies was isolated and utilized for measurements. Studies of lower resolution (non–3 T) and studies with excessive motion artifact were excluded as well as studies with tumors or other pathology that distorted the normal shoulder anatomy. Studies in patients who were <18 years of age were also excluded.

MRI scans were obtained with the patient lying supine and the arm positioned by the side of the body and in neutral rotation with the thumb pointing upward. All MRI examinations were performed using 3-T MRI magnets via either a 3-T GE Signa HDxt or 3-T GE Discovery MR750w system (GE Healthcare) with a dedicated shoulder array coil. The MRI examinations consisted of routine unenhanced shoulder protocols that comprised 1 axial fluid-sensitive, 2 sagittal oblique, and 2 coronal oblique sequences. These sequences included axial proton density–weighted fat-suppressed (repetition time [TR] range [in milliseconds]/echo time [TE] range [in milliseconds], 2000-3000/20-40), coronal oblique T1 (TR/TE, 500-600/10-15), coronal oblique intermediate weighted fat-suppressed (TR/TE, 3000-4000/40-60), sagittal oblique T1 (TR/TE, 500-600/10-15), and sagittal oblique intermediate fat-suppressed sequences (TR/TE, 3000-4000/40-60). The field of view ranged from 12 to 14 cm in each plane. The matrix varied based on the plane and sequence, and typical matrices ranged from 200 to 300.

Images were reviewed, and all measurements were made using a radiology information system PACS (Evorad Research PACS; Evorad). Four blinded reviewers, including 1 musculoskeletal radiologist (W.W.) and 3 orthopaedic surgeons (M.Y.S., B.C.M., M.H.), measured the AHI. A subset of 20 randomly selected T1-weighted MRI scans were measured on 2 separate instances by all raters to determine reliability. The specific MRI slice for measurement was chosen at the discretion of the reader. The 4 reviewers measured the AHI in the midcoronal plane, from the superiormost aspect of the humeral head directly cranial to the inferior portion of the acromion. Measurements were made on the slice of the MRI sequence that demonstrated the shortest AHI as measured from the subchondral bone plate of the humeral head to the cortical margin of the acromial undersurface (Figure 1).

Rotator cuff tear grade was determined from the radiology report created by our academic institution's fellowship-trained musculoskeletal radiologists and was designated as no tear, low-grade partial thickness (<3 mm deep or <25% thickness), moderate-grade partial thickness (3-6 mm deep or approximately 50% of the thickness of the tendon), high-grade partial thickness (>6 mm deep or more than half of the thickness of the tendon), or complete or full thickness (100% thickness) (Figure 2).

Statistical analysis was performed using IBM SPSS Statistics for Windows Version 26 (IBM Corp). Spearman ρ was utilized to determine whether a significant linear correlation existed with increasing number of tears and increasing severity of tear. Analysis of variance was performed to assess for differences in AHI depending on the

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presence of rotator cuff tear and also grade of rotator cuff tear within each tear type. In situations where there was >1 group being compared and the main effect P value was significant, Bonferroni post hoc pairwise comparisons were performed. Alpha was set to $P < .05$ to declare significance. Inter- and intrarater reliability were assessed using an intraclass correlation coefficient (ICC) computed using 1-way random-effect models and single rater unit, with >0.75 being considered "excellent." Interrater reliability was evaluated utilizing the average of the 2 intrarater measurements.

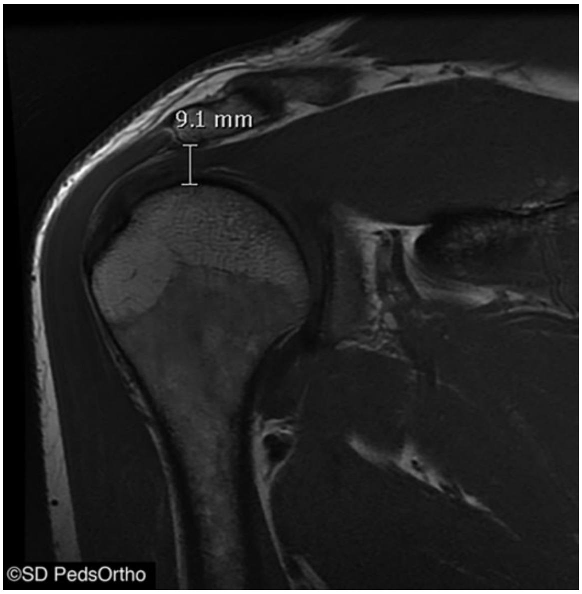

Figure 1. Acromiohumeral interval as measured on a magnetic resonance imaging scan. Image courtesy of SD Peds Ortho.

RESULTS

There were 5967 MRI scans identified in our institutional imaging software; of these, 257 shoulder MRI scans met the inclusion criteria. The mean patient age was 52.3 years, 56% were male (144/257), and 54% (138/257) of the scans were on the right side. Of the total, 77% (199/257) had at least 1 rotator cuff tear, of which 35.6% (71/199) were isolated to 1 rotator cuff tendon. Of the patients with a rotator cuff tear, 75 had a single-tendon tear, 73 had 2 tendons involved, 49 had 3 tendons involved, and 2 had all 4 tendons involved.

Intra- and interobserver reliability were excellent (ICC $\geq$ 0.88) for all AHI measurements (Table 1). The mean AHI was 8.3 mm for patients with a rotator cuff tear compared with 8.7 mm in patients without a tear (Table 2). The mere presence of a rotator cuff tear was not associated with a decrease in AHI ($P = .161$). The breakdown of the presence

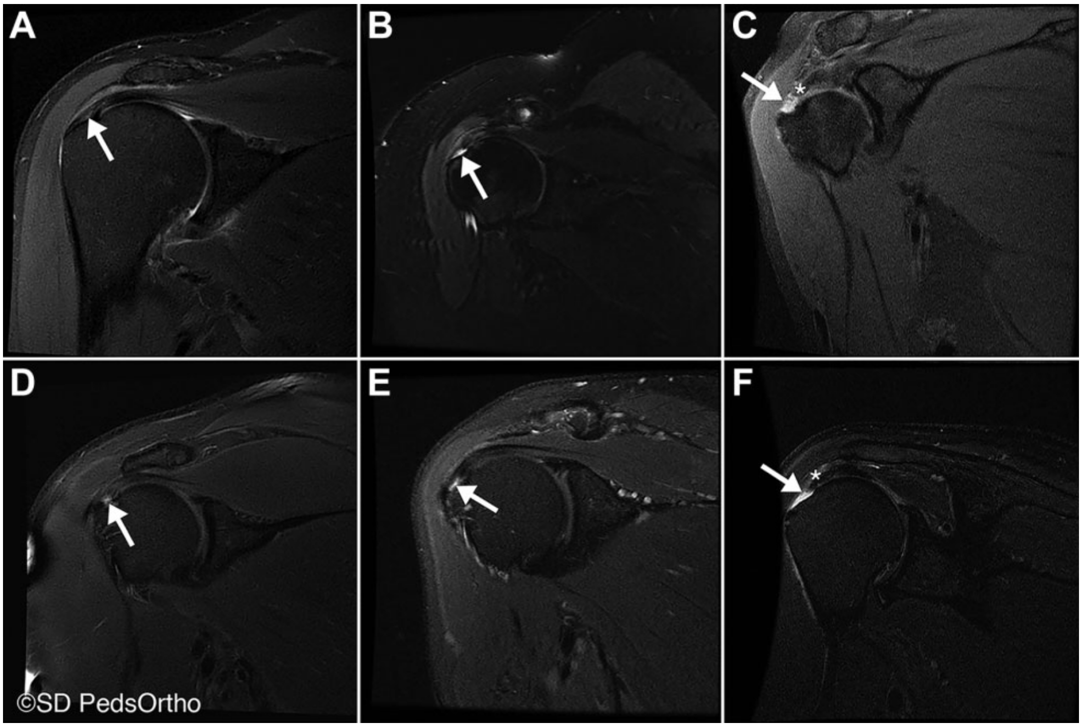

Figure 2. Coronal T2-weighted sequences of supraspinatus tears demonstrating (A) a low-grade, intrasubstance, partial-thickness tear of the distal supraspinatus tendon (arrow); (B and E) a high-grade, articular-sided, partial-thickness tear of the distal supraspinatus tendon (arrows); (D) a moderate-grade, articular-sided, partial-thickness tear of the distal supraspinatus tendon (arrow); and (C and F) a full-thickness tear of the distal supraspinatus tendon (arrows). Asterisks denote retracted tendon fibers. Images courtesy of SD Peds Ortho.

TABLE 1
Intra- and Interobserver Reliability Statistics for the Measurement of AHI on MRI[a]

	ICC for AHI
Intraobserver agreement	
Reviewer 1	0.95
Reviewer 2	0.93
Reviewer 3	0.95
Reviewer 4	0.88
Interobserver agreement	0.97

[a]The intraclass correlation coefficient (ICC) indicated excellent agreement for all measurements. AHI, acromiohumeral interval; MRI, magnetic resonance imaging.

TABLE 2
Mean AHI Based on the Presence or Absence of Rotator Cuff Tear[a]

	n	AHI, mm, mean ± SD	*P* Value
Presence of tear			.161
No tear	58	8.7 ± 1.7	
Tear	199	8.3 ± 1.9	
Total	257	8.4 ± 1.9	

[a]AHI, acromiohumeral interval.

TABLE 3
Mean AHI Based on Type of Rotator Cuff Tear[a]

Tear Type	n (%)	AHI, mm, mean ± SD
Supraspinatus tendon	174 (68)	8.4 ± 1.9
Infraspinatus tendon	119 (46)	8.0 ± 2.1
Subscapularis tendon	80 (31)	8.2 ± 2.2
Teres minor tendon	3 (0.1)	5.5 ± 1.4

[a]AHI, acromiohumeral interval.

of the 4 different tendon tears is seen in Table 3. The corresponding AHI is also demonstrated; however, because of many patients having multiple tears, statistical comparison of these averages is not reported.

Table 4 demonstrates the frequency of grade of tear for each of the 4 tear types, with percentages calculated relative to the entire cohort. Figure 3 shows the AHI for each grade within each tear type. Full-thickness supraspinatus tendon tears were associated with decreased AHI (7.1 mm) when compared with low-, moderate-, or high-grade supraspinatus tears ($P < .001$). Likewise, full-thickness infraspinatus tendon tears were associated with decreased AHI (5.3 mm) when compared with all other grades of infraspinatus tear ($P < .001$). Regarding the subscapularis tendon, full-thickness tears were associated with decreased AHI (6.8 mm) compared with all tear severities except for high-grade tears ($P < .001$). The frequency of the different complete tear combinations and their AHIs is seen in Table 5.

TABLE 4
Frequency Breakdown of Tear Severity Within Each Tear Type

	n (%)
Supraspinatus tendon	
No tear	83 (32)
Low grade	60 (23)
Moderate grade	35 (14)
High grade	33 (13)
Complete	46 (18)
Infraspinatus tendon	
No tear	138 (54)
Low grade	75 (29)
Moderate grade	16 (6)
High grade	12 (5)
Complete	16 (6)
Subscapularis tendon	
No tear	177 (69)
Low grade	35 (14)
Moderate grade	21 (8)
High grade	9 (3.5)
Complete	15 (6)
Teres minor tendon	
No tear	254 (99)
Low grade	2 (0.8)
Moderate grade	0 (0)
High grade	1 (0.4)
Complete	0 (0)

Acromiohumeral Interval

Higher-degree tears of the supraspinatus, infraspinatus, or teres minor tendons were associated with significant decreases in AHI (Table 6).

Patients With Multiple Tears

In patients with multiple tears, having a larger number of torn rotator cuff tendons was associated with decreased AHI ($\rho = -0.157$; $P = .012$) (Table 6). The frequency of the grade of the most severely torn tendon is seen in Table 7. When analyzing the relationship between the most severely torn tendon and AHI, any full-thickness tear was associated with a decrease in AHI (7.23 mm) compared with a low-, moderate-, or high-grade tear ($P < .002$ for all) (Figure 4).

There were 15 isolated infraspinatus tendon tears that were associated with the lowest AHI (7.7 mm), which was significantly less than the AHI for the 51 isolated supraspinatus tendon tears (8.9 mm; $P = .047$). The only other tendon with isolated tears was the subscapularis, having 9 tears and an average AHI of 8.4 mm, which did not differ from the other 2 tear types ($P > .10$).

DISCUSSION

Before this study, there was mixed consensus in the literature in terms of which rotator cuff tendons were most responsible for maintaining the stability of the

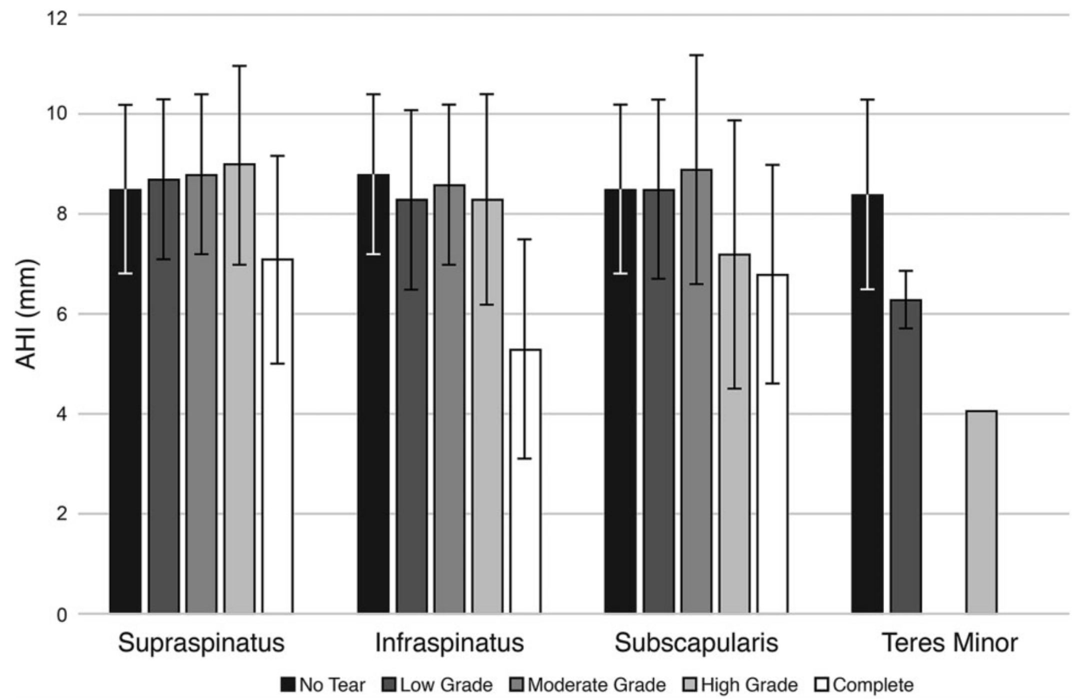

Figure 3. Mean acromiohumeral interval (AHI) for differing grades of rotator cuff tear for each tendon. There were not enough events to compare means for teres minor tears. The difference in means was significant at the .01 level for complete supraspinatus and infraspinatus tears compared with other tear severities ($P < .001$; 2-tailed). The difference in means was significant at the .05 level for complete subscapularis tears compared with all but high-grade tears ($P < .05$; 2-tailed). Error bars indicate SDs.

TABLE 5
Frequency of Different Combinations of Complete Tears With Their Associated AHIs[a]

Complete Tears	n	AHI, mm, mean ± SD
1 tendon		
Supraspinatus	27	8.1 ± 1.4
Infraspinatus	1	8.4
Subscapularis	4	8.5 ± 1.9
2 tendons		
Supraspinatus and infraspinatus	10	5.1 ± 2.1
Supraspinatus and subscapularis	4	7.5 ± 1.4
3 tendons		
Supraspinatus, infraspinatus, and subscapularis	5	5.4 ± 2.2
Supraspinatus, infraspinatus, and teres minor	0	N/A
4 tendons	0	N/A

[a]AHI, acromiohumeral interval; N/A, not applicable.

TABLE 6
Relationship Between AHI and Tear Severity and Number[a]

	Spearman ρ	P Value
More severe tears		
Supraspinatus tendon	–0.138[b]	**.027**
Infraspinatus tendon	–0.286[c]	**<.001**
Subscapularis tendon	–0.084	.178
Teres minor tendon	–0.159[b]	**.011**
No. of tears	–0.157[b]	**.012**

[a]Bolded values indicate statistical significance ($P < .05$). AHI, acromiohumeral interval.
[b]Correlation significant at the .05 level (2-tailed; $P < .05$).
[c]Correlation significant at the .01 level (2-tailed; $P < .001$).

glenohumeral joint and preventing superior migration associated with RCA. We found that full-thickness tears of the supraspinatus, infraspinatus, and subscapularis tendons were all associated with a significant decrease in AHI. This finding agrees with previous literature and offers a potential explanation for the heterogeneity of previous studies' conclusions.[2,3,5,11] The previous studies all offered different explanations but had smaller sample sizes compared with the present study. Given these present findings, we believe that any complete rotator cuff tendon tear (apart from teres minor because of the rarity of that pathology) as well as combinations of complete tears, especially those involving the infraspinatus, may destabilize the shoulder and compromise the dynamic shoulder stabilizers enough to allow the humeral head to escape superiorly as a result of the now unbalanced pull of the deltoid muscle.

In a small study of 5 cadavers, Sharkey and Marder[11] discovered that all components of the rotator cuff influenced the stability of the glenohumeral joint. Halder et al[5] found in 10 cadavers that superior humeral stability was a function of the infraspinatus and subscapularis tendons more than was the supraspinatus tendon. Bezer et al[2] offered a different explanation: the subscapularis was the major contributor to preventing superior migration of the

TABLE 7
Frequency of the Grade of the Most Severely Torn Tendon for Each Patient

Grade	No. of Patients (%)
No tear	58 (22.6)
Low grade	75 (29.2)
Moderate grade	37 (14.4)
High grade	36 (14.0)
Complete	51 (19.8)
Total	257 (100.0)

humeral head. Cetinkaya et al[3] directly contradicted all of the previous studies and found that isolated supraspinatus tears led to superior humeral migration even in the absence of a subscapularis tear. While these studies had different conclusions, they were all severely limited by sample sizes compared with the present study.

High-grade tears of the subscapularis tendon were the sole incomplete tear in the present study, with an AHI not significantly different from that of a full-thickness tear. This finding would seem to agree with the findings of Bezer et al[2] of 27 MRI scans because the presence of a high-grade tear in any other rotator cuff tendon was associated with a greater AHI than was the presence of a full-thickness tear. However, the effect size is still relatively small, and as noted, complete tears of any of the rotator cuff tendons may contribute significantly to superior humeral migration.

Interestingly, our findings suggest that of all rotator cuff tendons, tears of the infraspinatus are correlated with the smallest AHI. Higher-degree infraspinatus tears were associated with the largest decrease in AHI (>3 mm). Moreover, isolated infraspinatus tears were associated with a lower average AHI compared with isolated supraspinatus tears or a combination of tears. These findings may be explained by the broad insertion of the infraspinatus on the greater tuberosity, described anatomically by Mochizuki and colleagues[8] in a study of 113 cadaveric shoulders. In addition, the force vector of the infraspinatus has been shown to create an inferiorly directed shearing force of the humeral head on the glenoid.[1] This may explain the higher incidence of superior humeral head migration in the presence of full-thickness infraspinatus tears that was observed in this study. Although tears of any of the rotator cuff tendons can decrease the glenohumeral joint reactive force, the specific force vector deficit created by loss of a specific tendon may play an important role in the rate of development in RCA. Keener et al,[7] who used radiographs and ultrasound, found that tears involving the infraspinatus either alone or in conjunction with the supraspinatus led to more superior migration than did tears of the supraspinatus alone. They concluded that painful rotator cuff tears that extend into the infraspinatus predictably disrupted glenohumeral kinematics to the point that early surgery should be considered for larger tears to reestablish the force couple. A limitation of their study was grouping isolated infraspinatus tears with combined

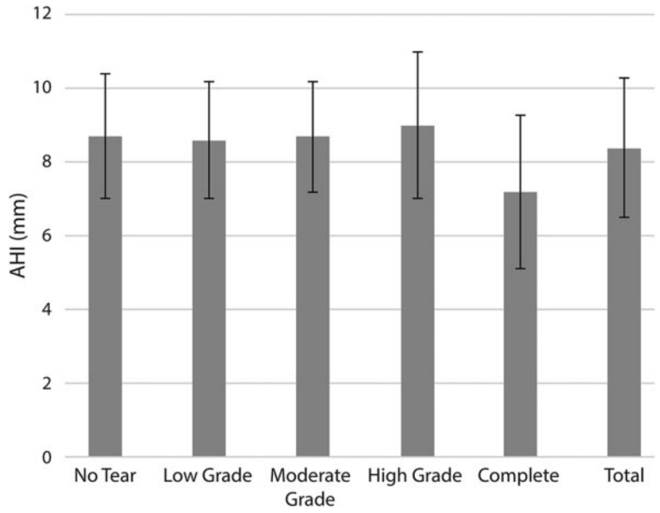

Figure 4. Relationship between the most severely torn rotator cuff tendon and acromiohumeral interval (AHI). Subgroup analysis comparing complete tears to all other tear grades revealed significantly lower AHI with a complete tear of any rotator cuff tendon ($P < .002$).

supraspinatus and infraspinatus tears because of the small sample size. Our study encountered a similar drawback, as our cohort only contained 15 isolated infraspinatus tears. Nonetheless, despite the small sample sizes of isolated infraspinatus tears in both studies, because of the rarity of this pathology in clinical practice, understanding the noteworthy effect of the infraspinatus on preventing superior humeral migration is vital to achieving a better understanding of rotator cuff and shoulder biomechanics.

Our study is not without its own limitations. The retrospective study design limited the ability to confirm rotator cuff pathology surgically in all patients. In addition, MRI scans were obtained with patients in the supine position, which may have affected the measurement of AHI, which was historically done on an upright plain film. However, although we could not obtain upright MRIs, all patients were positioned uniformly supine, thus minimizing variability in positioning. Moreover, this study used measurements from 4 different authors, and the specific slice measured was chosen at the discretion of the rater. While this may sometimes introduce heterogeneity of measurements, we believe that this results in greater generalizability to the population mimicking more of a real-life scenario of measurement. The average of each rater's 2 measurements were utilized for the interrater assessment, likely representing the phenomenon of regression toward the mean and thus a more accurate assessment of the true mean AHI. Furthermore, intra- and interobserver reliability were excellent (ICC $\geq$ 0.88) for all measurements. We believe the interrater measures were higher than were the interrater ones because of the averaging methodology utilized. Last, this study did not examine muscle atrophy, duration of symptoms, or capsular tears, which may affect AHI and are interesting future study directions.

CONCLUSION

Although various types of rotator cuff tears have been historically associated with humeral head migration and subsequent RCA, our study demonstrated that a complete tear in any rotator cuff tendon compromises the dynamic shoulder stabilizers and leads to significant superior humeral migration. The infraspinatus seemed to have the greatest effect on maintaining the native position of the humeral head perhaps because of the large footprint of the infraspinatus on the greater tuberosity. Further studies are needed to determine whether early repair of any full-thickness rotator cuff tear, especially one of the infraspinatus, can slow the fatty degeneration of the muscle that predisposes patients to failures of rotator cuff repair and, moreover, slow the progression of RCA.

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