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Quantitative evaluation of natural progression of fatty infiltration and muscle atrophy in chronic rotator cuff tears without tear extension using magnetic resonance imaging

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Background: The pathology of and mechanisms underlying muscle degeneration remain unclear. We aimed to quantitatively evaluate the natural changes in fatty infiltration and muscle atrophy in patients with chronic rotator cuff tears using 3-dimensional 2-point Dixon magnetic resonance imaging.

Methods: Thirty patients with nonoperatively observed rotator cuff tears without tear extension were evaluated using multiple magnetic resonance imaging examinations with a minimum interval of 2 years. The fatty infiltration ratio (%fat) and muscle volume of the rotator cuff muscles were compared between the 2 examinations in those with supraspinatus (SSP) tear <2 cm (<2 cm SSP group), SSP tear ≥2 cm (≥2 cm SSP group), and massive tear (massive group). The SSP) infraspinatus, and teres minor (ISP + TM), and subscapularis muscles were evaluated.

Results: The massive group showed a significantly greater %fat than the <2 and ≥2 cm SSP groups in the SSP ($P = .002$) and ISP + TM muscles ($P < .001$). The total muscle volume did not differ among the 3 groups for all rotator cuff muscle components. The %fat values did not change in any rotator cuff components during the follow-up period in all groups. The total muscle volume in the massive group significantly decreased in the SSP ($P = .018$) and ISP + TM muscles ($P = .013$).

Conclusion: The present results indicate that fatty infiltration of the torn muscle occurs in the early phase after a rotator cuff tear, whereas muscle atrophy appears to progress gradually in chronic rotator cuff tears. Early intervention before muscle degeneration should be considered if the tear involves the infraspinatus tendon.

The clinical outcomes of rotator cuff repair are generally favorable.[28] However, the presence of muscle atrophy and fatty infiltration of the torn muscles is a predictor of irreparable tears[8] and a risk factor for retear after surgical repair of rotator cuff tears.[7,12] Although muscle degeneration is related to poor clinical outcomes, its pathology and the mechanisms of the muscle degeneration remain unclear.

Fatty infiltration and muscle atrophy of the rotator cuff muscles were originally assessed on computed tomography scans,[8,9] but muscular degeneration is now mainly evaluated on magnetic resonance imaging (MRI).[4,6,7] The Goutallier grading classification is widely used for the assessment of muscular fatty infiltration, and rotator cuff tears with muscular fatty infiltration grades 3 and 4 are believed to be irreparable.[8,9,18,19] A cross section of an oblique sagittal image can show the fatty infiltration of all rotator cuff muscles in the same slice.[4,6,7] Similarly, atrophy of the rotator cuff muscles is usually assessed with the tangent sign or occupation ratio on the oblique sagittal slice of MRI.[7,30,34] However, muscular retraction following tendon tear is reported to cause overestimation of the fatty infiltration and muscle atrophy due to assessment of a different part of the muscles.[5,11,32] Recently, the Dixon-based water-fat separation technique,[2,3] which enables precise quantification of the muscle/fat fraction, is reported to assess fatty infiltration of the rotator cuff muscles.[13,15,20-22] Furthermore, recent 3-dimensional MRI enables quantitative analysis of the whole rotator cuff muscles.[10,17]

Several previous studies have quantitatively evaluated the condition of the rotator cuff muscles.[3,13,17,22] However, the natural progression of muscle degeneration has rarely been assessed,[1] and

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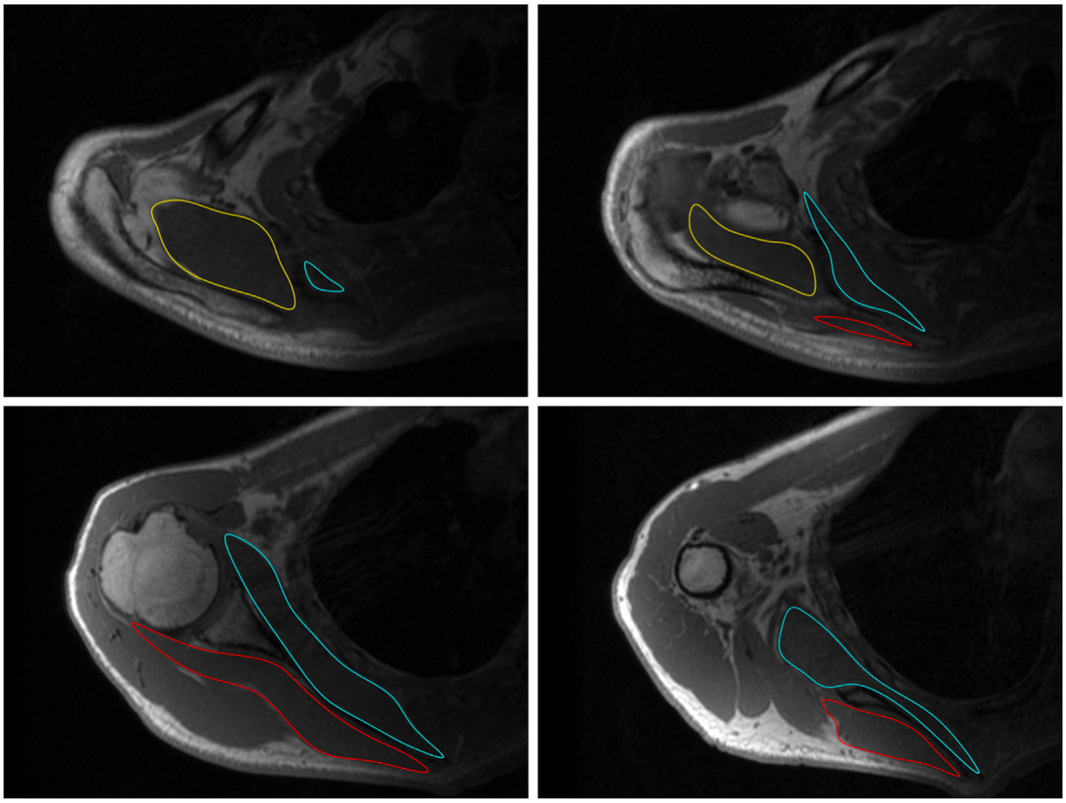

Figure 1 Segmentation of the boundaries of the rotator cuff muscles on the in-phase images of a 3-dimensional 2-point Dixon MRI. The muscle boundaries of the SSP, ISP and TM, and SSC muscles are manually outlined on all slices, including the rotator cuff muscles of in-phase axial images of the 3-dimensional 2-point Dixon sequence (*yellow line*, SSP muscle; *red line*, ISP and TM muscles; *blue line*, SSC muscle). *SSP*, suprapsinatus muscle; *ISP*, infraspinatus muscle; *TM*, teres minor muscle; *SSC*, subscapularis muscle; *MRI*, magnetic resonance imaging.

no study has quantitatively evaluated the entire rotator cuff muscles. It is important to understand the pathology and mechanisms underlying muscle degeneration. This study aimed to quantitatively evaluate the natural changes in fatty infiltration and atrophy of the rotator cuff muscles in patients with chronic rotator cuff tears using 3-dimensional 2-point Dixon MRI. We hypothesized that fatty infiltration and muscle atrophy of the torn muscles progress during the follow-up period in cases with chronic rotator cuff tears.

Materials and methods

Patients

Nonoperatively observed patients with chronic full-thickness rotator cuff tears were prospectively evaluated by multiple MRI examinations, including a 3-dimensional 2-point Dixon sequence with a minimum interval of 2 years. The inclusion criteria were patients with isolated supraspinatus (SSP) tears or massive rotator cuff tears involving the SSP and infraspinatus (ISP) tendons, under conservative observation for more than 2 years, and with chronic tears with symptom duration at the time of the first MRI of more than 6 months. Those with tear involving the subscapularis (SSC) tendon as well as those who underwent surgical intervention during follow-up period were excluded.

In MRI examinations on a 3.0-T MR scanner (Discovery MR 750; GE Healthcare, Milwaukee, WI, USA), axial images of 3-dimensional 2-point Dixon sequence were taken to include the entire scapula in addition to routine sequences of the shoulder. The 3-dimensional 2-point Dixon sequence created in-phase, out-of-phase, water-only, and fat-only images during the same scanning session. The imaging parameters of the sequence used were as follows: acquisition matrix size, 288×224 mm^2; repetition time/echo time, 4.2/1.7; flip angle, 1°; field of view, 260 mm; number of excitations, 2; slice thickness, 2×1 mm; slice spacing using the zero-fill interpolation processing technique.

Radiographic analysis

OsiriX MD version 13.0.2 (Pixmeo, Geneva, Switzerland) was used for radiographic analysis. First, tear size was measured as the maximum distance from the most lateral portion of the footprint on the greater tuberosity to the torn tendon edge of the SSP tendon on fat-suppressed T2-weighted oblique coronal slices.[5,15,21] The muscle boundaries of the SSP, ISP and teres minor (ISP + TM), and SSC muscles were manually outlined on all MRI slices, including the rotator cuff muscles of the in-phase axial images of the 3-dimensional 2-point Dixon sequence (Fig. 1). Each component of the rotator cuff muscles was identified on the MRI slices, and the fat portion outside the muscles was excluded from the segmentation of the muscles. In case muscle boundaries were difficult to identify on in-phase images, the other 3 sequence images were referred to determine the outline. Determining the border between the ISP and TM muscles was difficult in some cases; hence, they were evaluated together in this study.

After segmentation of the muscle boundaries of all slices, including the rotator cuff muscles, atrophy and fatty infiltration of the rotator cuff muscles were assessed. The SSP, ISP + TM, and SSC muscles were evaluated (Fig. 2). Fatty infiltration was measured using signal intensities for fat images (SI_{fat}) and water images (SI_{water}) using the Dixon method. The fatty infiltration ratio (%fat) was computed as $SI_{fat}/(SI_{fat} + SI_{water})$.[15,21,22,32] The signal intensity values were computed on a voxel-by-voxel basis and averaged

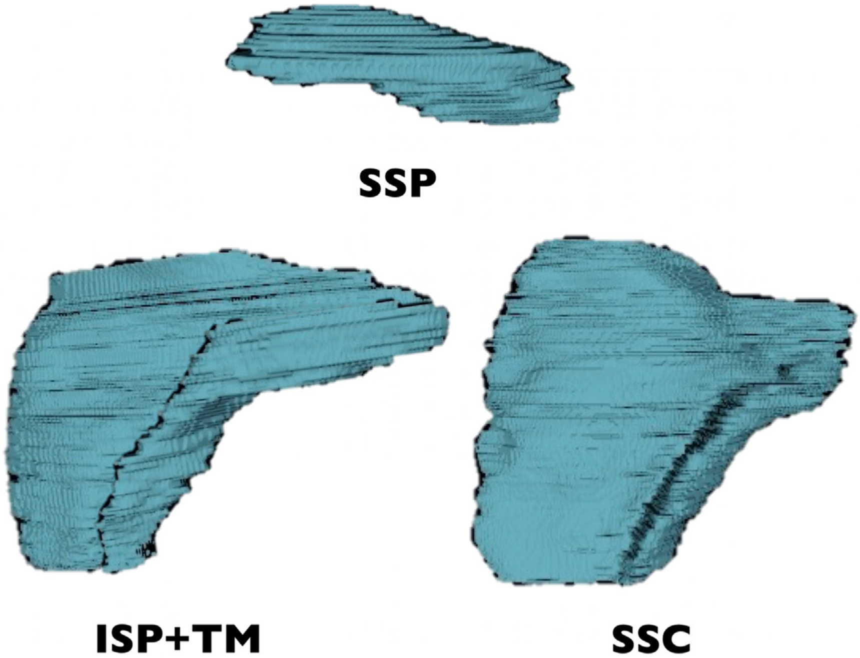

Figure 2 Three-dimensional surfaces of the SSP muscle (*Left*), ISP and TM muscles (*Middle*), and SSC muscle (*Right*). *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle.

across all voxels in the whole muscle. Then, the 3-dimensional whole-muscle volume of each rotator cuff muscle was evaluated.[10,31,32] Fat volume was converted by multiplying the total muscle volume and %fat, and the fat-free volume of each muscle was also calculated by subtracting the fat volume from the total muscle volume.[32] The reproducibility of the 3-dimensional quantitative assessment of fatty infiltration and muscle volume was reported to be excellent.[17]

Statistical analysis

SPSS Statistics version 28.0.1.0 (IBM Corp., Armonk, NY, USA) was used for statistical analyses. Intraclass correlation coefficients (ICCs) were used to evaluate intrarater and interrater reliabilities for the %fat and total muscle volume in randomly selected 10 cases. Repeated measurements by 2 observers with a 1-month interval (ICC model 1,1) and blinded measurements by 2 observers (ICC model 2,1) were performed. After reliabilities were evaluated, differences in tendon tear size, %fat, total muscle volume, fat volume, and fat-free muscle volume were evaluated by 1 observer, and the values between the first and second MRI scans were compared using paired *t*-tests.

Then, subanalyses among rotator cuff tear groups were performed. Patient characteristics (age, height, weight, symptom duration, duration between the first and second MRI examinations, and range of active elevation) and radiographic parameters at the time of the first MRI (tear size, %fat, total muscle volume, fat volume, and fat-free muscle volume of each muscle) were compared among those with isolated SSP tear with a length of tear <2 cm (<2 cm SSP group, n = 7 shoulders), those with isolated SSP tear with a length of tear ≥2 cm (≥2 cm SSP group, n = 10 shoulders), and those with massive tear involving the SSP and ISP tendons (massive group, n = 13 shoulders) using 1-way analysis of variance. With significant effects, post hoc Student's *t*-tests with Bonferroni correction were performed to identify the differences between the groups. Differences in tendon tear size, %fat, total muscle volume, fat volume, and fat-free muscle volume in each group were compared between the first and second MRI scans using paired *t*-tests. The significance level was set at 0.05 in all analyses.

Results

Two patients with tear involving the SSC tendon and five patients who underwent surgical intervention during the follow-up period were excluded. In a patient with an isolated SSP tendon tear in the first MRI, obvious extension of rotator cuff tear to the ISP tendon and superior part of the SSC tendon was found in the second MRI. In this patient, the tear size progressed from 2.5 to 4.7 cm, %fat increased in SSP (from 22.4% to 50.6%), ISP + TM (from 17.5% to 35.7%), and SSC (from 6.1% to 21.1%), and muscle volume decreased in SSP (from 28.9 to 25.0 cm^3), ISP + TM (from 147.7 to 104.1 cm^3), and SSC (from 116.2 to 113.2 cm^3). Meanwhile, no obvious progression of cuff tear was found in the other patients, and the tear size values were not significantly different between the first and second examinations (3.0 ± 1.3 to 3.0 ± 1.2 cm, $P = .584$). Thus, 1 case with tear extension was excluded from the statistical analyses. Finally, 30 chronic rotator cuff tears without tear extension (11 men and 19 women) were statistically analyzed in this study. The average age of the patients was 71.4 ± 8.4 years (range, 52.9-83.9 years), and the average duration of symptoms at the time of the first MRI evaluation was 2.4 ± 2.8 years (range, 0.5-11.3 years). The average duration between the first and the second MRI examinations was 2.7 ± 0.8 years (range, 2.0-4.5 years), and the average range of active elevation of the affected shoulder was 145° ± 8° (range, 120°-150°). The clinical symptoms of the patients did not worsen during follow-up.

Intrarater and inter-rater reliabilities for %fat exceeded 0.96 in all rotator cuff muscles. Compared with those of %fat, the reliabilities for total muscle volume were relatively low but exceeded 0.9 in all analyses and were regarded as excellent (Table I). The %fat values did not change in any rotator cuff component during the follow-up period (SSP, $P = .707$; ISP + TM,

Table I
Intrarater and inter-rater reliabilities of quantitative evaluation of the rotator cuff muscles.

	ICC (95% CI)	
	Intrarater reliability	Inter-rater reliability
Fatty infiltration ratio		
SSP	0.988 (0.955-0.997)	0.980 (0.924-0.995)
ISP + TM	0.997 (0.988-0.999)	0.997 (0.989-0.999)
SSC	0.978 (0.919-0.994)	0.965 (0.865-0.991)
Total muscle volume		
SSP	0.932 (0.766-0.982)	0.906 (0.582-0.977)
ISP + TM	0.971 (0.895-0.993)	0.945 (0.794-0.986)
SSC	0.974 (0.907-0.993)	0.950 (0.822-0.987)

ICC, interclass correlation coefficient; *CI*, confidence interval; *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscle; *SSC*, subscapularis muscle.

Table II
Differences in MRI parameters between the first and second scans.

	First MRI	Second MRI	*P* value
Tear size (cm)	3.0 ± 1.3	3.0 ± 1.2	.584
Fatty infiltration ratio (%)			
SSP	29.2 ± 14.4	29.7 ± 14.6	.707
ISP + TM	25.5 ± 13.7	25.6 ± 15.0	.903
SSC	19.0 ± 4.3	18.8 ± 6.7	.837
Total muscle volume (cm^3)			
SSP	20.5 ± 6.3	18.2 ± 6.8	.004†
ISP + TM	78.8 ± 28.6	72.9 ± 31.7	.011*
SSC	87.3 ± 28.3	83.1 ± 26.8	.009†
Fat volume (cm^3)			
SSP	5.7 ± 2.8	5.0 ± 2.2	.117
ISP + TM	18.2 ± 7.7	16.9 ± 9.1	.247
SSC	16.5 ± 5.8	15.6 ± 7.9	.343
Fat-free muscle volume (cm^3)			
SSP	14.8 ± 6.3	13.2 ± 6.7	<.001‡
ISP + TM	60.6 ± 28.5	56.1 ± 31.2	.016*
SSC	70.8 ± 23.8	67.1 ± 22.8	.019*

MRI, magnetic resonance imaging; *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle.
* $P < .05$.
† $P < .01$.
‡ $P < .001$.

P = .903; SSC, P = .837). Meanwhile, the total muscle volume significantly decreased in all components (SSP, P = .004; ISP + TM, P = .011; SSC P = .009). Although the fat volume values did not differ between the 2 examinations (SSP, P = .117; ISP + TM, P = .247; SSC, P = .343), the fat-free muscle volume significantly decreased in all muscles (SSP, $P < .001$; ISP + TM, P = .016; SSC, P = .019) (Table II).

No significant differences were found among the 3 groups with respect to age (P = .162), height (P = .714), weight (P = .375), duration of symptoms (P = .718), duration between the first and second MRI examinations (P = .187), and range of active elevation of the affected shoulder (P = .751). Tear size values were significantly higher in the massive group (4.3 ± 0.4 cm; range, 3.6-5.2 cm) followed by the ≥2 cm SSP (2.3 ± 0.3 cm; range, 2.0-2.8 cm) and <2 cm SSP groups (1.5 ± 0.3 cm; range, 1.0-1.9 cm) ($P < .001$ for all). The massive group showed a significantly greater %fat than the <2 and ≥2 cm SSP groups in the SSP (P = .011 and P = .004, respectively) and ISP + TM muscles ($P < .001$ for both), but there was no significant difference in the SSC muscle (P = .154). The total muscle volumes were not different among the three groups in the SSP (P = .665), ISP + TM (P = .162), or SSC muscle (P = .426). The fat volumes in the SSP muscle were significantly larger in the massive group than in the ≥2 cm SSP group (P = .022). The fat volumes in the ISP + TM muscles were significantly larger in the massive group than in the <2 cm SSP (P = .007) and ≥2 cm SSP groups ($P < .001$). The fat-free muscle volume in ISP + TM muscles was significantly smaller in the massive group than in the <2 cm SSP group (P = .021). There was no significant difference among the 3 groups in fat volume of the SSC muscle (P = .514) or fat-free muscle volume of the SSP (P = .095) and SSC muscles (P = .394). No significant difference in %fat, total muscle volume, fat volume, or fat-free volume of all rotator cuff muscles was found between the <2 and ≥2 cm SSP groups (Table III).

The tear size values were not significantly different between the first and second examinations in the <2 cm SSP (from 1.5 ± 0.3 to 1.6 ± 0.3 cm, P = .654), ≥2 cm SSP (from 2.3 ± 0.3 to 2.5 ± 0.4 cm, P = .145), or massive group (from 4.3 ± 0.4 to 4.2 ± 0.5 cm, P = .490). The %fat values did not change in any rotator cuff component

Table III
Demographic parameters of the patients.

	<2-cm SSP group (n = 7)	≥2-cm SSP group (n = 10)	Massive group (n = 13)	*P* value
Age (y)	66.3 ± 7.8	71.9 ± 8.5	73.8 ± 8.0	.162
Height (cm)	162.3 ± 10.1	160.5 ± 13.2	158.6 ± 5.4	.714
Weight (kg)	64.8 ± 12.0	58.3 ± 11.5	58.4 ± 8.9	.375
Duration of symptoms (y)	2.5 ± 3.8	2.3 ± 2.0	3.3 ± 3.2	.718
Interval between MRI (y)	3.2 ± 1.0	2.7 ± 0.8	2.4 ± 0.7	.187
Active elevation (degrees)	147.1 ± 4.9	146.5 ± 6.7	144.6 ± 9.7	.751
Tear size (cm)	1.5 ± 0.3	2.3 ± 0.3	4.3 ± 0.4	<.001‡
Fatty infiltration ratio (%)				
SSP	21.7 ± 5.1	21.5 ± 7.5	39.1 ± 15.9	.002†
ISP + TM	15.2 ± 3.9	18.3 ± 7.6	36.5 ± 13.0	<.001‡
SSC	17.9 ± 3.7	17.6 ± 4.6	20.8 ± 4.0	.154
Total muscle volume (cm^3)				
SSP	21.8 ± 7.4	21.2 ± 7.3	19.4 ± 4.9	.665
ISP + TM	95.2 ± 34.4	79.4 ± 32.6	69.6 ± 18.3	.162
SSC	99.7 ± 37.1	84.8 ± 32.3	82.6 ± 18.6	.426
Fat volume (cm^3)				
SSP	4.6 ± 1.5	4.3 ± 1.6	7.3 ± 3.2	.013*
ISP + TM	14.7 ± 6.9	13.0 ± 3.4	24.0 ± 6.7	<.001‡
SSC	18.2 ± 7.7	14.5 ± 5.4	17.1 ± 5.1	.514
Fat-free muscle volume (cm^3)				
SSP	17.2 ± 6.3	16.8 ± 6.6	12.0 ± 5.2	.095
ISP + TM	80.4 ± 28.3	66.4 ± 31.4	45.6 ± 17.9	.019*
SSC	81.4 ± 29.9	70.3 ± 28.1	65.4 ± 15.1	.394

SSP, supraspinatus muscle; *MRI*, magnetic resonance imaging; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle.
* $P < .05$.
† $P < .01$.
‡ $P < .001$.

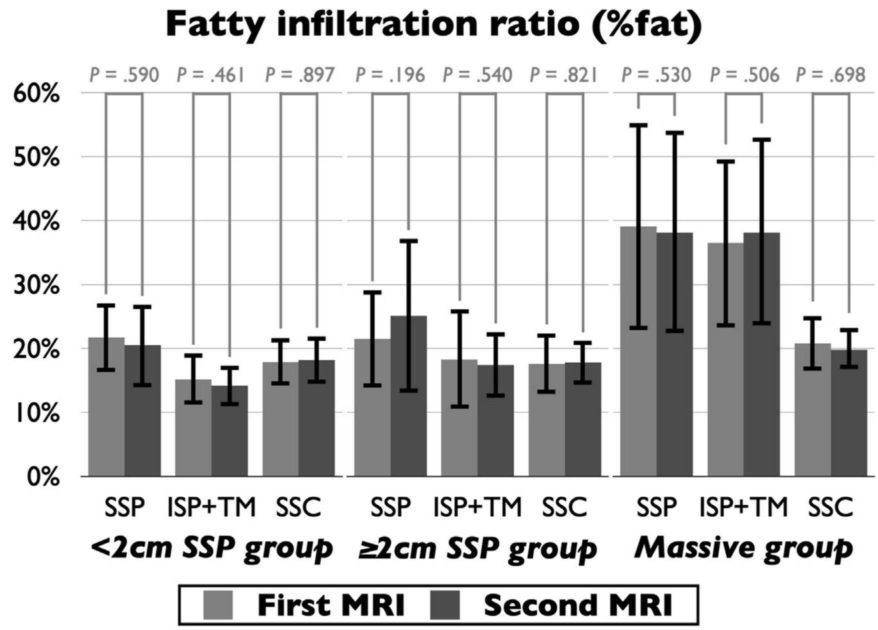

Figure 3 Fatty infiltration ratio (%fat). *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle; *MRI*, magnetic resonance imaging.

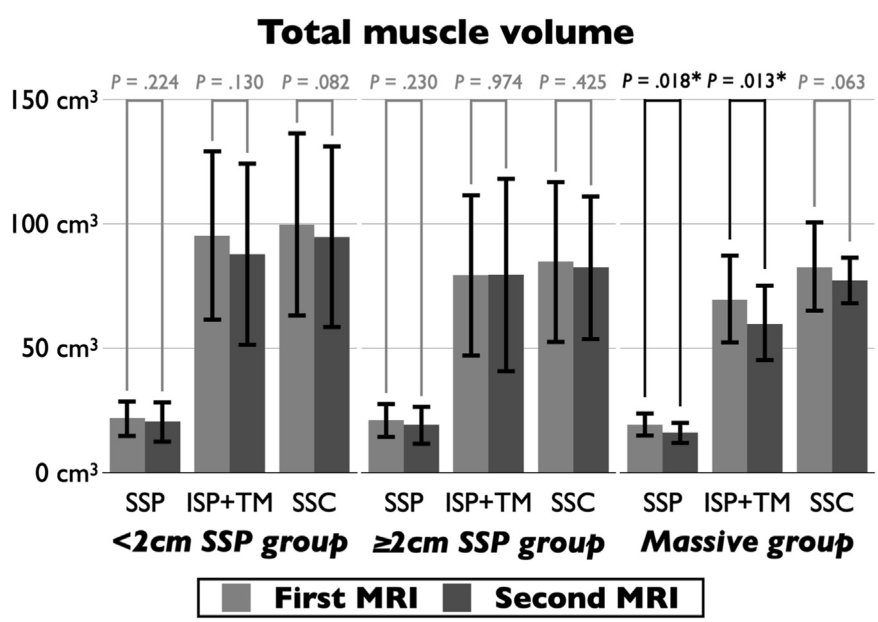

Figure 4 Total muscle volume. *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle; *MRI*, magnetic resonance imaging; *$P < .05$.

during the follow-up period in the <2 cm SSP (SSP, $P = .590$; ISP + TM, $P = .461$; SSC, $P = .897$), ≥2 cm SSP (SSP, $P = .196$; ISP + TM, $P = .540$; SSC, $P = .821$), or massive group (SSP, $P = .530$; ISP + TM, $P = .506$; SSC, $P = .698$) (Fig. 3). Although the total muscle volume did not differ between the 2 examinations in the <2 cm SSP (SSP, $P = .224$; ISP + TM, $P = .130$; SSC, $P = .082$) and ≥2 cm SSP groups (SSP, $P = .230$; ISP + TM, $P = .974$; SSC, $P = .425$), the total muscle volume in the massive group significantly decreased in the SSP ($P = .018$) and ISP + TM muscles ($P = .013$). The SSC muscle in the massive group did not differ significantly between the 2 examinations ($P = .063$) (Fig. 4). The fat volume values in all muscle components did not differ between the 2 examinations in the <2 cm SSP (SSP, $P = .411$; ISP + TM, $P = .083$; SSC, $P = .479$), ≥2 cm SSP (SSP, $P = .877$; ISP + TM, $P = .852$; SSC, $P = .969$), or massive group (SSP, $P = .072$; ISP + TM, $P = .542$; SSC, $P = .475$) (Fig. 5). In contrast, the fat-free muscle volume significantly decreased in the SSP muscle of the ≥2 cm SSP group ($P = .041$), SSP muscle of the massive group ($P = .018$), and ISP + TM muscles of the massive group ($P = .010$) (Fig. 6).

Discussion

The present study quantitatively evaluated the natural changes in fatty infiltration and muscular volume after rotator cuff tears in the whole rotator cuff muscles. In chronic rotator cuff tear without tear extension, the fatty infiltration ratio and fat volume in the rotator cuff muscles did not change, but the total muscle volume

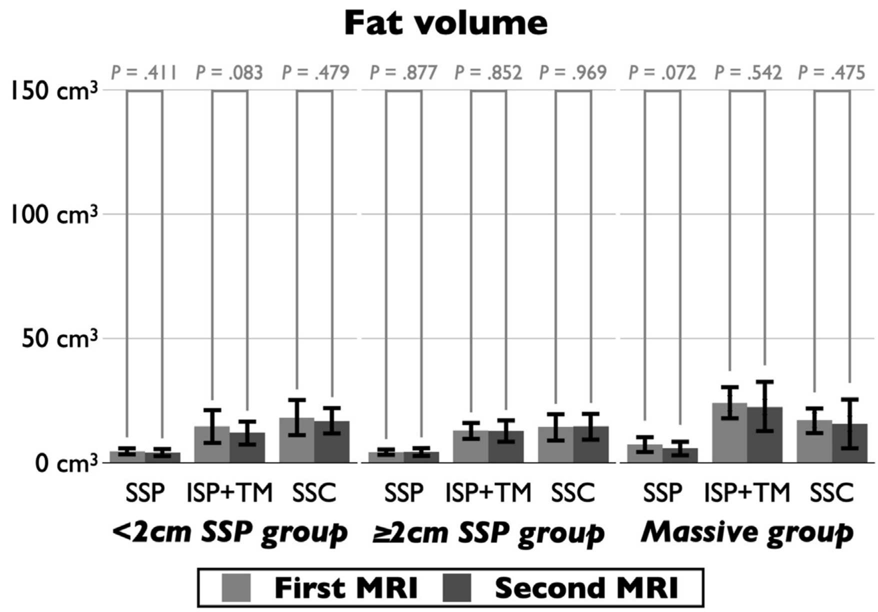

Figure 5 Fat volume. *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle; *MRI*, magnetic resonance imaging.

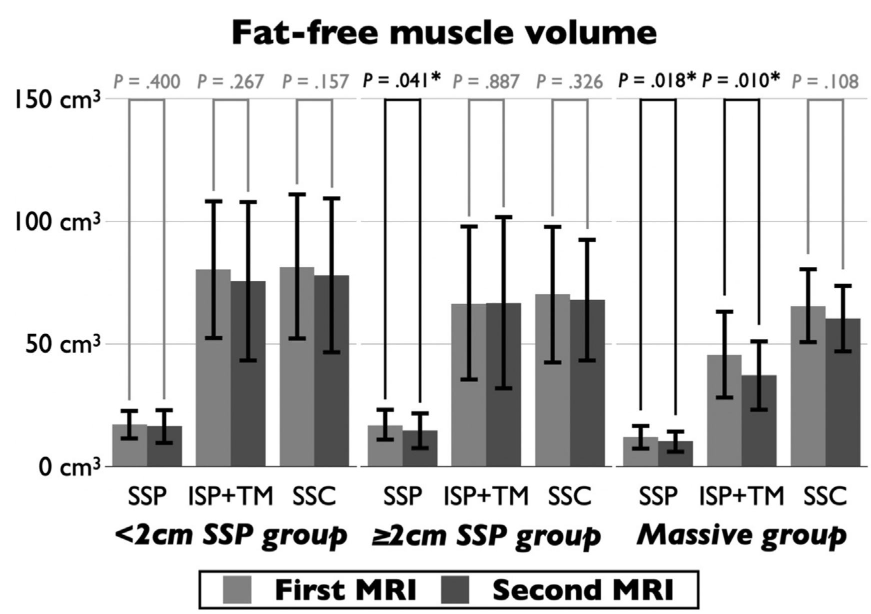

Figure 6 Fat-free muscle volume. *SSP*, supraspinatus muscle; *ISP + TM*, infraspinatus and teres minor muscles; *SSC*, subscapularis muscle; *MRI*, magnetic resonance imaging; *, *P* < .05.

and fat-free muscle volume decreased between 2 MRI scans. In previous studies,[18,22] the degree of muscular fatty infiltration is reported to be directly correlated with the degree of muscle atrophy. We hypothesized that fatty infiltration and muscle atrophy progress over time, but the present results indicate that fatty infiltration of the torn muscle occurs in the early phase after a rotator cuff tear, whereas muscle atrophy appears to progress gradually.

Muscular fatty infiltration was mainly assessed using the Goutallier classification on a single slice of oblique sagittal MRI.[4,6,7] However, the Goutallier classification is not a quantitative method and its reproducibility is limited.[23,25,27] Furthermore, the assessment of a single slice might not represent fatty infiltration of the whole muscle.[16,32] In addition, rotator cuff tears usually cause tendon retraction, and evaluation of scans at different time points might assess a different part of the muscles.[5,11] Vidt et al[32] compared the values of the 3-dimensional quantitative measurements of fatty infiltration and muscle atrophy with those of conventional single-image assessment and observed no associations between them. Although it remains unclear which measurement represents the muscular situation more accurately, this study evaluated the fatty infiltration of the entire rotator cuff muscle using the Dixon method to clarify the pathology and mechanism of muscle degeneration. In the assessment of fatty infiltration of the rotator cuff muscles, some recent studies have used 3- and 6-point Dixon MRIs.[13,14,35] However, 2-point Dixon-based MRI measurements have been reported to allow for accurate quantification of the muscle/fat fraction,[3,26] and we believe that this sequence has the advantage of short acquisition time and 3-dimensional imaging, which enables quantitative assessment of fatty infiltration of whole muscles and muscle volume.

In the present study, the massive group showed a greater %fat in the SSP and ISP + TM muscles than in the groups with isolated SSP tendon tear. The tears did not show an obvious extension between measurements, and the %fat or fat volume did not increase during an average follow-up period of 2.7 $\pm$ 0.8 years. Although the threshold of the %fat for irreparable tears remained unclear, the average %fat of the SSP muscle in groups of isolated SSP tendon tear (21.6%) was relatively close to that of the ISP + TM and SSC muscles whose tendons were not torn (16.0% and 18.0%, respectively). These results indicate that the SSP muscle does not cause severe fatty infiltration in cases of isolated SSP tears, but that fatty infiltration becomes severe in massive tears involving the ISP tendon. Meanwhile, a patient with tear extension to the ISP and SSC tendons after isolated SSP tear showed increased %fat in SSP, ISP + TM, and SSC. Compared with muscle atrophy, fatty infiltration of the torn muscle is believed to occur in the early phase after tendon rupture or tear extension. Based on the present results, isolated SSP tears can be observed if the patient is asymptomatic. However, early surgical repair should be considered when cuff tears involve the ISP tendon.

In contrast to fatty muscle infiltration, muscle atrophy progressed in the SSP and ISP + TM muscles of the massive group during follow-up. Although the fat volume did not change between the 2 examinations for all muscle components, the fat-free muscle volume significantly decreased in torn muscles, even without tear extension. As tear size did not increase during this period, the muscular portion was believed to gradually become atrophic, even with chronic tears. As the volume of the SSC muscle also decreased, muscle atrophy may be caused by a combination of tendon rupture, disuse atrophy due to decreased activity, and age-related degeneration. Although whether muscle atrophy is reversible remains debatable,[6,7,24,29] late intervention after the progression of muscular degeneration is believed to result in poor outcomes in patients with massive rotator cuff tears. The present results indicate that early intervention before muscle degeneration should be considered in patients with massive rotator cuff tears.

Fat volume and fat-free muscle volume were calculated from the %fat and total muscle volume. Although the total volume of the SSP muscle in the $\geq$2 cm SSP group did not show a significant difference between measurements, the fat-free muscle volume significantly decreased in our patients. Even with isolated SSP tendon tear, the SSP muscle might cause degenerative atrophy in cases with relatively large tear. The assessment of the total muscle volume included the fat portion in the muscle, and increased fatty infiltration in the muscles could possibly offset the effect of muscle atrophy. To evaluate the condition of the muscle accurately, the assessment of fat-free muscle volume, rather than total muscle volume, might be adequate.

This study has several limitations. First, it included a small sample of patients with rotator cuff tear who were nonoperatively observed with a minimum interval of 2 years. Although there were significant differences in muscle volume between the 2 examinations, an increased number may indicate significance in fatty infiltration. An average period of 2.7 years might be not enough to evaluate muscle degeneration, and a further study with a longer follow-up period is desirable to clarify the details of muscle degeneration. Second, this study evaluated the natural progression of muscle degeneration with a minimum interval of 2 years; however, the duration between the first and second MRI examinations was not uniform. The MRI interval ranged from 2.0 to 4.5 years, which might have affected the results. Furthermore, symptom duration of the patients ranged from 0.5 to 11.3 years. As determining the accurate time of tendon rupture is difficult, chronic tears with symptom duration of more than 6 months were included in this study. However, a nonconstant duration of symptoms could be a possible limitation. Third, the ISP + TM muscles were evaluated together during segmentation. Determining the border between the 2 muscles was difficult in some cases. The TM muscle is often absent, and hypertrophy and hypotrophy of the TM muscle frequently occur in cases of massive rotator cuff tears.[33] Although the TM muscle can be easily identified in cases with hypotrophic ISP muscle and hypertrophic TM muscle, segmentation became difficult if the ISP was hypertrophic. We considered that the segmentation between the ISP and TM muscles might cause incorrect results; hence, posterior external rotators were evaluated together in this study, and intrarater and inter-rater reliabilities for %fat and muscle volume in ISP + TM were excellent. However, separate evaluation of the 2 muscles may be desirable to clarify the mechanism of muscular degeneration in patients with rotator cuff tears. Finally, this study included nonoperatively observed patients with chronic rotator cuff tears. The activities of the patients were relatively low, and their clinical symptoms did not worsen during the follow-up period. Our patients may not accurately represent the average population with rotator cuff tears, and selection bias is another possible limitation of this study.

Conclusion

As the pathology and mechanisms of muscle degeneration were unclear, this study quantitatively evaluated the natural changes in fatty infiltration and muscular volume after rotator cuff tears in the entire rotator cuff muscles. The present results indicate that fatty infiltration of the torn muscle occurs in the early phase after a rotator cuff tear, whereas muscle atrophy appears to progress gradually in chronic rotator cuff tears. Early intervention before muscle degeneration should be considered if the tear involves the ISP tendon.

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