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Delamination in rotator cuff tears: Explanation of etiology through anatomical dissection

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Abstract

The prognostic significance of delaminated rotator cuff tears remains controversial. However, as the surgical goal is to maximize the contact area between layers, the macroscopic appearance of partial delaminated rotator cuff tears is essential. The aim of this anatomical study was to investigate the morphology of delaminated rotator cuff tears. We hypothesized that delamination zones at the intersection of the supraspinatus and infraspinatus tendon fibers are the origin of articular-side degenerative rotator cuff tears. Forty anatomical specimens were evaluated in this study. The supraspinatus and infraspinatus muscles were dissected, the origins were meticulously worked out and followed to their insertions at the humeral head. Fiber exchanges, overlays and delamination zones between the supraspinatus and infraspinatus muscles were photographically documented and measured. Delamination of rotator cuff tears can be classified into articular-side and bursal-side tears. The articular-layer consists of capsuloligamentous tissue, which included the rotator-cable/rotator-crescent complex, the joint capsule and a small part of the supraspinatus tendon. The bursal-side layer represents the tendinous tissue, which consists of the parallel, tendinous parts of the supraspinatus and infraspinatus muscles. Delamination of rotator cuff tears can be classified into articular-side and bursal-side tears. Present model of degenerative tears might explain the high prevalence of articular-side tears, which expand into the rotator-cable/rotator-crescent complex. It may be important for surgeons to incorporate these anatomical findings and considerations into the surgical planning.

KEYWORDS

delamination, infraspinatus, rotator cuff, supraspinatus, tendon injury

1 | INTRODUCTION

Delamination of the rotator cuff is usually described as a horizontal split of the tendon (Han et al., 2013; Sonnabend et al., 2001). However, the definition is vague and the prognostic significance in rotator cuff tears remains unclear (Iannotti et al., 2013; Ok et al., 2017). Some authors consider delaminated tears as a negative prognostic factor, while in the clinical routine little attention has been given to this condition. It is considered to represent degenerative changes, which might be the first step in the cascade of rotator cuff ruptures

(Fukuda, 2003; Kim et al., 2010). Prevalence in literature varies from 38% to 92% which can be explained by the different examination approaches (radiologic method, arthroscopic and open examination) (Han et al., 2013; Sonnabend & Watson, 2002).

The myotendinous insertion of the rotator cuff is a complex construct of tendons and ligaments splaying out and intermingling with each other to form a common, continuous plate at the humeral head. Between the tendons and the fibrous layer of the joint capsule, there are fibers of the coracohumeral and glenohumeral ligaments concentrated in an extra plane. Overall, five different histological layers have been characterized to form the rotator cuff insertion at the humeral head: (1) fibers from the coracohumeral ligament (ca. 1 mm), (2) large parallel tendon fascicles from the infraspinatus and supraspinatus muscles (ca. 3–5 mm), (3) smaller tendon fascicles from the infraspinatus and supraspinatus muscles meeting at an angle of approximately 45° (ca. 3 mm), (4) connective tissue with collagen fibers continuing anteriorly into the coracohumeral ligament (ca. 1 mm), (5) fibrous layer of the joint capsule (ca. 1.5–2 mm) (Clark & Harryman 2nd, 1992). Different fiber orientations and contrary shear stresses might be one reason for delaminations at this area (Nakajima et al., 1994). Two additional morphological landmarks are important to be aware of in the rotator cuff. The rotator cable is a thickening of the insertion plate and provides steady force distribution. It passes over into the rotator crescent, which is a thin sheet of the distal fibers of the supraspinatus und infraspinatus tendon (Gyftopoulos et al., 2012; Macarini et al., 2011; Rahu et al., 2017).

From a clinical standpoint, knowledge about which layers are affected in delaminated rotator cuff tears is essential for adequate arthroscopic repair surgeries. The surgical goal is to maximize the contact area between the tendon fibers and the humeral head (Apreleva et al., 2002; Park et al., 2005). However, the macroscopic appearance especially of partially delaminated rotator cuff tears has yet not been described.

The aim of this study was to evaluate the macroscopic morphology of delaminated rotator cuff tears and to establish a pathomechanical model of affected layers. We hypothesized that degenerative changes expressed as delamination zones at the intersection of the supraspinatus and infraspinatus tendon fibers are the origin of degenerative rotator cuff tears.

2 | MATERIALS AND METHODS

A total of 53 fresh-frozen anatomical specimens were examined. The mean age of included specimens was 74.9 ± 10.5 years. All specimens originated from voluntary body donations to the *Center for Anatomy and Cell Biology of the Medical University of Vienna*. All donors provided informed written consent prior to their death to have their bodies used in medical education and research. The study was approved by the Human Ethics Committee and the institutional review board of the *Medical University of Vienna (EK.Nr.: 1500/2015)*.

Inclusion criteria were specimen availability and appropriate tissue quality. Exclusion criteria were severe degenerative changes to the shoulder joint (i.e., complete rupture of the supraspinatus and/or infraspinatus muscles) and previous surgical procedures such as rotator cuff repair, plating of humeral head fractures and shoulder replacements.

3 | DISSECTION AND EVALUATION

All specimens were mounted in a custom-made vice as commonly used in anatomical arthroscopic procedures. Soft tissue was removed to expose the supraspinatus and infraspinatus muscles. The muscles were dissected from proximal to distal and each bundle was carefully followed to their insertion by noting their fiber-exchanges. For the supraspinatus and infraspinatus muscles the following parameters were evaluated: delamination zone, number of muscle bundles, pennation angles, insertion areas, overlays between supraspinatus and infraspinatus muscles. A reference line through the superior angle of the scapula and the humeral head was used for the pennation angle.

Every step of the dissection process was documented photographically in a standardized fashion. Insertion areas of the different parts of the supraspinatus and infraspinatus muscle were marked, measured and recorded using ImageJ (accessed 2021, https://imagej.nih.gov/ij/).

Statistical analysis was performed with IBM SPSS Statistics (IBM Corp. Released 2018. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.). Descriptive statistics (mean, SD, minimum, and maximum) were computed for all metric variables. Normal distribution of data was evaluated by visualization in boxplots and by the Shapiro–Wilk test. Fisher's exact test was used to determine whether there is a statistically significant difference between the expected and observed frequencies in a contingency table ($n < 20$). For normally distributed metric data, a Student's t-test was used, while non-normally distributed variables were analyzed using a Mann–Whitney U-test. For categoric variables, chi-square test was performed. A p-value <.05 was considered significant. Bonferroni correction was applied in multiple testing.

4 | RESULTS

A total of 13 shoulders had to be excluded due to massive degenerative changes ($n = 12$) and evidence of prior surgical procedures ($n = 1$), thus 40 shoulders (8 paired, 24 unpaired, 21 female, 19 male) remained for evaluation. Partial superficial ruptures of the rotator cuff were found in 27.5% ($n = 11$) and partial profound ruptures in 47.5% ($n = 19$). In eight shoulders (20%) a delaminaton was identified between the supraspinatus and infraspinatus muscles. Degenerative changes in terms of fatty degeneration and/or inflammatory tissue were found in 57.5% of all shoulders.

4.1 | Morphology of the supraspinatus muscle

Insertion areas and pennation angles are presented in Table 1 and visualized in Figure 1. Three different parts of the supraspinatus muscle could be separated. In between there were layers of connective tissue containing nerves and vessels. Part 1 (SSP1) was the most prominent one and of tubular shape. Its origin was at the supraspinous fossa and runs into the strong anterior tendon. Part 2 (SSP2) was situated posterior to

SSP1 and could be separated bluntly. Its origin was at the scapular spine. It runs into the strong anterior tendon of SSP1. The third part (SSP3) was found profound to SSP1 and SSP2 and originated at the lateral part of the supraspinous fossa. It runs dorsolateral to the tendon of the infraspinatus muscle. The posterior part of the supraspinatus muscle is covered by the tendon of the infraspinatus muscle.

4.2 | Morphology of the infraspinatus muscle

Insertion areas are presented in Table 1 and visualized in Figure 2. There were two constant parts of the infraspinatus muscle. Part 1 (ISP1) was the largest part and had its origin at the infraspinous fossa. Part 2 (ISP2) was smaller, had its origin at the inferior border of the spine of the scapula and runs into the strong tendon of ISP1. In two shoulders a third part was found distal to ISP1, which inserted into the 4th layer of the rotator cuff. This musculous slip was considered an anatomic variation (Figure 3).

4.3 | Myotendinous morphology in rotator cuff tears

In delaminated rotator cuff tears, there was a constant delamination between an articular- and bursal side layer. The articular layer was a composition of the rotator cable/rotator-crescent complex, the joint capsule, and fibers of the posterior part of the supraspinatus muscle (SSP3), while the bursal side consisted of parallel, tendinous parts of the supraspinatus (SSP1, SSP2) and infraspinatus muscles (ISP1, ISP2). The SSP3 was always fused with the 4th layer of the insertion plate, while SSP1 and SSP2 united more distally to form the rotator cable.

TABLE 1 Areas of origin of the supraspinatus and infraspinatus muscle

Bundle	Origin in mm^2	Percentage of origin
SSP1	225.71 ± 57.98 (109.2–347.6)	83.89
SSP2	26.25 ± 13.03 (10.3–64.5)	9.76
SSP3	17.09 ± 8.3 (2.6–53.1)	6.35
ISP1	573.52 ± 99.63 (395.7–795.2)	88.17
ISP2	76.45 ± 23.33 (38.7–129.2)	11.67
ISP3 ($n = 2$)	19.95 ± 1.06 (19.2–20.7)	—

4.4 | Insertion morphology at the humeral head

There was a constant overlay area of the infraspinatus muscle over the posterior part of the supraspinatus muscle (95%). Distally, these fibers can only be separated by sharp dissection due to their extensive fiber exchange. The width of this overlay area was 6.5 ± 4.2 mm in all shoulders, which represents 27.4% of the width of the supraspinatus tendon (Figure 2). The pennation angle between the supraspinatus and infraspinatus muscles was 41.6° ± 14.1°. Before inserting into the rotator cable-crescent complex the tendon of the supraspinatus muscle fuses with the 4th layer of the rotator cuff.

5 | DISCUSSION

The most important finding of this study is the constant delamination between an articular- and bursal-side layer. According to the literature, articular-side ruptures are the most common tears of the rotator cuff with a frequency of 91% (Gartsman & Milne, 1995). We were able to show, that in these cases the rotator crescent was not visible anymore. The high prevalence of degenerative changes at the described overlay area of the supraspinatus and infraspinatus muscles supports the theory that the starting point of rotator cuff tears is at this location (Kim et al., 2010). The thin joint capsule, the thin rotator crescent and the hypervascularization presented in previous studies furthermore support this theory (Ling et al., 1990). Small partial ruptures in this region (Step 1, Figure 4A) can extend to the rotator crescent (Step 2, Figure 4B) and ultimately lead to a full thickness tear (Step 3, Figure 4).

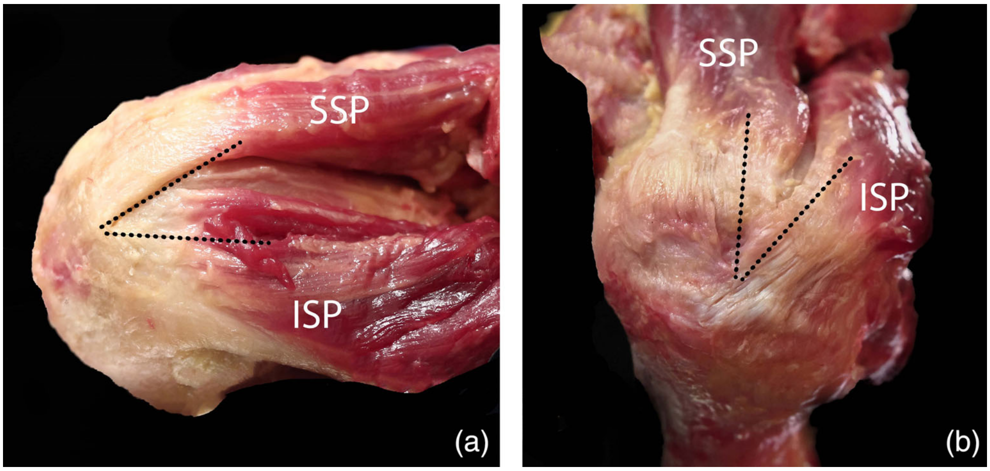

FIGURE 1 Left shoulder, view from superoposterior (A) and from superolateral (B). Visualization of the constant overlay of the infraspinatus muscle over the supraspinatus muscle. The pennation angle between these two layers, which might contribute to the shear forces are presented as dotted lines. ISP, infraspinatus muscle; SSP, supraspinatus muscle

Another contributing factor for this theory is the pennation angle between the supraspinatus and infraspinatus muscles presented in the results. The different orientations of tensile loads and shear forces can lead to aggravation of these ruptures and ultimately to full thickness tears. This has already been described and theorized in literature (Cha et al., 2016; Nakajima et al., 1994). While pennation angles have not been characterized before, Nakajima et al. (1994) were able to demonstrate in their biomechanical study, that the articular-side layer is more easily ruptured compared to the bursal-side layer. This can be explained by the different histological structure of these two layers. While the bursal-side layer was mostly composed of longitudinal tendon bundles, fibers of the articular-side layer were thinner and interlaced lengthwise as well as crosswise. Therefore the articular-side layer was more vulnerable to tensile loading (Nakajima et al., 1994). Figure 5 shows an archetype of this theory. Sonnabend et al. (2001) were able to show that after delamination of the rotator cuff, synovial cells can be present in between the articular-side and bursal-side layers. This hinders consolidation of affected layers and ultimately sustains the delamination.

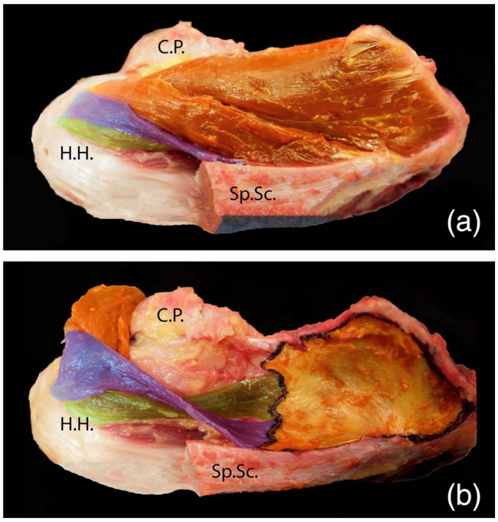

FIGURE 2 Superior view of a left shoulder. The three different parts of the supraspinatus muscle are visible before (A) and after (B) removing of SSP1. Orange, SSP1; violet, SSP2; green, SSP3. C.P, coracoid process; HH, humeral head; Sp.Sc., spina scapulae

Regarding the supraspinatus muscle, we found that the SSP3 was always fused with the 4th layer of the insertion plate, while SSP1 and SSP2 unite more distally to form the rotator cable. It was demonstrated that the articular-side layer is a complex consisting of the rotator cable/rotator-crescent complex, the fibrous layer of the joint capsule and fibers of the posterior part of the supraspinatus muscle (SSP3). These layers correspond to the 3rd, 4th and 5th layer described by Clark and Harryman 2nd (1992). Based on these findings we support the conclusions of Czyrny (2012) to sum the five histological layers up to two clinically relevant layers:

1. Capsuloligamentous layer which represents the articular-side of the delamination. It consists of the SSP3, the rotator-cable-crescent complex and the joint capsule. These are the third, fourth and fifth layer according to Clark and Harryman 2nd (1992).
2. Tendinous layer which represents the bursal-side of the delamination. It consisted of parallel, tendinous parts of the supraspinatus (SSP1, SSP2) and infraspinatus muscles (ISP1, ISP2). This is the second layer according to Clark and Harryman 2nd (1992).

The course of both the supraspinatus and infraspinatus muscles of our study are consistent with the findings of Mochizuki et al. (2008). We agree that the anterior part of the infraspinatus muscle constantly covers parts of the posteralateral part of the supraspinatus muscle (see Figure 1). Mochizuki et al. (2008) were able to show two different portions of the supraspinatus muscle: a long and thick and a short and thin one. Contrary to that, we constantly observed three different portions of the supraspinatus muscle (see Figure 2), which is to the best of our knowledge the first description of this morphological aspect. Whether this is due to different specimen characteristics or the different fixation methods (fresh-frozen vs. formalin-ethanol) cannot be finally clarified. However, Schwarz and Hirtler (2019) were able to show that the frequency distribution of aberrant pectoralis minor tendons are similar between Caucasians and Mongolians, which might predict similarities in the supraspinatus muscle as well. Our results on the infraspinatus muscle are in

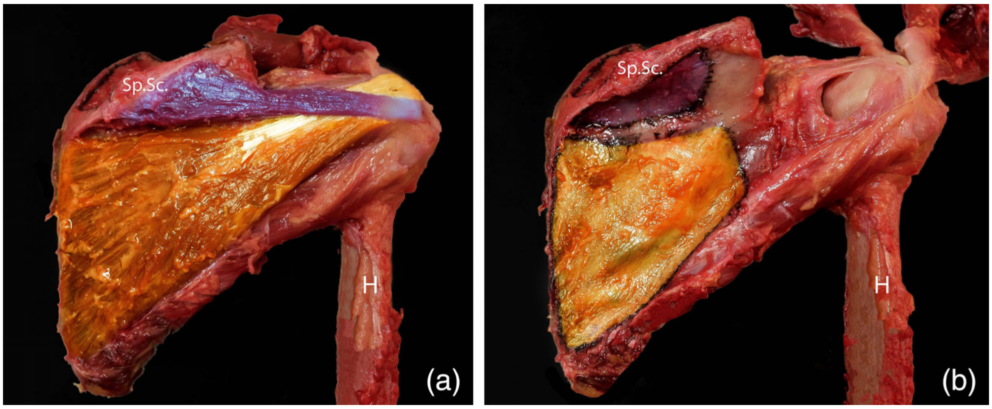

FIGURE 3 Posterior view of a right shoulder. Visible are two different parts of the infraspinatus muscle before and after removal of the ISP1 and ISP2. Orange, ISP1; violet, ISP2. H, humerus; Sp.Sc., spina scapulae

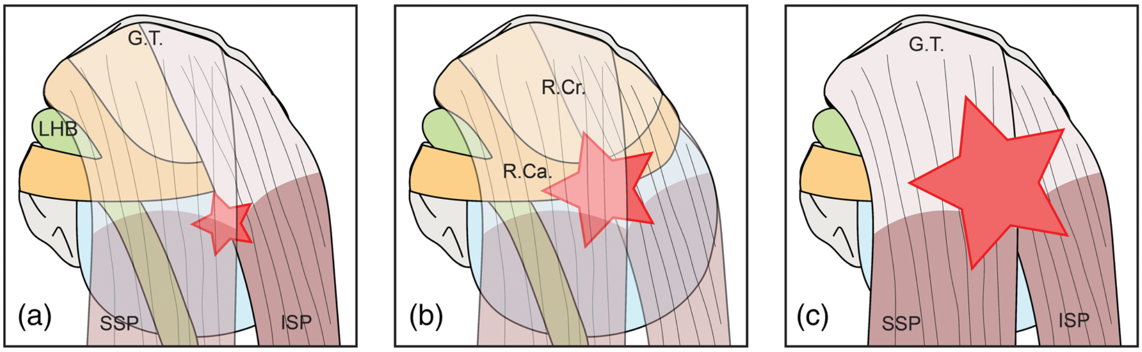

FIGURE 4 Right shoulder, view from superior. Proposed pathomechanism of articular-side ruptures. Ruptures start at the profound layer (A) and extend to the rotator crescent (B) until a full thickness tear is apparent (C). LHB, long head of the biceps brachii muscle; G.T., greater tubercle; ISP, infraspinatus muscle; R.Ca., rotator cable; R.Cr, rotator crescent; SSP, supraspinatus muscle

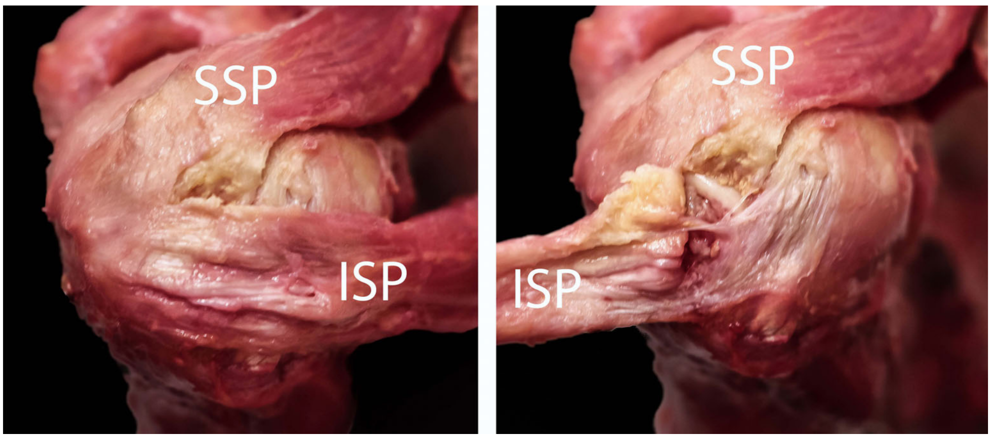

FIGURE 5 Left shoulder with an archteype of articular-side partial ruptures with the delamination zone between the articular-layer and bursal-layer before (A) and after (B) folding away the infraspinatus muscle. ISP, infraspinatus muscle; SSP, supraspinatus muscle

accordance with previous results (Mochizuki et al., 2008). The infraspinatus muscle regularly consists of two main portions.

6 | LIMITATIONS

As in all anatomic studies, the high age of examined specimens is commonly named as the most important limiting factor. However, we believe that especially the high age is of little concern in this study setting, as atraumatic rotator cuff tears are typical conditions of elderly people und thus allowed us to investigate the proposed hypothesis. Correlations between clinical symptoms and delaminations could not be investigated, because the individual's physical activity prior to their death was not obtainable. We were not able to quantify the retraction distances of each layer, as muscle tension cannot be simulated in a post-mortem study design. Another limitation is the low number of investigated specimens, which does not allow conclusions of general prevalence for delaminated rotator cuff tears. However, we believe that our sample size is sufficient to provide evidence on the etiology of rotator cuff delaminations. The strengths of our study lie in the precise anatomical dissection, which accuracy cannot be achieved through radiological investigation and in refraining from using embalmed specimen, as the correct identification of tissue layers may be influenced by embalming fluids.

7 | CONCLUSIONS

Delamination of rotator cuff tears can be classified into articular-side and bursal-side tears. Presented model of degenerative tears could explain the high frequency of articular side ruptures, which expand into the rotator-cable/rotator-crescent complex. It may be important for surgeons to incorporate these anatomical findings and considerations into the surgical planning to properly restore the topography of the supraspinatus and infraspinatus muscles.

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The authors sincerely thank those who donated their bodies to science so that anatomical research could be performed. Results from such research can potentially increase mankind's overall knowledge that can then improve patient care. Therefore, these donors and their families deserve our highest gratitude (Iwanaga et al., 2021).

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