Structural disorders at the insertion of the supraspinatus tendon

RELATION TO TENSILE STRENGTH

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We examined macroscopically and microscopically 55 cadaver rotator-cuff tendons attached to their humeral heads to determine the distance between the edge of the articular cartilage and the tendon insertion of the supraspinatus (the width of the sulcus) and the score of regressive changes at the sulcus. In 33 specimens we measured the tensile strength. The width of the sulcus was correlated with the score of regressive changes and with the ultimate tensile strength of the supraspinatus tendon.

The width of the sulcus correlated positively with the score of regressive changes ($r = 0.66$, $p < 0.0001$), but there was a negative correlation between the latter and the ultimate tensile strength ($r = -0.81$, $p = 0.001$) and between the width of the sulcus and the ultimate tensile strength ($r = -0.74$, $p = 0.004$).

We believe that the width of the sulcus is a simple and useful clinical indicator of the integrity and the tensile strength of the supraspinatus tendon.

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In 1934 Codman¹ defined the sulcus as the interval between the edge of the articular cartilage and the insertion of the tendon at the rotator cuff (Fig. 1). He believed that widening of the sulcus was due to rim rents attributable to incomplete tears of the rotator cuff at the articular side. At the site of these rim rents, he described the presence of "caverns" and "volcanoes" which develop after localised resorption of bone. We prefer, however, the term 'crater' since this describes better the appearance of sites of bone resorption. Apposition of new bone to the exposed bare bone produced 'eburnation', appearing on radiographs as "a heavy plaque of bone". Codman¹ believed that rim rents accounted for most painful shoulders.

In the past 60 years little of significance has been added to Codman's observations. We have therefore attempted to clarify and quantify the disorders occurring at the articular side of the insertion of the supraspinatus tendon and at the sulcus. The correlation between the width of the sulcus, the degree of regressive changes, and the ultimate tensile strength of the tendon was determined. In addition, we wished to verify Codman's contention that there was a relationship between thickening of the subchondral bone plate and widening of the sulcus.

Materials and Methods

Specimens. We collected 60 fresh cadaver rotator-cuff tendons, attached to their humeral head, from 30 post-mortems within 24 hours of death. We excluded five shoulders with full-substance cuff tears (3 unilateral, 1 bilateral).

Fig. 1

Diagram of the insertion of the supraspinatus and the sulcus.

Fig. 2

Biomechanical testing of the supraspinatus tendon. Tensile load to destruction is applied to the tendon strip in 45° of abduction at a constant cross-head speed of 25.4 mm/min using an Instron machine. The extent of the freezing zone (arrow) does not extend into the area of study.

Of the remaining 55 shoulders, from 29 cadavers, 34 were from men and 21 from women. Their median age was 65 years (39 to 84). We performed an immediate macroscopic examination for the presence of incomplete tears and other pathological conditions such as large acromial spurs and osteoarthritis. The humeral heads were then wrapped in saline-soaked gauze and stored at a temperature of -20°C until biomechanical testing was carried out.

Macroscopic measurement of the width of the sulcus.

We defined the width of the sulcus as the distance between the edge of the articular cartilage and the attachment of intact cuff fibres. We measured it with a calliper at two sites in the middle portion of the insertion of the supraspinatus tendon 10 mm apart and divided the sum by two. To assess the reliability of the measurement, two independent observers also measured the width of the sulcus in 24 humeral heads. From these measurements an intraclass correlation coefficient was calculated.

Biomechanical testing. Before biomechanical testing, the specimens were thawed gradually to room temperature. The first 22 were only evaluated histologically. This was done because the length of the harvested humeral shaft in these specimens was not sufficient to allow for the type of fixation that was required for mechanical testing. Subsequently, after standardisation of our harvesting and testing methods, we tested the tensile strength in the next 33 specimens.

We cut a longitudinal tendon strip 10 mm wide at the centre of each supraspinatus tendon without damaging the bony insertion using a custom-made knife with two parallel blades. This strip was used for mechanical testing. Since artefacts caused by mechanical testing interfere with the assessment of histological features, we used the parts of the supraspinatus immediately anterior and posterior to the tested strip for histological examination.

The tendinous end was frozen with liquid nitrogen and the bone potted in bismuth alloy as previously described.^{2,3} The strips of supraspinatus tendon were mounted at 45° of abduction using the Instron TM tabletop materials testing machine (Instron Engineering Corp, Quincy, Massachusetts) (Fig. 2). Rigid fixation of the humeral head was obtained by allowing the molten bismuth alloy to solidify at room temperature around the humeral shaft in a potting cup. To eliminate slippage between the specimen and the grip, the myotendinous junction of the strip was frozen rapidly in the grip with liquid nitrogen. Freezing never extended into the area of study (Fig. 2). Tensile load to failure was then applied to the strip at a fixed cross-head speed of 25.4 mm/min. The data were analysed for load at failure (maximum tensile load) using the Sigma Plot (Jandel Scientific, San Rafael, California). The cross-sectional area at the insertion was measured on the histological sections.³ The maximum tensile load divided by the cross-sectional area was defined as the ultimate tensile strength.

Histological evaluation. After biomechanical testing, the intact parts anterior and posterior to the tested strip were removed with their bony insertion, fixed in 10% neutralised formalin for one week and then decalcified in EDTA. After decalcification, the specimens were embedded in paraffin and cut in the direction of the tendon fibres. The sections were stained with haematoxylin and eosin and Heidenhain's azan.

We performed two types of quantitative assessment. First, we determined the severity of regressive changes at the site of the sulcus. The surface of the supraspinatus tendon at the joint side and the presence of craters were assessed and graded (Table I). For each slide a point score was obtained and averaged for both slides to reach an overall score (score of regressive changes, 0 to 6 points). These assessments were done blindly by two independent observers and the interobserver reliability was evaluated. A mean score of regressive changes between two observers was established and used for further analyses. For the determination of the intraobserver reliability, the principal observer scored all specimens again.

Secondly, to assess the degree of bony sclerosis (eburnation), we measured the area of subchondral bone from the sulcus towards the bursal side of the insertion of the

Table I. Scoring systems for the histological changes

	Score (points)
Surface of supraspinatus tendon at joint side	
Smooth, normal surface of the tendon	0
Microscopically frayed surface	1
Only microscopic disruption of the tendon fibres	2
Macroscopic presence of a small incomplete tear	3
Macroscopic presence of a large incomplete tear	4
Craters at the level of the sulcus	
None	0
Small	1
Large	2

Fig. 3

Macroscopic findings at the sulcus of the insertion of the supraspinatus (supraspinatus tendons are reflected). Figure 3A – Normal status. The sulcus is very narrow (0.45 mm) and there is no incomplete tear on the joint surface (56-year-old woman, right humeral head). Figure 3B – A wide sulcus (4.96 mm) due to resorption of the edge of the articular cartilage. There is no incomplete tear on the articular surface (71-year-old man, right humeral head). Figure 3C – A wide sulcus (9.88 mm) due to an incomplete tear of the articular surface of the supraspinatus. There is no resorption at the edge of the articular cartilage (66-year-old woman, right humeral head).

supraspinatus tendon. A solid-state colour video camera (VK-C350; Hitachi, Tokyo, Japan) was mounted on a standard Olympus microscope. A Snappy Video Snapshot (Play Incorporated, Rancho Cordova, California) video-digitiser system was used to capture the images which were then processed on a personal computer using Image Tool software (version 1.25; University of Texas Health Science Centre, San Antonio, Texas). Images of constant size (2.03×2.67 mm), located at the margin of the articular cartilage and adjusted to the blue line, were captured and saved. Two adjoining fields of identical dimensions lateral to the first field were then captured. The total area of subchondral bone, including the calcified cartilage, was measured in each field and a mean value of measurements, made at the anterior and posterior sections, determined for the 55 specimens. To assess the reproducibility of this measurement, ten fields were chosen randomly and measured again.

Statistical analysis. We calculated pairwise Spearman rank correlation coefficients for the five variables of age, the width of the sulcus, the score of regressive changes, the ultimate tensile strength and the area of subchondral bone (Statview for Macintosh; Abacus Concept Inc, Berkeley, California). Intraclass correlation coefficients were calculated for the width of the sulcus, the score of regressive changes and the area of subchondral bone (SPSS software package, version 7.0; SPSS Inc, Chicago, Illinois). Continuous data were summarised using either the median (min,max) or the mean (standard deviation).

Results

Macroscopic findings. Small incomplete tears were observed at the site of the joint in six shoulders and large incomplete tears in four. Fifteen specimens showed slight osteoarthritic changes of the humeral head, but no osteoarthritis was seen.

The intraclass correlation coefficient for the measurement of the width of the sulcus was 0.83. Inter- and intraobserver intraclass correlation coefficients for the score of regressive changes were 0.85 and 0.88, respectively. The

reliability coefficient for the repeated measurement of the area of subchondral bone was 0.86.

Figure 3 shows specimens of various sulcus widths. Those with the narrowest sulcus (Fig. 3A) were most often normal whereas those with a wider sulcus were usually associated with an incomplete tear (Fig. 3C). One specimen from a 51-year-old man showed severe resorption of the edge of the articular cartilage without evidence of an incomplete tear of the side of the joint; the width of the sulcus was 4.96 mm (Fig. 3B).

The width of the sulcus correlated positively with the score of regressive changes ($r = 0.66$, $p < 0.0001$, Fig. 4), but there was no correlation between age and the width of the sulcus or between age and the score of regressive changes.

Fig. 4

The relationship between the width of the sulcus and the score of regressive changes. The width of the sulcus correlates positively with the score of regressive changes in all 55 specimens ($r = 0.66$, $p < 0.0001$). It increases with progression of regressive changes at the joint side of the supraspinatus insertion.

Fig. 5

The relationship between the width of the sulcus and the ultimate tensile strength. The width of the sulcus correlates negatively with the ultimate tensile strength of the supraspinatus ($r = -0.74$, $p = 0.004$).

Fig. 6

The relationship between the score of regressive changes and the ultimate tensile strength. There is a negative correlation between the score of regressive changes and the ultimate tensile strength of the supraspinatus tendon ($r = -0.81$, $p = 0.001$).

Fig. 7a

Fig. 7b

Figure 7a – Photomicrograph of a barely-widened sulcus with a small crater in a 72-year-old man. The crater starts to appear at the edge of the articular cartilage. Tendon fibres in the articular portion of the supraspinatus show thinning (A, articular cartilage of humeral head; T, tendon proper; Heidenhain's azan original magnification $\times 8$). Figure 7b – Typical crater and fraying of the joint surface of the tendon in a 68-year-old woman. The crater involves the edge of the articular cartilage. The cuff fibres closest to the crater show fraying (A, articular cartilage of humeral head; C, crater; T, tendon proper; Heidenhain's azan original magnification $\times 2$).

Biomechanical findings. There was a negative correlation between the width of the sulcus and the ultimate tensile strength of the supraspinatus ($r = -0.74$, $p = 0.004$, Fig. 5), and also between the score of regressive changes and the ultimate tensile strength ($r = -0.81$, $p = 0.001$, Fig. 6).

The area of subchondral bone did not correlate with the width of the sulcus or with the score of regressive changes or with age.

Histological findings. All intermediary stages were observed ranging from 0.18 mm for the narrowest sulcus to 9.55 mm for the widest. Thirteen specimens showed a

widened sulcus with the presence of craters which were not limited to the insertion of the tendon but included also the edge of the articular cartilage showing signs of erosion (Fig. 7). Disruption of tendon fibres was most pronounced between the zone of the tendon proper and unmineralised fibrocartilage. With the progression of fraying, the presence of incomplete tears was seen between the tendon proper and the unmineralised fibrocartilage. The next stage seemed to be the disappearance of the fibrocartilaginous stump (Fig. 8). The exposed subchondral bone was now covered by a thin layer of loose connective tissue and was also the

Fig. 8

Photomicrograph of a large sulcus in a 77-year-old man. The exposed subchondral bone is covered by a thin layer of connective tissue and formation of new bone is seen in this area. The joint surface of the remaining tendon is smooth and covered by a synovial membrane. The two arrows are placed at the limits of the sulcus (A, articular cartilage of humeral head; T, tendon proper; haematoxylin and eosin original magnification $\times 2$).

site of occasional formation of new bone. The joint surface of the remaining cuff tendon was smooth and covered by a synovial membrane.

Discussion

Codman¹ believed that widening of the sulcus was the result of an incomplete tear of the rotator cuff at the joint side. He also suggested that the formation of craters contributed to the process of widening. Our results confirm his observation. The width of the sulcus correlated positively with the score of regressive changes, an assessment that included both the degree of incomplete tears and the resorption of articular cartilage (Fig. 3).

Cotton and Rideout⁴ stated that either avulsion or resorption of a flake of bone increased the width of the sulcus. They noted that the degree of this bony change corresponded accurately to the severity of the tear of the rotator cuff. They did not mention that the resorption of the edge of the articular cartilage also contributed to the process of widening. We did not find a single instance of bony avulsion.

Based on radiological measurements, Brewer⁵ reported that regressive changes at the sulcus were related to chronological age, but failed to quantify his results. Our study has shown no correlation between age and the width of the sulcus, or between age and the score of regressive changes. We suggest that histological examination of the cuff tendons does not allow any conclusion as to the individual's age.^{6,7}

We also attempted to determine whether there was any relationship between the width of the sulcus and the tensile properties of the supraspinatus tendon. Our results showed that the width of the sulcus correlated negatively with the ultimate tensile strength of the supraspinatus tendon (Fig. 5). There was also a negative correlation between the score of

regressive changes and the ultimate tensile strength (Fig. 6). In a recent study, we reported that intrinsic degeneration decreased the tensile strength at the insertion of the supraspinatus tendon^{2,3,8} and that incomplete tears at the joint surface seemed to act as stress risers.^{2,3,9,10} We have shown that the consequences of a widened sulcus are not limited to the extent of incomplete tears at the joint surface and the presence of osteochondral defects, such as craters, but also involve a decrease in the tensile properties of the tendon. We conclude therefore that as the width of the sulcus increases, the tensile properties of the supraspinatus tendon decrease.

Codman¹ stated that "eburnation" at the sulcus accompanied incomplete tears. We found no correlation between the area of exposed bone and the width of the sulcus or the score of regressive tendinous changes. Several factors could have influenced these findings. First, we did not perform a radiological examination. Secondly, our material did not include any full-substance and only four large incomplete tears. Unfortunately, Codman¹ failed to describe his material in this respect. Thirdly, the area of bare bone may be affected not only by tears but also by other factors such as gender, hand dominance, level of activity, and the use of the arm. Our clinical data gave no information on the last three points. Brewer⁵ noted cortical atrophy in the presence of full-substance tears. Codman¹ thought that "eburnation" was not "of much importance practically" and our results seem to confirm this.

Our histological study did not allow the progression of an individual cuff lesion to be documented but it gave some indication of the histological course of events. The first sign seems to be the appearance of craters at the junction between the articular cartilage and the insertion of tendon fibres. This erosion involves not only the tendinous insertion but also the articular cartilage. At the same time the joint surface of the cuff shows signs of fraying, mostly at the level between the unmineralised fibrocartilage of the insertion zone and the tendon proper. The next stage appears to be an incomplete tear, invariably between the unmineralised fibrocartilage of the insertion and the thinned and fibrillated fascicles of the tendon proper. Fraying and incomplete tears are evidence of degeneration.^{6,8} The fibrocartilaginous stump remains attached to bone which then undergoes progressive resorption, thereby exposing bare bone. We observed collagen type III in the depth of the craters. Yamanaka and Fukuda¹¹ suggested that this represented an attempt at repair. Our experience (personal observations) is that collagen type III is always absent at the sites of frayed tendon. Clinical observation supports our interpretation of these histopathological events. In fresh ruptures, a stump of tissue remains attached to bone whereas in older tears the bone is bare. The exposed subchondral bone becomes the site of some formation of new bone and this phase is accompanied by a reformation of the synovial layer covering the tendinous surface.⁸

In regard to assessment and management of chronic shoulder pain our study has considerable clinical relevance.

First, in contrast to Codman's¹ teaching, the degree of bony sclerosis at the level of the sulcus and the tendon insertion (eburnation) does not support the diagnosis of either a regressive tendinous change or an incomplete tear of the rotator cuff. Furthermore, the width of the supraspinatus sulcus which can be evaluated arthroscopically¹² appears to have a prognostic significance. Our findings support the view of Codman¹ that a widened sulcus indicates an incomplete tear of the articular side and since it is often accompanied by craters and a frayed tendon surface at the joint side, also suggests weakening of the tensile properties of the supraspinatus insertion. Our study, however, cannot ascertain whether symptomatic patients with a widened supraspinatus sulcus require regular follow-up because of the risk of progressing to a full-substance tear.

Our findings are not applicable to the infraspinatus and subscapularis in which the sulcus is much wider than that of the supraspinatus (unpublished observation). The often unclear definition of the border of the articular cartilage of these tendons did not allow for a reliable measurement of the width of the sulcus.

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References

1. **Codman EA.** *The shoulder: rupture of the supraspinatus tendon and other lesions in or about the subacromial bursa.* 2nd ed. Boston: Thomas Todd, 1934.
2. **Sano H, Ishii H, Yeadon A, Brunet JA, Uhthoff HK.** Degeneration at the insertion weakens the tensile strength of the supraspinatus tendon. *Trans Orthop Res Soc* 1997;22:860.
3. **Sano H, Ishii H, Yeadon A, et al.** Degeneration at the insertion weakens the tensile strength of the supraspinatus tendon: a comparative mechanical and histologic study of the bone-tendon complex. *J Orthop Res* 1997;15:719-26.
4. **Cotton RE, Rideout DF.** Tears of the humeral rotator cuff: a radiological and pathological necropsy survey. *J Bone Joint Surg [Br]* 1964;46-B:314-28.
5. **Brewer BJ.** Aging of the rotator cuff. *Am J Sports Med* 1979;7:102-10.
6. **Uhthoff HK, Sarkar K.** Pathology of rotator cuff tendons. In: Watson MS, ed. *Surgical disorders of the shoulder.* Edinburgh, etc: Churchill Livingstone, 1991:259-70.
7. **Uhthoff HK, Sarkar K.** The effect of aging on the soft tissues of the shoulder. In: Matsen FA III, Fu FH, Hawkins RJ, eds. *The shoulder: a balance of mobility and stability.* Rosemont, Illinois: The American Academy of Orthopaedic Surgeons, 1992:269-78.
8. **Uhthoff HK, Sano H.** Pathology of failure of the rotator cuff tendon. *Orthop Clin North Am* 1997;28:31-41.
9. **Macnab I.** Rotator cuff tendinitis. *Ann R Coll Surg Engl* 1973;53:271-87.
10. **Welsh RP, Macnab I, Riley V.** Biomechanical studies of rabbit tendon. *Clin Orthop* 1971;81:171-7.
11. **Yamanaka K, Fukuda H.** Ageing process of the supraspinatus tendon with reference to rotator cuff tears. In: Watson MS, ed. *Surgical disorders of the shoulder.* Edinburgh, etc: Churchill Livingstone, 1991:247-58.
12. **Ellman H.** Diagnosis and treatment of incomplete rotator cuff tears. *Clin Orthop* 1990;254:64-74.