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Tendon of the normal supraspinatus muscle : correlations between MR imaging and histology

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Summary: The aim of this study was to attempt to specify the nature of the signal modifications observed in MRI in the supraspinatus tendon apart from any pathology of the shoulder, and due, according to certain authors, to an artefact associated with MRI. Five macroscopically normal supraspinatus tendons were removed from 4 young subjects (14-28 years), 30 min after cardiac arrest, with the authorisation of the ethical committee. These tendons were examined by MRI in the frontal oblique plane along the axis of the muscle with a surface coil of 4 cm diameter, using a T2-weighted spin-echo sequence, and then studied histologically using the same plane of section. 22 control subjects (18-24 years) were examined by MRI with the same T2-weighted spin-echo sequence. All the tendons examined possessed a dark signal with zones of intermediate signal on the first echo of the sequence. There was a complete correlation between the MRI appearances of the 5 tendons and their histologic description. Three histologic appearances were described : fibrillary degeneration, fibrous dystrophy, and eosinophil transformation of the tendinous collagen. All the tendons examined in healthy volunteers exhibited hetereogenic images at the first echo; in the second echo the hyposignal was uniform and obvious. The good correlation obtained suggests that modifications of the tendon signal from the supraspinatus m. are not related to an artefact described in MRI, but are linked with premature degeneration of this tendon, probably associated with the severity of the mechanical constraints to which it is subject.

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Tendon du muscle supra-épineux normal : corrélations entre l'imagerie par IRM et l'histologie

Résumé : Le but du travail était d'essayer de préciser la nature des modifications de signal observées en IRM dans le tendon du m. supra-épineux en dehors de toute pathologie de l'épaule, et dûes, selon certains auteurs, à un artefact lié à l'IRM. Cinq tendons macroscopiquement normaux de m. supra-épineux ont été prélevés chez 4 patients jeunes (14 à 28 ans), 30 mn maximun après l'arrêt cardiaque, après autorisation du comité d'éthique. Ces tendons ont été examinés en IRM dans le plan frontal oblique suivant l'axe du muscle avec une antenne de surface de 4 cm de diamètre en utilisant une séquence écho de spin T2, puis ont été analysés en histologie en utilisant le même plan de coupe. Vingt-cinq sujets témoins (18 à 34 ans) ont été examinés en IRM avec la même séquence écho de spin T2. Tous les tendons de m. supra-épineux examinés possédaient un signal noir avec des zones de signal intermédiaire sur le premier écho de la séquence. Il existait une parfaite corrélation entre l'aspect en IRM des 5 tendons prélevés et leur description en histologie. Trois aspects histologiques ont été décrit : dégénérescence fibrillaire, dystrophie fibreuse, transformation éosinophile du collagène tendineux. Tous les tendons examinés chez les volontaires sains présentaient, au premier écho, des images hétérogènes ; au second écho, l'hyposignal était homogène et franc. La bonne corrélation obtenue permet de suggérer que les modifications du signal du tendon du m. supra-épineux ne sont pas en rapport avec un artéfact décrit en IRM mais sont liés à une détérioration précoce de ce tendon, vraisemblablement liée à l'importance des contraintes mécaniques qu'il subit.

Key words: Shoulder — Supraspinatus — Histology — MRI

The generality of tendons of the human body normally exhibit in MRI a dark signal in both the first and second

echos of the T2-weighted sequence . However, the supraspinatus tendon is an exception to this rule. Several authors, such as Erickson [5], Kjellin [9] and Mirowitz [13] have found zones with an intermediate signal in the supraspinatus tendon in control subjects, using a T2-weighted spin-echo sequence or a T2-weighted spin-echo fat saturation sequence. To explain this peculiarity of signal, Erickson and Mirowitz have suggested that the effect of the magic angle described by Fullerton [6] contributes to give rise to these anomalies of intratendinous signal. Kjellin [9] has shown that the zones of intermediate signal he observed with a T2-weighted spin-echo sequence in the shoulders of cadavers were associated with intratendinous degeneration. The object of this study was to complement these studies to determine whether the modifications of signal from the supraspinatus tendon observed in the first echo of T2 sequence are related to artefacts or to histologic modifications of the tendon.

Material and method

In vitro study of 5 supraspinatus tendons

Five supraspinatus tendons obtained from four brain-dead subjects aged from 14 to 28 years were removed less than 30 min after cardiac arrest. This study was made after receipt of the necessary authorisation. During removal, these tendons were considered to be macroscopically normal and the shoulders without any evidence of bursitis or subacromial impingement. Pending MRI study, the tendons were frozen at -18°. After thawing to 20°, the tendons were examined with a surface coil using a local gradient system. This coil, 4 cm in diameter, has already been used for imaging the skin [5]. The examination of the tendons was made with a 1.5 Tesla MR System (Signa, General Electric). The images were acquired in parallel and perpendicular to the axis of traction of the supraspinatus tendon, with a T2-weighted spin-echo sequence (TE = 25/75, TR = 2000). The field of view was 4 cm, the thickness of the sections 3 mm, the matrix 256 x 128, and the interval between sections 1.5 mm. Five sections were obtained for each tendon. Immediately after the MRI study, the tendons were fixed in a 10% formol solution and sent to the histology department.

For the right tendon of the youngest subject (tendon 1), we obtained a measure of relaxation time T2 by using an T2-weighted spin-echo sequence with 4 echos (TE = 25 - 50 - 75 - 100 ms, TR = 2000). This measurement was obtained by positioning the long axis of the tendon parallel to the magnetic field, and then at an obliquity of 30°, 60° and 90°. In each position, two measurements were made by determining a relevant region of 3 mm per side in a site where the tendon presented hyposignal bands parallel to one another at the first acquisition.

After section into five equal parts, using the same program as for MRI, three stains were made: hematoxylin-eosin-saffron, orcein, and Masson's trichrome. Histologic study of the tendons was made in the presence of the radiologist to facilitate correlation of the findings.

Study of signal from supraspinatus tendon in 25 control subjects under normal conditions for MRI investigation of the shoulder

25 volunteers (20 women and 5 men) aged from 18 to 34 years, average age 24.5 years, were examined by MRI. These control subjects had no history of traumatic or painful pathology of the shoulder. For these studies a coil of circular surface (5 inches GP) was placed round the arm and then ascended until the ring rested on the acromion and in the axilla. Oblique frontal sections were made with a T2-weighted spin-echo sequence identical with the foregoing. The field of view was 10 cm, the matrix 256 x 256, and the sections were 3 mm thick at intervals of 1.5 mm.

Table 1. Histologic and MRI appearances observed in 5 tendons examined
Aspects histologiques et IRM observés sur les 5 tendons examinés

	Sex	Age	Side	Histologic appearance	MRI appearance
1	M	14	R	Normal appearance of collagen, moderate fibrillary degeneration	Bands in hyposignal, parallel and regular
2	M	14	L	**Anterior part**: fibrillary degeneration with fibrous dystrophy and loss of parallelism of collagen **Posterior part**: collagen normal in appearance	**Anterior part**: discrete disorganisation of bands in hyposignal **Posterior part**: bands in hyposignal, parallel and regular
3	F	21	R	Collagen of normal appearance with discrete fatty infiltration and moderate fibrillary degeneration	Bands in hyposignal, parallel and regular
4	M	24	R	**Anterior part**: eosinophil degeneration **Posterior part**: fibrillary degeneration with discrete infiltration of histiocytes and fibrocytes	**Anterior part**: uniform zone of increased signal **Posterior part**: bands in hyposignal, parallel and regular
5	M	28	R	**Anterior part**: eosinophil degeneration **Middle part**: fibrous dystrophy and loss of parallelism of collagen **Posterior part**: fibrillary degeneration with discrete infiltration of histiocytes and fibrocytes	**Anterior part**: uniform zone of increased signal **Middle part**: disorganisation of bands in hyposignal **Posterior part**: bands in hyposignal, parallel and regular

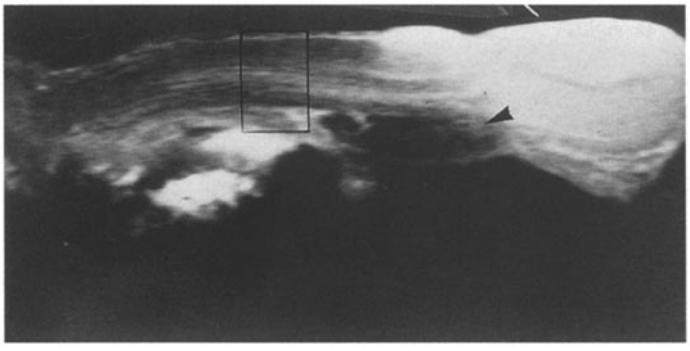
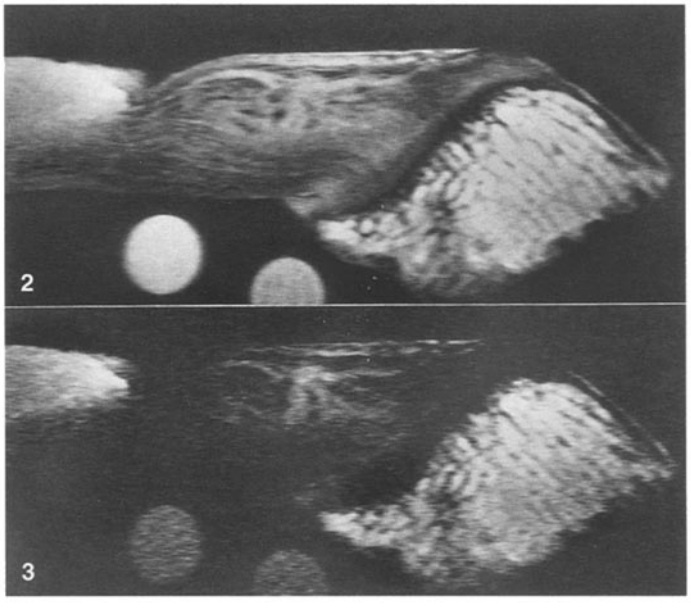


Fig. 1
Tendon No. 1 (14-year-old male). T2-weighted multi-echo sequence with a TE of 25 ms. The tendon consists of black bands of hyposignal, regular and parallel to the long axis of the muscle. The termination of the tendon of the long head of the biceps brachialis m. is visible close to the muscle fibers (*arrowhead*). The frame isolates the zone studied histologically

Tendon n° 1 (sujet de 14 ans). Séquence écho de spin T2 multi-écho avec un TE de 25 ms. Le tendon est constitué de bandes noires en hyposignal, régulières, parallèles au grand axe du muscle. La terminaison du tendon du chef long du m. biceps brachial est visible à proximité des fibres musculaires (*tête de flèche*). Le cadre localise la zone étudiée en histologie



Figs. 2, 3
Middle part of tendon No. 5 (28-year-old male). T2-weighted multi-echo spin sequence (**Fig. 2** : TE = 25 ms, **Fig. 3** : TE = 100 ms). The inferior part of the tendon has a normal appearance with regular parallel black bands (minor fibrillary degeneration), the central part is reworked with disorganisation of these bands in hyposignal (fibrous dystrophy) and a zone of increased signal on the late echo (eosinophil transformation of collagen). The *circles* correspond to the support on which the specimen rests

Partie moyenne du tendon n° 5 (sujet de 28 ans). Séquence écho de spin T2 multi-écho (**fig. 2** : TE = 25 ms ; **fig. 3** : TE = 100 ms). La partie inférieure du tendon a un aspect normal avec des bandes noires parallèles et régulières (légère dégénérescence fibrillaire), la partie centrale est remaniée avec une désorganisation de ces bandes en hyposignal (dystrophie fibreuse) et une zone de signal élevé sur l'écho tardif (transformation éosinophile du collagène). Les *cercles* correspondent au support sur lequel repose la pièce

Results

Study of the 5 excised tendons (Table 1)

MRI analysis of these tendons revealed three different appearances in the first echo of the T2 sequence: (1) bands in hyposignal, parallel and regular, oriented along the axis of traction of the supraspinatus m. (Fig. 1); (2) bands in hyposignal of disorganised appearance (Figs. 2 and 3); (3) plaques of intense signal only for tendons 4 and 5 (Fig. 4). In the second echo, the tendons appeared in hyposignal, except at the plaques of high intensity observed at the first echo, where the signal was now intermediate.

All the tendons exhibited histologic anomalies. Four different pathologic appearances were found: (1) fibrous degeneration of the collagen, with or without cellular infiltration by fibrocytes and loss of parallelism between the collagen bands; (2) fibrous dystrophy with loss of parallelism of the bundles of collagen fibers; (3) eosinophil degeneration of the collagen; (4) some localised zones of fatty infiltration in the third tendon.

To secure correlations between the MRI images and the histologic findings, we postulated that any modification of the MRI appearances must be shown in the histologic specimen if this measured at least 2 mm per side. This condition was necessitated by the fact of the difference in thickness between the MRI images (3 mm) and the histologic sections (5 microns). Excellent topographic correlation was obtained between the different MRI appearances

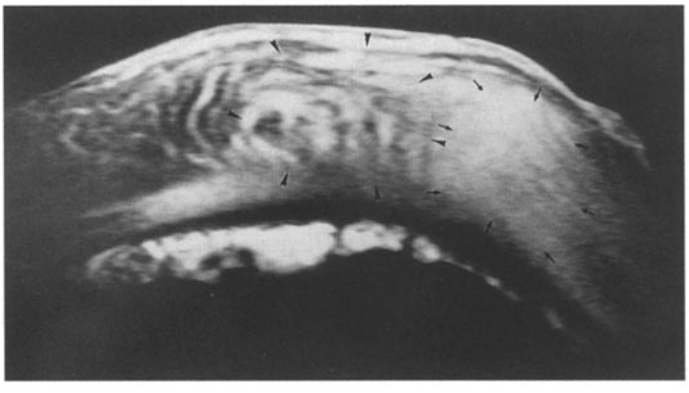


Fig. 4
Tendon No.5 (28-year-old male). Sagittal section perpendicular to long axis. T2-weighted multi-echo spin sequence, TE = 25 ms. In the sagittal plane there are three appearances in MRI. In front there is a hypersignal (eosinophil transformation of collagen (*arrowed*)); in the middle portion there is disorganisation of the bands in hyposignal (*arrowheads*); and behind there are bands in hyposignal in organised pattern (minor fibrous dystrophy)

Tendon n° 5 (sujet de 28 ans). Coupe sagittale perpendiculaire au grand axe. Séquence écho de spin T2 multi-écho, TE = 25 ms. On retrouve dans le plan sagittal les trois aspects IRM de ce tendon. En avant un hypersignal (transformation éosinophile du collagène (*flèches*)), dans sa partie moyenne une désorganisation des bandes en hyposignal (*têtes de flèches*), en arrière des bandes en hyposignal de disposition organisée (légère dystrophie fibreuse)

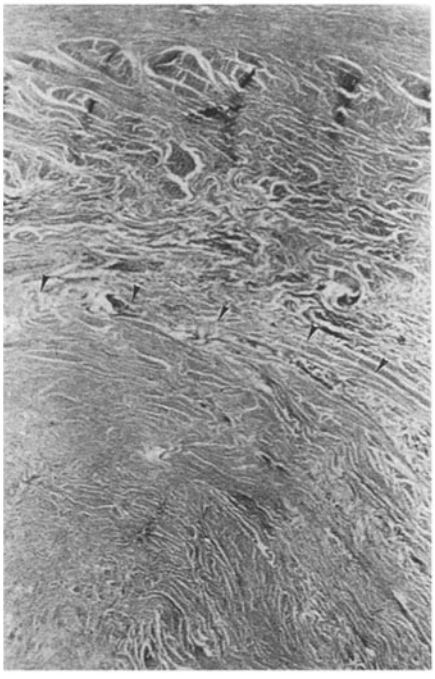


Fig. 5
Longitudinal histologic section of middle portion of tendon No. 5. Fibrous dystrophy is seen at the upper part of the tendon, and eosinophil transformation in its middle part (*arrowheads*). The superficial part of the tendon is at the top of the photograph

Coupe histologique longitudinale de la partie moyenne du tendon n° 5. La dystrophie fibreuse est visible à la partie supérieure du tendon. Une transformation éosinophile est retrouvée dans la partie moyenne (*têtes de flèches*). La partie superficielle du tendon est en haut de la photographie

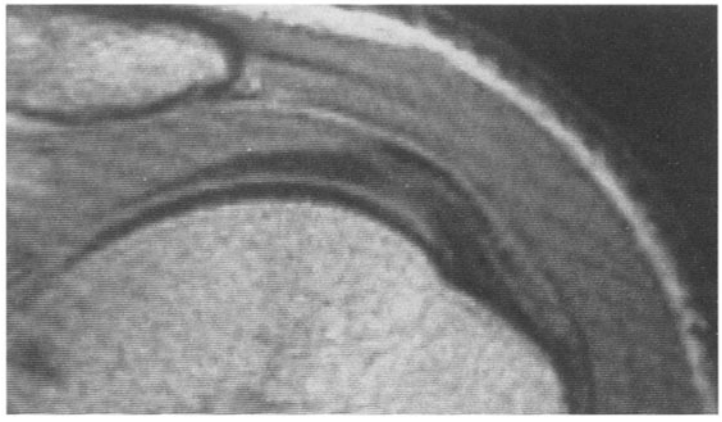


Fig. 6
Control subject of 16 years, left shoulder, spin-echo sequence (TE = 25, TR = 2000). The tendon is globally in hyposignal with an alternation of grey and black bands

Sujet témoin de 26 ans, épaule gauche, séquence écho de spin TE = 25, TR = 2000. Le tendon est globalement en hyposignal avec une alternance de bandes grises et de bandes noires

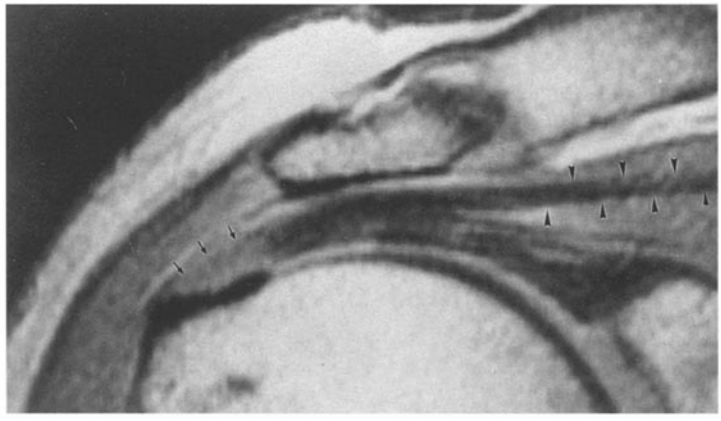


Fig. 7
Control subject of 27 years, right shoulder, frontal view, spin-echo sequence (TE = 25, TR = 2000). There is a wide zone of grey signal (*arrows*) in the axis of fibrous reinforcement of the supraspinatus m. (*arrowheads*). This zone appears in uniform hyposignal in T2-weighting, which formally excludes rupture; this "tendinopathy" cannot unfortunately be studied histologically

Sujet témoin de 27 ans, épaule droite, vue frontale, séquence écho de spin TE = 25, TR = 2000. Il existe une large zone de signal gris (*flèches*) dans l'axe du renforcement fibreux du m. supra-épineux (*têtes de flèches*). Cette zone apparaît en hyposignal homogène en T2 ce qui exclut formellement une rupture. Cette "tendinopathie" ne peut malheureusement pas être étudiée histologiquement

and the histologic findings. The radiologist was able to indicate to the histologist where to find the zones where he should be able to find tissue changes. The conclusions of this correlation were as follows: (1) the parallel regular bands in hyposignal corresponded to bundles of collagen fibers which were normal or exhibited fibrillary degeneration, possibly associated with some local cellular infiltrations of histiocytes or fibrocytes; (2) the zones of disorganised bands and in hyposignal corresponded to fibrous dystrophy; (3) the zones of intense signal corresponded to eosinophil degeneration (Fig. 5). Only those zones of fatty infiltration described by the histologist in the tendon were not located in MRI; these zones measured less than 1 mm per side.

There was no modification of the relaxation time T2 in relation to the orientation of the tendon in the magnetic field; the relaxation time T2 was 17 ± 6 ms.

In vivo study of the supraspinatus tendon in 25 control subjects

On the first echo of T2-weighted spin-echo sequence, all the tendons appeared in the form of a band in hyposignal with one or more zones of intermediate signal. The latter had two different appearances: either (1) an alternation of fine lines in hyposignal separated by lines of intermediate signal parallel to one another, oriented along the axis of traction of the tendon (Fig. 6); or (2) plaques of intermediate signal (Fig. 7). An extensive plaque of intermediate signal was seen in 4/25 cases, at the level of the anterior and lateral part of the tendon, near its insertion into the

greater tubercle (Fig. 7). In the other cases, no particular topography for these zones of intermediate signal was described. With the second echo, all the tendons gave a frank hyposignal.

Discussion

The conditions of removal of the tendons allowed maximum limitation of histologic damage to the tendon. Any post-mortem degeneration could be diffuse and non localised.

Studies have suggested that these zones of intermediate signal observed in the supraspinatus tendon in the T2-weighted spin-echo sequence derived from an artefact described by Fullerton [6]. This author showed that the relaxation time T2 measured in vitro in tendons of animal origin (dog, pig, rat, sheep) varied by 228 ms depending on the orientation of the tendon in relation to the magnetic field (T2 was 250 ms if the tendon was in the axis of the field and 22 ms if it made an angle to it of 55° or 125°). Erickson [5] and Mirovitz [13] therefore suggested that the zones of intermediate signal they observed in MRI in the supraspinatus tendons of normal controls might be explained by this phenomenon.

We felt that it was premature to suggest, like these authors, that the artefact of the magic angle described *in vitro* in cylindrical tendons with a very precise measurement system could be observed *in vivo* in a flat tendon with an imaging system providing images of poorer quality. The measurements of the T2 relaxation time made by us in one of the tendons show that it was not possible to record variations in the T2 relaxation time with clinical MR system. Again, the histologic analysis of the 5 tendons removed in young subjects showed that no tendon was strictly normal as regards the histologic appearances, and that the artefact of the magic angle is explicable only if the physico-chemical structure of the tendinous collagen is completely respected [6].

Finally, we noted that the zones of intense signal observed in these 5 tendons were perfectly correlated with the histologic anomalies, so that there is currently no tangible proof that the modifications of the signal from the supraspinatus tendon were associated with the artefact of the magic angle. On the other hand, the precision of the correlations between the MRI and histologic findings obtained in our work, and the studies of Kjellin [2] and Rafii [16] suggest that these zones of intermediate signal are associated with histologic changes. Nor can the other artefacts recognised in MRI be implicated: (1) the artefact of chemical schift, with the sequence we used, cannot deform the image beyond a distance of 1.76 pixels, which corresponds to 0.68 mm; therefore it can be excluded that this artefact may be the cause of these high intratendinous signals; (2) the truncation artefact causes the appearance on the image of bands of a variable signal, which should be arranged in symmetric fashion within the tendon, which was not the case in our study.

Incidence of signal anomalies

Mirovitz [13] found zones of intermediate signal in 8/15 cases with the T2-weighted spin-echo sequence, and in every case with a spin-echo sequence with saturation of the fat. In our control series we regularly observed these signal anomalies with a T2-weighted spin-echo sequence. The particular positioning of the circular surface coil of 5 inches GP locates the scapulohumeral articulation at the center of the coil, which significantly increases the signal/noise ratio and allows study of the scapulohumeral joint with a field of view of 10 cm and a high-resolution matrix (256 x 256), while maintaining an intense signal. This particular technique probably explains why we can better observe these zones of intermediate signal in the T2-weighted spin-echo, though without explaining why these are best visualised in the sequence with suppression of the fatty signal used by Mirovitz [13].

Topography of signal anomalies

According to the study of Mirovitz [13], the regions of intense signal are most often located in the lateral part of the tendon just at the level of its insertion, though this author does not specify the anteroposterior topography of these anomalies. In 4 control subjects and 2 tendons studied *ex vivo*, we observed that a zone of intermediate signal was clearly individualised at the level of the anterior part of the tendon (Fig. 7). This is interesting insofar as this region corresponds, as will be seen, to the axis of traction of the supraspinatus m. On the other hand, we observed no topographic correlation between the site of the vascular foramen (or "critical zone") as first described by Codman [2] and the site of the histologic anomalies or abnormal signal seen in MRI. This hypovascular region of the supraspinatus tendon, which increases in size with age, is located opposite the upper pole of the humeral head, 1 cm medial to the greater tubercle on the superficial aspect of the supraspinatus tendon [10, 11, 14, 17]. The frequency of signal modifications within presumably normal tendons in our control series is therefore an accepted fact, and it is certainly impossible to draw the least histologic correlation. However, the resemblance of this control series to the five tendons studied does suggest that these modifications correspond to real histiologic deterioration and not to signal modifications of artefactual origin.

Physiopathology of the supraspinatus tendon

The anatomic description of the scapulohumeral articulation explains the precocious appearance and progressive increase (from the age of 14) [3] of degenerative changes in the suraspinatus tendon. This tendon actually has a very special anatomic position, since it is squeezed between the humeral head and the subacromial vault [15]. In this strangulating bottleneck it is subjected to strains in very different axes, which is quite unusual for a tendinous structure. These constraints, which are combined during the play of the articulation, are of three kinds: (1) traction constraints during muscular contraction; (2) compression constraints when

the humeral head is forced against the acromion, probably associated with ischemia in the narrowest zone of the subacromial corridor [7]; (3) torsion constraints during movements of forced medial and lateral rotation. These constraints are maximal in the axis of traction of the supraspinatus m., which is defined by the presence within the muscle belly of a bulky tendon directed laterally and forward to become attached to the most anterior part of the greater tubercle [8, 4, 12].

The sum of these anatomic observations explains (1) the precocity and frequency of degenerative changes on the suprapsinatus tendon; (2) the preferential anterior site of the histiologic changes as we noted in 3 of the 5 tendons removed; (3) the presence of a zone of intermediate signal clearly more marked at the anterior part of the tendon in 4 control subjects and 2 tendons studied *ex vivo*.

The progressive deterioration of these tendinous lesions leads to rupture of the supraspinatus tendon, preferentially located (when it is incomplete) in the anterior part of the tendon. On the other hand the significance of the vascular foramen remains imprecise. Is this a constitutional vascular fragility, or an acquired anomaly? The severity of the mechanical constraints exerted on the tendon certainly explains the early and repeated appearance of intratendinous lesions. These possibly heal less well in a tendinous zone subject to ischemia. This defective healing damages the vascular plexus and may be the origin of the hypovascular zone described by Codman [2].

Conclusions

This study confirms the frequency of signal modifications observable in control subjects in the supraspinatus tendon on the first echo of T2-weighted spin-echo sequence. Such signal anomalies were also found in a high-resolution MRI study in tendons removed from young subjects and are very clearly correlated with histologic changes. The very specific anatomic situation of the supraspinatus tendon accounts for the early development of these histologic changes predominantly in the anterior part of the tendon layer, along the axis of traction of the supraspinatus muscle. The progressive deterioration in these histologic changes explains the development of rupture of the tendon. There is no topographic correlation between the site of the vascular foramen and the anomalies observed in MRI and histology. These results confirm the prudence which must be exercised in interpretation of the MRI findings concerning tendinopathic lesions of the supraspinatus tendon.

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