Three-Dimensional Analysis of the Width of the Subacromial Space in Healthy Subjects and Patients with Impingement Syndrome

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OBJECTIVE. The aim of this study was to perform a three-dimensional analysis of the width of the subacromial space during passive and active arm abduction in healthy volunteers and patients with impingement syndrome.

SUBJECTS AND METHODS. The shoulders of 10 healthy subjects and 10 patients with impingement syndrome were imaged with an open MR system during abduction, with and without activation of the shoulder muscles. An apparatus was designed for applying an adduction force of 10 N to the distal humerus during image acquisition, and the minimal acromiohumeral distance was measured after three-dimensional reconstruction.

RESULTS. In the 10 healthy volunteers, muscle activity led to a significant decrease (–32%; $p < .05$) of the acromiohumeral distance at 60° of abduction, whereas at 120° of abduction the distance was significantly increased (+44%; $p < .05$). In these volunteers, muscle activation caused no significant effect at 90° of abduction. However, in the 10 patients with impingement syndrome, muscle activity led to a significant decrease in the width of the subacromial space compared with that of the healthy contralateral side (–68%; $p < .05$).

CONCLUSION. Muscle activity and arm position were found to cause systematic changes in the width of the subacromial space. However, functional deficits of the supraspinous muscle in patients with early-stage impingement syndrome were not apparent during muscle relaxation.

Impingement syndrome is a frequent cause of chronic pain and disability in the shoulder, and it has been suggested that reduction of the subacromial space plays an important part in the pathogenesis of this syndrome [1–4]. The pain is typically provoked by actions that carry the arm above the head, and therefore the patient is usually examined clinically during active elevation of the shoulder [1, 5, 6]. Biomechanical studies in cadaver specimens have shown that reduction of the width of the subacromial space is most marked between 60° and 120° of abduction [7, 8], but the current radiologic workup of impingement syndrome is usually based on radiographs, CT scans, or MR images acquired in the neutral-0 position [9, 10]. To our knowledge, no quantitative in vivo data exist on the changes of the width of the subacromial space during abduction of the arm.

Although electromyographic studies [11, 12], biomechanical shoulder models [8, 13, 14], and clinical examinations [1, 2, 15, 16] have shown the relevance of shoulder muscle activity—especially that of the supraspinous muscle—in impingement syndrome, imaging is usually performed with the shoulder muscles relaxed. MR imaging studies have been focused on describing qualitative morphologic alterations of the rotator cuff (e.g., changes of signal intensity or continuity, intrasubstance fraying of rotator cuff tendons), the soft tissue (e.g., fluid in the subacromial–subdeltoid bursa), and the adjacent bones [9, 10, 17–21], but the technique has so far not been applied in examining functional deficits of the supraspinous muscle in patients with impingement syndrome.

One possible means for quantifying the subacromial space width is to measure the acromiohumeral distance. This distance has been reported to range from 6 to 14 mm on radiographs of healthy subjects in the neutral-0 position and has been found to be reduced in 50% of patients with rotator cuff disease [22–25]. However, because radiography projects the bone images onto a plane, quantitative data may be seriously compromised by projectional artifacts. A limitation of X-ray tomography, two-dimensional (2D) CT, and 2D MR imag-

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ing studies is the limited reproducibility of the plane and orientation of a specific section [9, 26, 27]. A previous study found that this disadvantage can be overcome by acquiring complete three-dimensional (3D) data sets of the shoulder, using an open MR system, and measuring the true minimal 3D distance between the humerus and acromion after 3D reconstruction of these structures [28].

The objective of the present investigation was to extend the 3D open MR imaging technique to the in vivo study of changes of the subacromial space width at different degrees of abduction during muscle activity, and to analyze potential functional deficits of the supraspinous muscle in patients with impingement syndrome. We hypothesized that in early-stage impingement syndrome, reduction of the acromiohumeral distance would become apparent only during activity of the abductor muscles, not during muscle relaxation.

Subjects and Methods

MR Imaging

Ten healthy volunteers (four women and six men, 23–35 years old) without symptoms or history of shoulder disease were examined. Ten patients with unilateral impingement syndrome (five women and five men; 39–64 years old) in whom the diagnosis had been confirmed clinically (by Jobe, Hawkins, and Neer tests) and by MR imaging with a 1.5-T scanner (Magnetom Vision; Siemens, Erlangen, Germany) were also examined. The Jobe test was rated as positive if the typical pain was provoked during internal rotation at 90° of abduction. The Hawkins test was used for evaluating subcoracoidal impingement, in which the pain is pronounced during adduction of the arm in an internally rotated and elevated position. Finally, the Neer test was considered positive when the pain occurred at 60–120° of anteversion. Six of the patients had stage I or II impingement syndrome (Neer classification [1]) revealed on MR imaging, showing changes in signal intensity without signs of a complete rupture. Three patients had a full-thickness rotator cuff tear with signs of tendon retraction, and one had pronounced osteoarthrosis of the acromioclavicular joint. This patient had a large spur of the acromioclavicular joint without additional abnormalities of the rotator cuff. In the 10 patients, a standard MR protocol (T1- and T2-weighted sequences) was also used for assessment of potential morphologic changes of the asymptomatic contralateral shoulder to exclude pathology.

For the functional assessment, an open-configuration MR scanner (Magnetom Open; Siemens) (0.2 T main field strength, ±15 mT gradient strength) was used, allowing us to examine the shoulder at various degrees of arm abduction. Because the aim of the study was to quantitatively analyze the width of the subacromial space during muscle activity, a sequence with high in-plane resolution, small slice thickness, and short imaging time was required, and thus a T1-weighted 3D gradient-recalled echo sequence (TR/TE, 16.1/7.0; flip angle, 30°) was applied at a spatial resolution of $1.88 \times 0.86 \times 1.56$ mm^3 (field of view, 220 mm^2) with an imaging time of 4 min 28 sec. The healthy control subjects and the patients were placed on the patient table in a 30° oblique supine position, with one arm abducted in the scapular plane (Fig. 1A). Oblique coronal images were obtained parallel to the long axis of the scapula.

The healthy subjects were examined using complete 3D gradient-recalled echo sequence data sets at 60°, 90°, and 120° of abduction (Fig. 1A). Internal or external rotation of the arm was precisely controlled by a special positioning device and by visual inspection. For determining the effects of muscle activity on the subacromial space width, an adduction force of 10 N was applied to the distal end of the humerus by using a 1-kg weight with a nylon rope and a pulley so that the abductor muscles were isometrically contracted. To prevent movement artifacts and ensure that the humerus was maintained in a constant position during image acquisition, a board was installed to which the arm was attached firmly (Fig. 1B). Both the diseased and healthy shoulders of the 10 patients were imaged during muscle relaxation at 30° and 90° of abduction and with muscle activity at 90° of abduction.

Before MR imaging, the activity of the anterior and middle fibers of the deltoid muscle was analyzed with the subjects in the scanning (30° oblique supine) position for 4 min 30 sec, using electromyographic surface electrodes that work at a frequency of 625 Hz, to ensure that the muscles remained contracted during image acquisition. This test showed continuous activity of the middle and anterior parts of the deltoid muscle for the entire period of imaging at all degrees of abduction.

The study design was approved by the local ethics committee.

Digital Image Processing and Statistical Analysis

After transferring the complete 3D MR image data sets to a symmetric multiprocessing computer (ONYX; Silicon Graphics, Mountain View, CA) with two high-performance graphics systems (Infinite Reality; Silicon Graphics), the supraspinous muscle, the humerus, the clavicle, and the scapula were segmented semiautomatically on a section-by-section basis, using a gray value–orientated region-growing algorithm. Shape-based interpolation and 3D reconstruction of the segmented structures were performed, using a contour-based interpolation and an optimized surface-constructing algorithm [29]. For quantification of the subacromial space width, the minimal spatial acromiohumeral and claviculohumeral distances

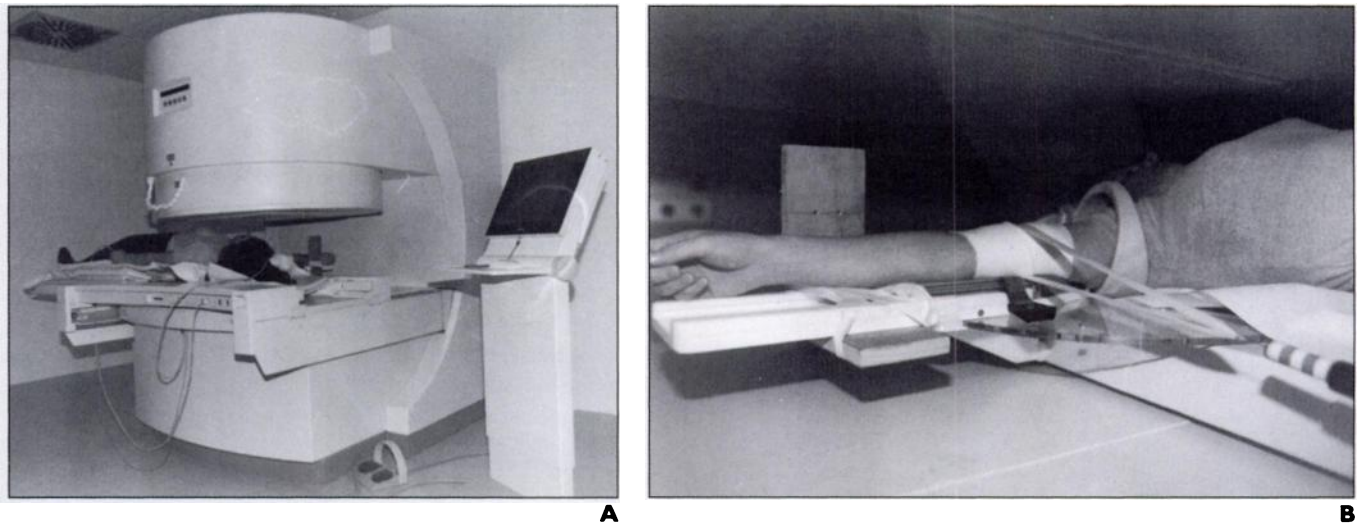

Fig. 1.—27-year-old healthy woman.
A, Photograph shows subject placed in 30° oblique supine position on open MR table with arm abducted to 120° angle in scapular plane.
B, Photograph shows arm placed at 90° angle of abduction with adduction force of 10 N applied to distal humerus.

were determined by 3D Euclidean distance transformation, as described in a previous study [28]. The complete time required for interactive segmentation, 3D reconstruction, and minimal distance analysis was about 45 min for each joint position.

The minimal distances in the healthy subjects and the patients with early-stage impingement syndrome were analyzed statistically with the Wilcoxon's signed rank test for matched pairs (Statview 4.5; Abacus Concepts, Berkeley, CA), comparing values at different degrees of abduction and values determined with and without shoulder muscle activity. In the patients, the diseased shoulder was also compared with the unaffected healthy shoulder.

Results

Healthy Control Subjects

The acromiohumeral and claviculohumeral distances varied widely between individuals at different degrees of abduction, the relative SD amounting to between 14% and 51% for the acromiohumeral and between 23% and 29% for the claviculohumeral distance. Without muscle activity, the mean minimal acromiohumeral distance decreased (no statistical significance) during abduction from an average of 6.7 mm (range, 5.1–7.8 mm) at 60° of abduction to 5.4 mm (range, 1.9–7.8 mm) at 90° of abduction. The distance decreased significantly ($p < .05$) from 90° to 120° of abduction (range, 1.7–6.1 mm; mean, 3.6 mm) (Fig. 2A). This decrease was caused—at least in part—by the greater tuberosity, which approached the acromion as abduction increased. At 120° of abduction, the minimal distance vector between the acromion and the humerus was located lateral to the supraspinous muscle, whereas at 60° and 90° of abduction it passed through the supraspinous tendon.

When the shoulder muscles were activated, the acromiohumeral distance was significantly reduced at 60° of abduction (mean, –32%; $p < .05$) compared with the data obtained without muscle activity, whereas at 120° of abduction the distance was increased (mean, +44%; $p < .05$) (Fig. 3). At 90° of abduction, no significant change could be observed relative to the relaxed state (mean, –7.8%; $p = .15$) (Figs. 2A and 3). When the muscles were active, the mean acromiohumeral distance remained almost constant at all three degrees of abduction (60° = 4.7 ± 2.4 mm [mean ± SD]; 90° = 4.1 ± 2.5 mm; 120° = 4.8 ± 2.0 mm) (Fig. 2A).

When the muscles were relaxed, the claviculohumeral distance showed almost no change from 60° of abduction (range, 9.9–19.6 mm; mean, 14.8 mm) to 90° of abduction (range, 9.6–19.8 mm; mean, 14.9 mm) and a slight decrease from 90° to 120° of abduction (range, 7.6–21.2 mm; mean, 11.8 mm) that was not statistically significant (Fig. 2B). When the shoulder muscles were active, the claviculohumeral distance showed no important differences among 60° (mean, 13.4 ± 3.5 mm), 90° (mean, 13.2 ± 3.9 mm), and 120° (mean, 12.1 ± 3.9 mm) of abduction. The values obtained during muscle relaxation and those observed during muscle activity (Fig. 2B) were not significantly different.

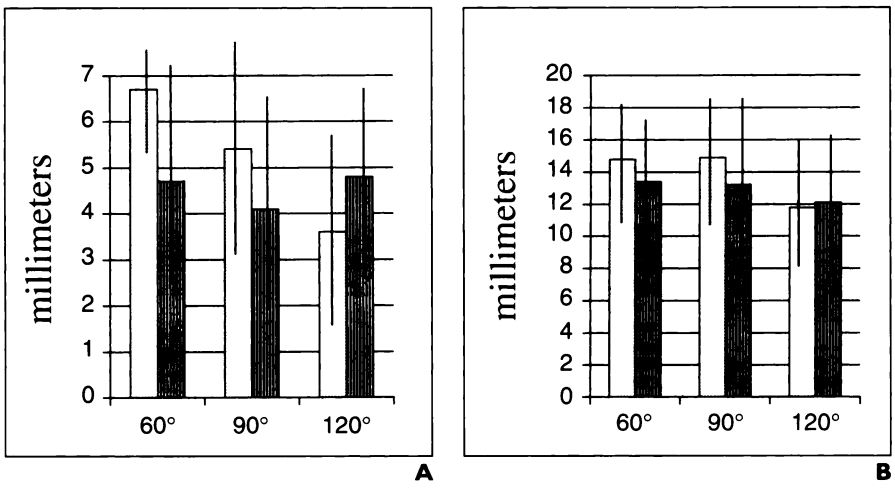

Fig. 2.—Changes in width of subacromial space in 10 healthy control subjects measured at different levels of abduction with and without muscle activity. Dotted bar indicates width during muscle relaxation; striped bar indicates width during muscle activity.

A, Bar graph shows mean acromiohumeral distance and SD at 60°, 90°, and 120° of abduction with and without muscle activation. Acromiohumeral distance decreases significantly from 90° to 120° during muscle relaxation. During muscle activity, no significant differences are observed for 60°, 90°, and 120° of abduction.

B, Bar graph shows mean claviculohumeral distance and SD at 60°, 90°, and 120° of abduction, with and without muscle activity. No significant changes are seen at 60°, 90°, and 120° of abduction.

Patients

The distance values obtained in the patients with impingement syndrome were dependent on the stage of the rotator cuff disease, the abduction angle, and the influence of muscle activity.

Analysis of the six patients with early-stage impingement syndrome (stages I and II) at 30° of abduction during muscle relaxation revealed no significant difference in acromiohumeral distance between the healthy (mean, 6.5 mm ± 0.7 mm) and diseased (mean, 6.5 mm ± 1.2 mm; $p = .75$) shoulders (Fig. 4). The claviculohumeral distance also showed no obvious difference between the healthy (mean, 12.4 mm ± 0.7 mm) and diseased (13.1 mm ± 0.7 mm) shoulders. At 90°, only two of the six patients with early-stage impingement syndrome showed both the acromiohumeral and claviculohumeral distances to be somewhat smaller in the diseased shoulder during muscle relaxation, and thus no significant difference existed between the sides (Fig. 4). However, during muscle activity, the acromiohumeral distance was dramatically smaller in the diseased shoulder (1.4 mm ± 1.1 mm versus 4.4 mm ± 1.5 mm; $p < .05$), and the distance was significantly reduced compared with the images of the same shoulder during muscle relaxation (1.4 mm ± 1.1 mm versus 3.8 mm ± 1.1 mm; $p < .05$) (Figs. 4, 5A, and 5B). The claviculohumeral distance in the diseased shoulder was also decreased during muscle activity in five of six patients (10.0 mm ± 2.1 mm [mean ± SD] versus 11.3 mm ± 1.9 mm [mean ± SD]) (Figs. 5A and 5B).

In the three patients with a full-thickness rotator cuff tear, the distances were substantially smaller at 30° and 90° of abduction compared with the healthy shoulder (Figs. 4, 5C, and 5D), both during relaxation and muscle activity. However, the minimal acromiohumeral distance decreased even further during muscle activity relative to the measurements obtained during muscle relaxation (Fig. 4).

The patient with pronounced acromioclavicular osteoarthrosis showed no obvious differences between the minimal distances on the two sides, and the distances were not smaller in the diseased shoulder during muscle activity compared with the contralateral shoulder. However, the 3D reconstruction made it possible to visualize local compression of the supraspinous muscle by an acromioclavicular osteophyte. The mechanical irritation was most pronounced at 60° of abduction, which corresponded with the clinical symptoms in this patient (Fig. 5E).

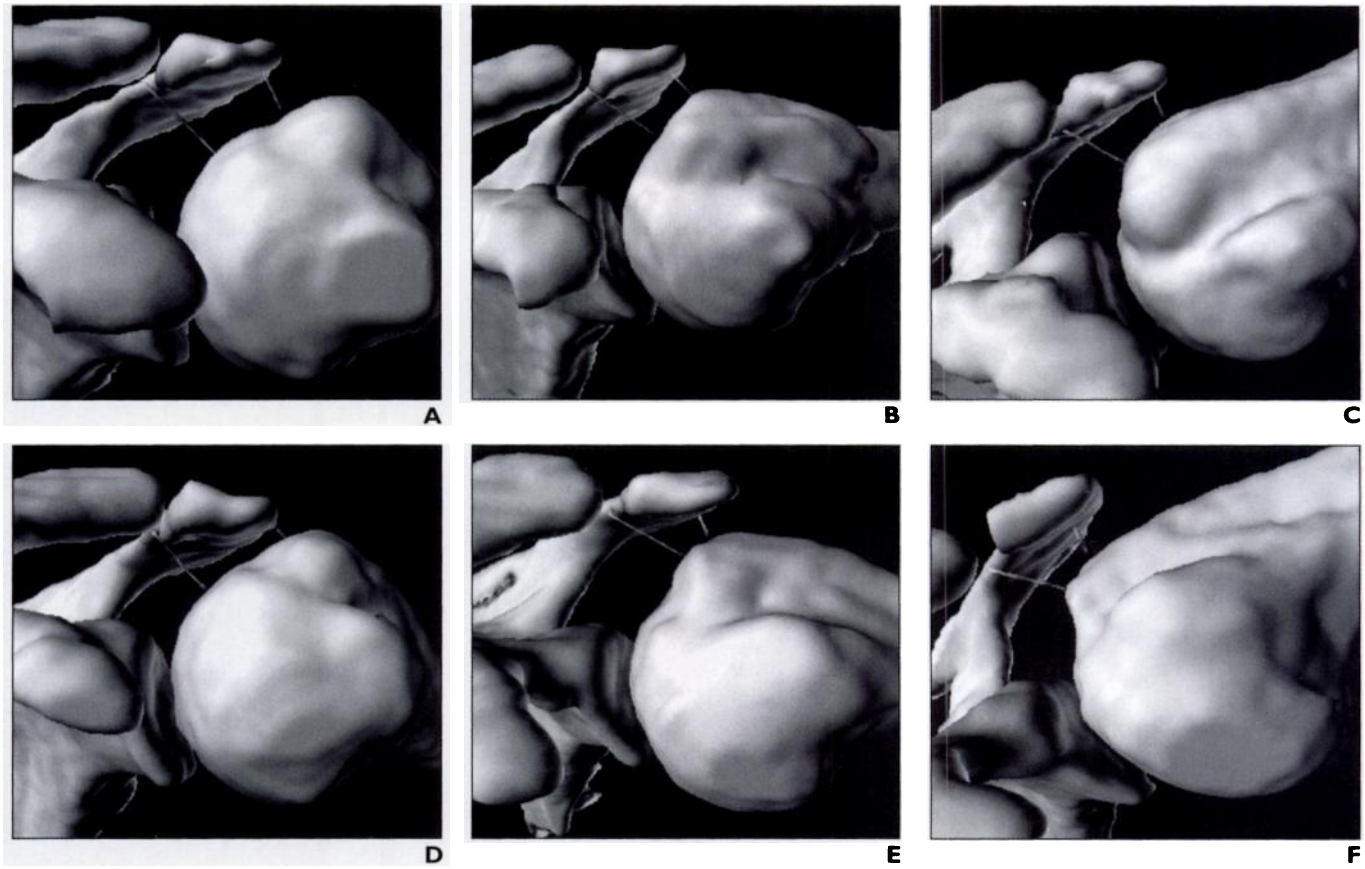

Fig. 3.—27-year-old healthy woman.
A–C, Three-dimensional (3D) reconstruction images of control subject at rest shows shoulder at 60° (**A**), 90° (**B**), and 120° (**C**) of abduction.
D, 3D reconstruction image obtained during muscle activity shows shoulder at 60° of abduction. Compared with data obtained without muscle activity, minimal acromiohumeral distance is reduced.
E, 3D reconstruction image obtained during muscle activity shows shoulder at 90° of abduction. No obvious difference relative to relaxed state can be observed.
F, 3D reconstruction image obtained during muscle activity shows shoulder at 120° of abduction. During muscle activity, the minimal acromiohumeral distance is increased compared with distance without muscle activity.

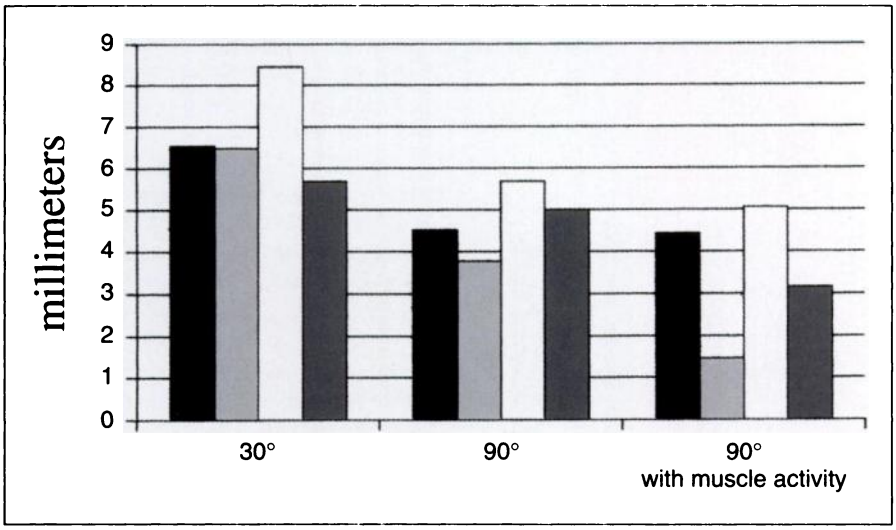

Fig. 4.—Bar graph shows changes of mean width of acromiohumeral distance in patients with impingement syndrome and patients with full-thickness rotator cuff tear. Three patients with full-thickness rotator cuff tear show decrease of distance compared with healthy shoulder during muscle relaxation at both 30° and 90° of abduction. Conversely, patients with early-stage impingement syndrome show significant changes only during muscle activity at 90° of abduction, but not during muscle relaxation at 30° and 90° of abduction. Black bar = healthy shoulders of patients with impingement syndrome; light gray bar = diseased shoulders of patients with impingement syndrome; white bar = healthy shoulders of patients with full-thickness rotator cuff tears; dark gray bar = diseased shoulders of patients with full-thickness rotator cuff tears.

Discussion

In this study we analyzed the 3D changes of the width of the subacromial space during active and passive arm elevation using an MR imaging–based technique. We showed that functional deficits of the supraspinous muscle that are not apparent during muscle relaxation are observed during muscle activity in patients with early-stage impingement syndrome.

Muscle activity is known to be a relevant factor in joint stability and function, especially in the shoulder [30, 31]. Our study shows that in healthy control subjects, muscle activity leads to a small decrease in the width of the subacromial space at 60° of abduction and a slight increase at 120° of abduction. These changes may depend on the different level of activity and different extent of leverage of the deltoid and supraspinous muscles at the various degrees of abduction, as has been suggested in previous electromyographic and biomechanical studies [8, 11, 12, 30–33]. These studies showed that early abduction (<60°) of the deltoid muscle produced upward displacement of the humeral head, whereas at greater

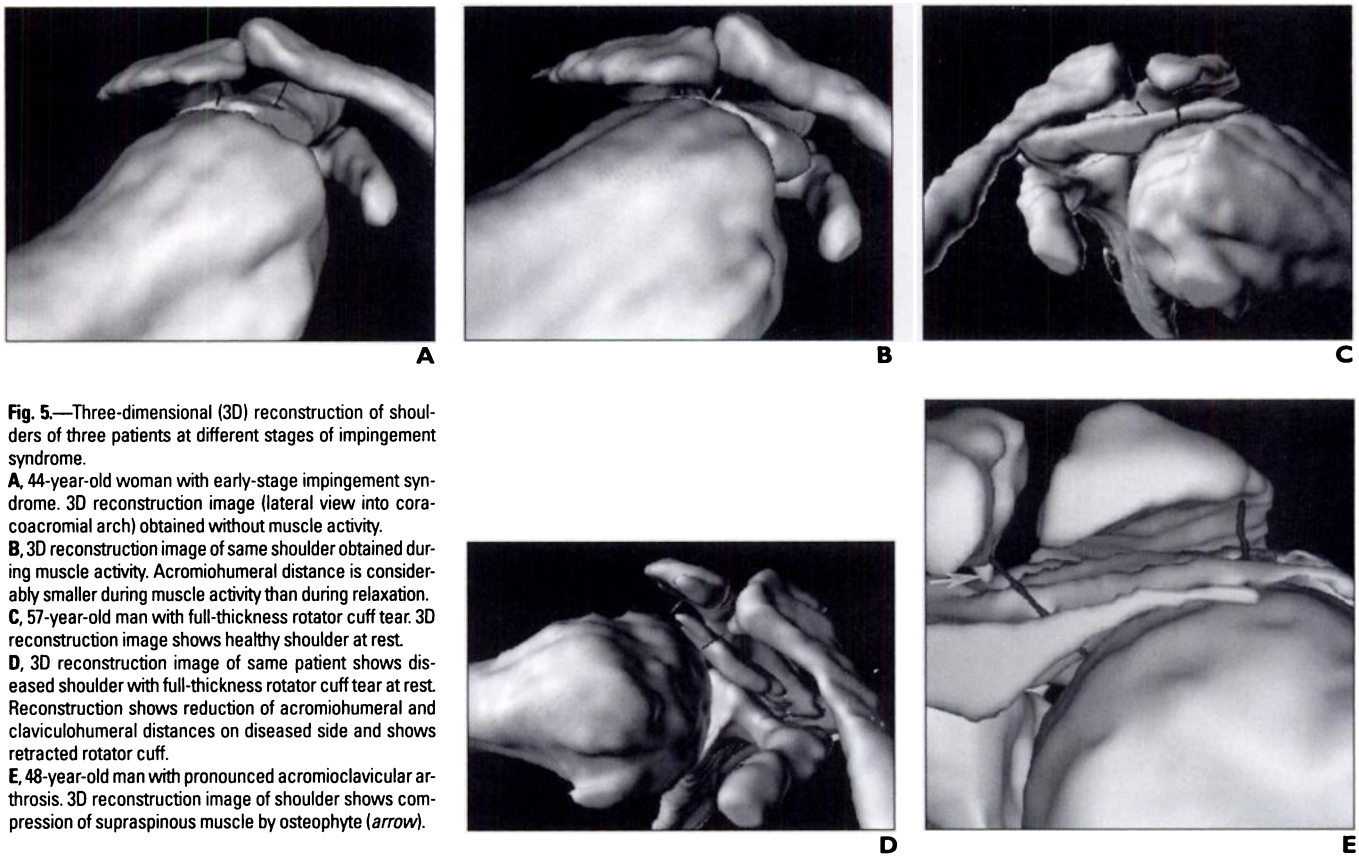

Fig. 5.—Three-dimensional (3D) reconstruction of shoulders of three patients at different stages of impingement syndrome.
A, 44-year-old woman with early-stage impingement syndrome. 3D reconstruction image (lateral view into coracoacromial arch) obtained without muscle activity.
B, 3D reconstruction image of same shoulder obtained during muscle activity. Acromiohumeral distance is considerably smaller during muscle activity than during relaxation.
C, 57-year-old man with full-thickness rotator cuff tear. 3D reconstruction image shows healthy shoulder at rest.
D, 3D reconstruction image of same patient shows diseased shoulder with full-thickness rotator cuff tear at rest. Reconstruction shows reduction of acromiohumeral and claviculohumeral distances on diseased side and shows retracted rotator cuff.
E, 48-year-old man with pronounced acromioclavicular arthrosis. 3D reconstruction image of shoulder shows compression of supraspinous muscle by osteophyte (*arrow*).

degrees of abduction the humeral head is centered by the supraspinous muscle and other parts of the rotator cuff (subscapular and infraspinous muscles) [7, 8, 30, 31]. In control subjects with healthy shoulders, the minimal distances are almost constant during muscle activity at all three degrees of abduction.

The relevance of performing a functional assessment of the shoulder during muscle activation (in addition to the standard morphologic evaluation) is clearly shown in patients with early-stage impingement syndrome. All six patients with impingement syndrome stages I and II [1] showed a significant reduction of the acromiohumeral and an obvious reduction of the claviculohumeral distance during muscle activity, whereas during muscle relaxation, the acromiohumeral and claviculohumeral distances were greater in the diseased shoulders of four patients. Upward migration of the humeral head and reduction of the subacromial space is thus only observed in these patients when the abducting muscles are active, not when they are relaxed. This effect is therefore not apparent on standard radiographic examinations. These results indicate that dyssynergic activity of the shoulder muscles may play an important role in the pathogenesis of impingement syndrome and may even precede degenerative or reparative morphologic changes of the rotator cuff [9, 10].

Patients with a full-thickness tear of the rotator cuff, on the other hand, showed a reduction of subacromial space width even during muscle relaxation, at both 30° and 90° of abduction. This is in agreement with findings of previous studies [23, 24] in which radiography was used to quantify the acromiohumeral distance [3, 22, 23, 34]. However, X-ray beams superimpose the image of the osseous structures onto one plane, leading to potentially serious projectional artifacts. X-ray tomography, 2D CT, and 2D MR imaging are also problematic because of the difficulty in standardizing a reproducible section position and orientation. In the present study, these problems were overcome by using a 3D MR imaging and reconstruction technique. Although this procedure is relatively time-consuming at present, improvements of the image contrast or the segmentation techniques may allow for much faster or even automatic segmentation of the shoulder joint components in the future.

Previous radiographic investigations undertaken at 0° of abduction and during muscle relaxation revealed a decrease in the acromiohumeral distance (relative to a healthy control population) in only 50% of the patients with rotator cuff disease [25]. Our findings lead us to hypothesize that some patients with apparently normal acromiohumeral distances may suffer from functional deficits of the rotator cuff that can only be detected when measurements are obtained during muscle activity. However, because of the small number of patients in our study, our results have to be considered preliminary.

Because of the high interindividual variability of the minimal acromiohumeral and claviculohumeral distances, it appears advantageous to compare these values with those of the healthy contralateral side in patients with unilateral impingement syndrome, rather than to relate the measurements to those made in a reference population of healthy subjects. Because MR imaging is not based on the use of ionizing radiation and because a low-field-strength system applies little radiation to the patient, a second acquisition of the healthy contralateral shoulder can be considered unproblematic.

To our knowledge, the MR imaging literature has focused on describing qualitative and morphologic changes in the rotator cuff. However, additional information about functional deficits of the rotator cuff can be important in the diagnosis of impingement syndrome and in monitoring and evaluating the success of surgical or conservative treatment. In this study,

patients with clinically and radiologically unambiguous impingement syndrome were assessed to determine if consistent functional changes in the width of the subacromial space are influenced by shoulder position, muscle activity, or both. Future studies will have to show whether this technique is also able to differentiate subacromial impingement from other causes of shoulder pain before morphologic alterations occur.

The technique presented shows the important influence of muscle activity on measurements of the width of the subacromial space in healthy control subjects and, in particular, in patients with impingement syndrome. We observed functional deficits of the rotator cuff at the early stage of impingement syndrome and reductions of the acromiohumeral distance during muscle activation that are not apparent when the shoulder is imaged in the relaxed state. Functional MR imaging analysis of the shoulder joint can thus add important information regarding the pathomechanics and biomechanical implications of impingement syndrome.

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