CLINICAL ARTICLE

Morphological Characteristics of Acromion and Acromioclavicular Joint in Patients with Shoulder Impingement Syndrome and Related Recommendations: A Three-Dimensional Analysis Based on Multiplanar Reconstruction of Computed Tomography Scans

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Objective
To find out which structure is crucial for the formation of shoulder impingement syndrome with the purpose of directing surgical procedures of subacromial decompression and discussing whether it is necessary to manage acromioclavicular joint during operation and how to do it properly.

Methods: This was a retrospective study. Clinical data and preoperative computed tomography (CT) images were collected from patients who were diagnosed with rotator cuff tears between January 2017 and August 2019 (sample size: 46) and those who were diagnosed without rotator cuff tears between March 2018 and August 2019 (sample size: 44) in our institution, respectively. Three-dimensional models of shoulders were established by multiplanar reconstruction of CT scans and measurements were performed on these models. The parameters such as the acromial length and width, the axial tilt, and the distance from acromial margin to glenoid plane were measured in an adjusted axial plane, and the critical shoulder angle and the spatial volume under acromioclavicular joint were measured in an adjusted coronal plane. The demographic characteristics, the acromial morphology and the spatial volume under acromioclavicular joint were compared to find significant differences between the two groups. The association between the axial tilt and the distance from acromial margin to glenoid plane was evaluated by an ordinary least squares linear regression.

Results: The patients with rotator cuff tears consisted of 16 males and 30 females, among which 30 right shoulders and 16 left shoulders were included. The patients without rotator cuff tears consisted of 28 males and 16 females, among which 15 right shoulders and 29 left shoulders were involved. Significant differences between the groups were found in the acromial width (3.332 cm *vs* 3.111 cm), the axial tilt (33.765° *vs* 23.829°), the critical shoulder angle (32.630° *vs* 30.363°), the distance from anterior 3 cm of lateral acromial margin (range, 2.476 cm–3.302 cm *vs* 1.993 cm–3.089 cm), and anterior 0.9 cm of medial acromial margin (range, 0.967 cm–2.369 cm *vs* 0.668 cm–1.993 cm) to glenoid plane, and the spatial volume under acromioclavicular joint (1.089 cm *vs* 1.446 cm) in the two groups. No significant differences were found in the age (60.0 years *vs* 58.3 years) or the acromial length (4.187 cm *vs* 4.184 cm). Significant association was revealed by linear regression analysis between the axial tilt and the

distance from anterior two-thirds of lateral acromial margin to glenoid plane, and similar association was also found in the anterior half of medial margin.

Conclusion: Anterior two-thirds of lateral acromial margin, anterior half of medial acromial margin, and inferior aspect of acromioclavicular joint are crucial structures and need to be fully decompressed when treating patients with rotator cuff tears.

Key words: Acromioclavicular joint; Acromion; Rotator cuff tears; Shoulder impingement syndrome; Three-dimensional analysis

Introduction

Shoulder impingement syndrome (SIS) is the most common disorder of the shoulder and has been thought to have a close relationship with rotator cuff tears (RCT). In 1972, Neer suggested that most RCT were caused by impingement of proliferative acromial spurs upon the rotator cuff tendons[1]. Some researchers proposed that the wear and lesions in the anterior one-third of undersurface of the acromion were important reasons for the development of RCT[2]. Nowadays, the mechanisms contributing to RCT are mainly classified into two groups: intrinsic factors and extrinsic factors. The intrinsic factors including tensile overload, aging, microvascular supply, and traumatisms which usually result in degeneration of the tendon itself[3]. The extrinsic factors are mainly some anatomic variables such as acromial morphologic characteristics, acromial spurs, morphology of coracoacromial ligament and acromioclavicular joint, which would narrow the subacromial space and increase pressure on tendons by impingement from bony structures or surrounding soft tissues[3,4]. There still exist debates on which mechanism is primary or secondary, but in some patients it seems to be an interaction between them.

To treat SIS, subacromial decompression and acromioplasty are regular methods that have been performed over a long period of time, but it is still controversial as to which part of the acromion should be resected or decompressed precisely. Most orthopaedists were used to focusing only on the anterolateral part and inferior surface of acromion and ignoring other parts. The critical shoulder angle (CSA) was first introduced by Moor *et al.* in 2013 and has been accepted as a parameter to measure lateral extension of acromion[5]. A larger CSA (more than 35°–38°) is associated with RCT because of massive overload on supraspinatus tendons. According to the theories of CSA, orthopaedists tried to reduce CSA to a normal level by acromioplasty, the effects of which also seem to be optimistic[6].

However, it is difficult to compare clinical results of subacromial decompression or acromioplasty because surgical techniques differ from surgeon to surgeon. Most orthopaedists concentrate on the anterior acromion[7–11], whereas others perform the acromioplasty on the inferior surface[8–10], the lateral side[11], or the medial side[8,12]. The crucial part of acromion which should be removed or decompressed during the procedures have not been determined accurately. The acromioclavicular (AC) joint is another important structure related with the SIS because the inferior clavicular spurs are considered as the culprit for the rupture of supraspinatus tendon[13]. Whether the AC joint should be operated on during the operation and to the extent of the intervention is still controversial. Barber recommended the coplaning technique to remove medial acromial spurs and portions of the distal clavicle to enlarge the space beneath the AC joint and protect the tendon from impingement[14]. Despite the satisfactory outcomes after long-term follow-up[15,16], some researchers pointed out that the coplaning technique led to AC joint symptoms and instability of AC joint, and queried the necessity of the intervention for AC joint[13,17,18].

To solve these problems, we designed the research concentrated on the morphological characteristics of lateral acromial roof and AC joint. According to the protocol, data was collected on three-dimensional (3D) images based on multiplanar reconstruction of computed tomography (CT) scans. The purposes of this study were (i) finding out which structure would be a potential risk factor for the development of SIS, (ii) directing surgical procedures of subacromial decompression according to the potential risk factors, and (iii) discussing the necessity of coplaning at acromioclavicular joint.

Materials and Methods

Patients

Patients who visited the department of orthopaedics in our hospital because of symptomatic shoulder disorders from January 2017 to August 2019 or those who were admitted to the trauma center in our hospital because of blunt trauma around shoulders from March 2018 to August 2019 were the interested population for our study. The inclusion criteria were: (i) definitively diagnosed with or without rotator cuff tears by radiologists; (ii) both magnetic resonance imaging (MRI) and CT of affected shoulder joint were performed. The exclusion criteria were: (i) tendinosis; (ii) osteoarthritis; (iii) previous fracture or dislocation around AC joint; (iv) previous scapular fracture; (v) previous surgery around shoulder; and (vi) sustaining a shoulder injury as a result of trauma. The cohort consisting of patients with rotator cuff tears was defined as the RCT group, and the cohort

consisting of patients without rotator cuff tears was defined as the normal group. We retrospectively collected clinical data and preoperative CT images of all patients included in this study. Valid CT scans were performed with patients lying supine with their arms by their side in neutral rotation. Those CT scans with patients raising their arms above their heads or crossing their arms upon their abdomens were excluded. Besides, because our measurement methods depend strongly on the glenoid orientation, we excluded patients with glenoid versions larger than ±10° from both RCT group and normal group. Finally, we got 46 shoulders for the RCT group and 44 shoulders for the normal group. The approval for our research was acquired from the Institutional Review Board.

Measurements

We used United Imaging Medical Processing Software (uWS-CT, version R004, United Imaging, Shanghai, China)
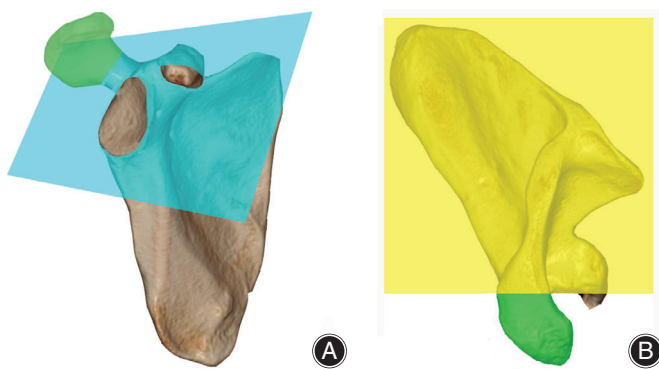

Fig 1 (A) Glenoid plane (blue) is perpendicular to the glenoid version and tangent to the upper and lower glenoid rim. Lateral acromial roof (green) is the part extending beyond the glenoid plane. (B) The lateral acromial roof (green) from another perspective.

to analyze the CT images with slice thickness of 1.0×0.8 mm. Through multiplanar reconstruction we could get a complete shoulder joint in 3D vision. Subsequent measurements were totally based on these 3D models.

Morphological Characteristics of Acromial Roof

Positional Adjustment of Scapula. As described by Beeler *et al.*[19], the glenoid plane is perpendicular to glenoid version and is a tangent to the upper and lower glenoid rim, and lateral acromial roof is defined as the part extending beyond the glenoid plane (Fig.1). In order to evaluate the characteristics of lateral acromial roof, moderate adjustment for the position of scapula is necessary. Within the axial view of shoulder joint, which is orthogonal with the glenoid plane, we rotated the scapula around an axis perpendicular to the glenoid plane to make the anteroposterior length of lateral acromial roof maximal (Fig. 2). The view with maximal anteroposterior length of the roof was selected for subsequent measurement.

Parameter Measurements. In this view, the acromion length (cm) and width (cm), the axial tilt (°), and the distance from lateral or medial acromial margin to glenoid plane (cm) were measured respectively. The acromion length represented the distance from the anterior tip to the posterior tip of acromial roof, and the acromion width was the distance from the most lateral margin of acromial roof to the glenoid plane (Fig. 3A). The axial tilt (Fig. 3B) was the angle between the glenoid plane and the line connecting the center points of the anterior third and the middle third of acromion. In order to simplify the measurement of the distance from lateral acromial margin to glenoid plane, the lateral acromial margin was segmented by points at 5 mm intervals from the anterior tip to the posterior base of acromion (Fig. 3C). These points were sequentially named L1, L2, L3, and so on, and the distance from each point to the glenoid plane was measured. The medial acromial margin was measured in the
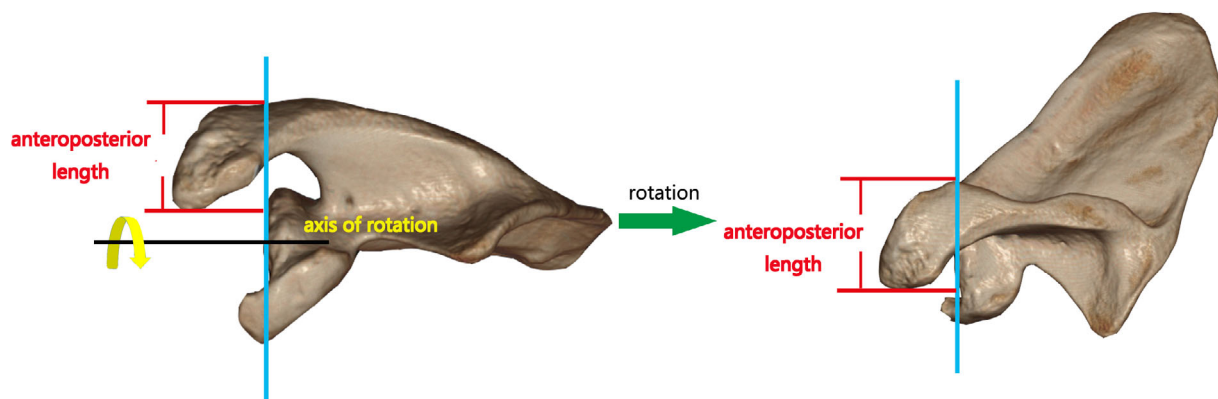

Fig 2 The adjustment of the axial view. In the axial view of shoulder joint, by rotating the scapula around the axis (the black line) perpendicular to the glenoid plane (the blue line), we can adjust the anteroposterior length of the lateral acromial roof. The view with maximal anteroposterior length of the roof is an ideal perspective for measurement.
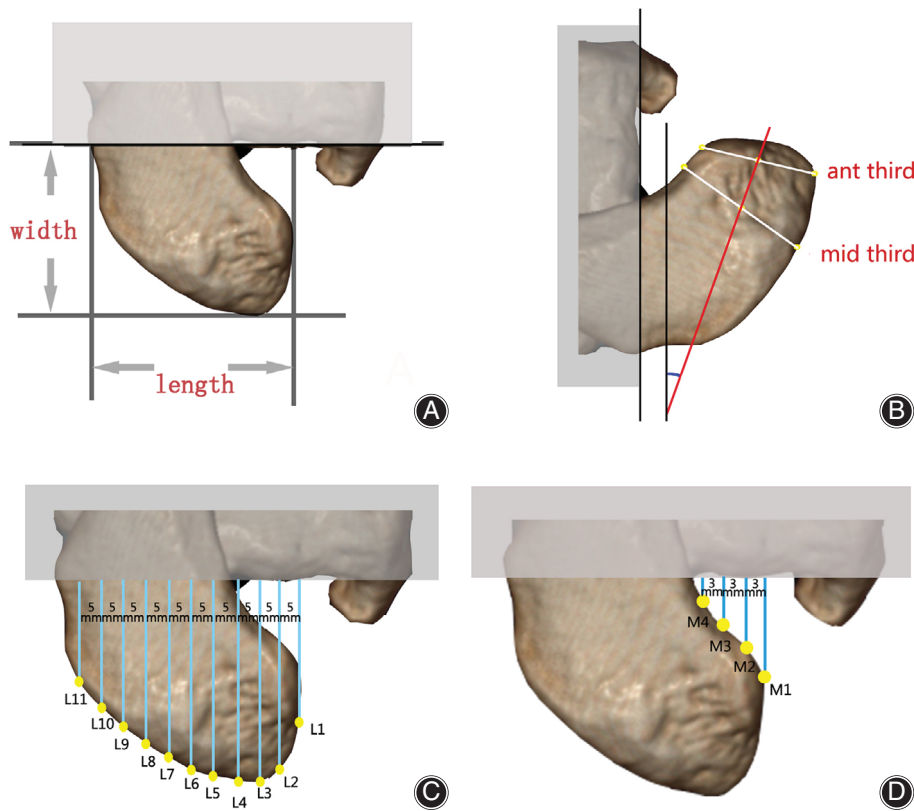
3D ANALYSIS FOR ACROMION AND AC JOINT

Fig 3 Measurement for the acromial roof. (A) Acromion length: distance from the anterior tip to the posterior tip. Acromion width: distance from the most lateral margin to the glenoid plane. (B) Axial tilt: angle between the glenoid plane and the line connecting the center points of the anterior third and the middle third of the acromion, represents the tilt of acromion in axial view. (C) The lateral acromial margin was segmented by points with 5 mm intervals. These points were defined as L1, L2, L3, and so on from anterior to posterior, and the distance from each point to the glenoid plane was measured. (D) The medial acromial margin was segmented by points with 3 mm intervals. These points were defined as M1, M2, M3, and so on from anterior to posterior, and the distance from each point to the glenoid plane was measured.

same way except the interval was 3 mm, and these separated points of the medial margin were sequentially named as M1, M2, M3, and so on (Fig. 3D).

The Critical Shoulder Angle
Establishing a Coordinate System. For the following measurement, a coordinate system established on the scapula was necessary. We defined the center of the best-fit circle of the inferior glenoid as the origin (the point O). The line connecting the origin and the point where the scapular spine intersected the medial border of the scapula (SM) was set as Z-axis. The plane determined by the Z-axis and the most inferior point on the inferior scapular angle (SI) was defined as YZ plane. The line starting from the origin and perpendicular to the YZ plane was X-axis, and the line beginning from the origin and perpendicular to the XZ plane was Y-axis (Fig. 4A). According to the opinions of Suter *et al.* and Karns *et al.*[20,21], by rotating the scapula around the Y-axis to correct the glenoid version, we could get a viewing perspective with an overlap of the anterior and posterior contour of the glenoid when looking perpendicular to the YZ plane, which was thought to resemble the true anteroposterior view of the shoulder joint (Fig. 4B).

Measurement of the Critical Shoulder Angle. In this view, we calculated CSA as the following: the first line connected the

inferior tip and the superior tip of the glenoid. The second line connected the inferior tip of the glenoid and the most lateral margin of the acromion. The angle generated by the crossing of these two lines was the CSA (Fig. 4B).

Spatial Volume Under Acromioclavicular Joint. The AC joint is another research objective in our study. In the previous coordinate system, we chose the picture parallel to the YZ plane (the same viewing perspective used for the CSA). In this view, the distance from the inferior edge of the AC joint to the superior tip of the glenoid was measured with the purpose to evaluate the spatial volume under the AC joint (Fig. 5). We defined this distance as the height of the AC joint. The number of shoulders with prominent spurs or osteophytes observed at the undersurface of AC joint was also documented.

To increase the accuracy of measurement, each value was measured three times and the average value was used for subsequent calculations.

Statistics
Statistical analysis was conducted with SPSS Statistics for Windows 24.0 software (IBM, Armonk, NY, USA). All quantitative values were reported as mean and standard deviation. Independent samples *t* tests and chi-square tests were used for differences of the characteristics between the RCT group and the normal group. The association between the axial tilt
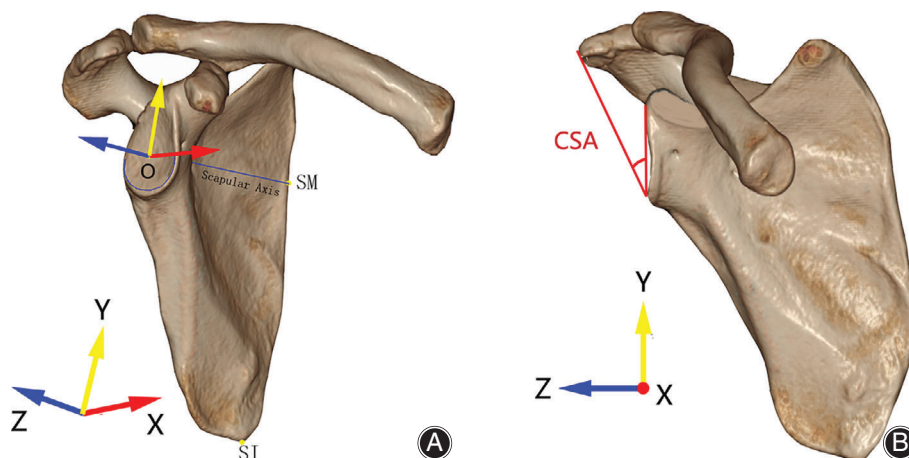
3D ANALYSIS FOR ACROMION AND AC JOINT

Fig 4 The coordinate system based on scapula. (A) The center of the best-fit circle of the inferior glenoid (O) was the origin. The line from O to SM was set as Z-axis (blue). The plane determined by O, SM, and SI was regarded as YZ plane. X-axis (red) was perpendicular to the YZ plane and Y-axis (yellow) was perpendicular to the XZ plane. (B) By rotating scapula around the Y-axis to correct the glenoid version, we got the viewing perspective parallel to the YZ plane, which represented the true anteroposterior view of shoulder joint. The CSA was generated by the line from the inferior tip to the superior tip of the glenoid and the other line from the inferior tip of the glenoid to the most lateral margin of the acromion.
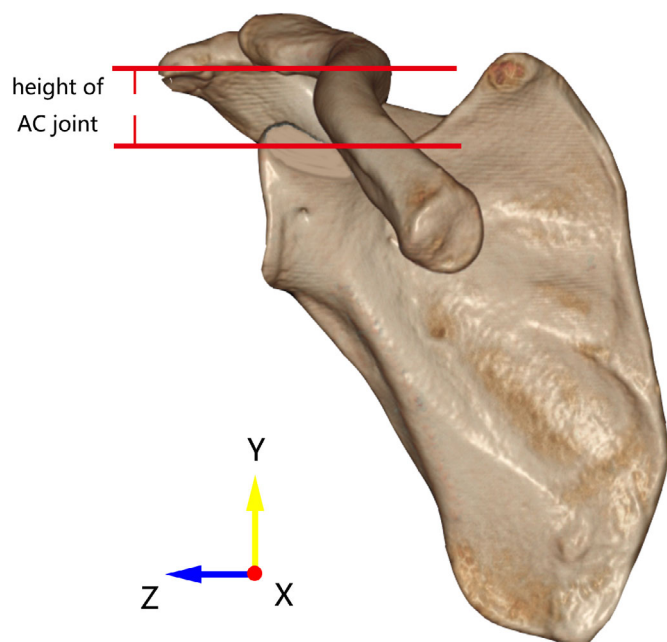
Results

Demographic Data

The demographics of the two groups are shown in Table 1. There were 16 males and 30 females in the RCT group, and 28 males and 16 females in the normal group. The *P* value for gender ratio between these two groups was 0.006, indicating a statistically significant difference. Sixteen left shoulders and 30 right shoulders were involved in the RCT group, and 29 left shoulders and 15 right shoulders were involved in the normal group, also showing a significant difference with regard to the proportion of affected sides between groups (*P* = 0.003). Age of the patients was described as mean ± standard deviation, and no difference was found between the two groups, with an average age of 60.0 years *vs* 58.3 years (*P* = 0.430).

Fig 5 The distance from the inferior edge of the AC joint to the superior tip of the glenoid was defined as the height of AC joint with the purpose to evaluate the spatial volume under AC joint.

and the distance from acromial margin to glenoid plane (L1–L9 for the lateral and M1–M7 for the medial) was evaluated by an ordinary least squares linear regression. Slopes, associated *P* values, and R^2 were reported. For all tests, a *P* value of <0.05 was considered statistically significant. The intraclass correlation coefficient (ICC) of each measured value was presented with 95% confidence interval (CI).

Morphological Characteristics of Acromial Roof in General

Statistically significant differences between the two groups were found in the acromial width (3.332 cm *vs* 3.111 cm, *P* = 0.020), the axial tilt (33.765° *vs* 23.829°, *P* = 0.000), the distance from lateral margin L1–L7 (range, 2.476 cm–3.302 cm *vs* 1.993 cm–3.089 cm, all *P* < 0.05), and from medial margin M1–M4 (range, 0.967 cm–2.369 cm *vs* 0.668 cm–1.993 cm, *P* = 0.000) to glenoid plane, and the CSA (32.630° *vs* 30.363°, *P* = 0.021). No significant differences were found in the acromial length (4.187 cm *vs* 4.184 cm, *P* = 0.980), the distance from lateral margin L8–L9 (range, 1.770 cm–2.040 cm *vs* 1.516 cm–1.859 cm, all *P* > 0.05) or from medial margin M5–M7 (range, 0.527 cm–0.695 cm *vs* 0.300 cm–0.550 cm, all *P* > 0.05) to glenoid

plane. Details are listed in Table 2 and described as following.

Lateral Acromial Roof

No statistical differences were found in the length of lateral acromial roof (4.187 cm vs 4.184 cm, $P = 0.980$), but the width was significantly larger with an average of 0.221 cm in the RCT group (3.332 cm vs 3.111 cm, $P = 0.020$). The axial tilt in the RCT group was an average of 9.936° higher than that of the normal group (33.765° vs 23.829°, $P = 0.000$). There existed statistically significant differences in the distance from the anterior 3 cm (approximately anterior 70%) of lateral margin (L1–L7; range, 2.476 cm–3.302 cm vs 1.993 cm–3.089 cm, all $P < 0.05$) and from the anterior

0.9 cm (approximately anterior 50%) of medial margin (M1–M4; range, 0.967 cm-2.369 cm vs 0.668 cm–1.993 cm, $P = 0.000$) to the glenoid plane, indicating a trend of outward extension of anterior acromial margin in shoulders with RCT. Posterior 1 cm of the lateral margin (L8–L9; range, 1.770 cm–2.040 cm vs 1.516 cm–1.859 cm, all $P > 0.05$) and posterior 0.9 cm of the medial margin (M5–M7; range, 0.527 cm–0.695 cm vs 0.300 cm–0.550 cm, all $P > 0.05$) had no statistical differences (Fig. 6). The CSA of the RCT group was a little larger, with an average difference of 2.267° (32.630° vs 30.363°, $P = 0.021$).

Acromioclavicular Joint

The mean value of the height of AC joint in the RCT group was 0.357 cm smaller than that in the normal group and the difference was significant (1.089 cm vs 1.446 cm, $P = 0.000$). Details are presented in Table 2. In the RCT group, 22 shoulders (47.8%) were observed with prominent spurs or osteophytes at the undersurface of AC joint, while in the normal group, the number was 10 (22.7%).

Measurement Reliability

In the RCT group, the ICCs of acromial length (0.994; 95% CI, 0.991–0.997; $P = 0.000$), acromial width (0.991; 95% CI, 0.985–0.995; $P = 0.000$), axial tilt (0.949; 95% CI, 0.886–0.975; $P = 0.000$), CSA (0.946; 95% CI, 0.910–0.969; $P = 0.000$), L1 (0.990; 95% CI, 0.983–0.994; $P = 0.000$), L2 (0.984; 95% CI, 0.975–0.991; $P = 0.000$), L3 (0.989; 95% CI,

TABLE 1 Demographic data		
Variable	RCT group (n = 46)	Normal group (n = 44)
Gender		
Men	16	28
Women	30	16
Side		
Left	16	29
Right	30	15
Age, yr. (Mean ± SD)	60.0 ± 9.8	58.3 ± 10.4

RCT, rotator cuff tears; SD, standard deviation.

TABLE 2 Descriptive values and correlations between the RCT group and the normal group						
Variable	RCT group (n = 46)		Normal group (n = 44)		Mean Difference	P Value
	Mean	SD	Mean	SD		
Acromial length, cm	4.187	0.568	4.184	0.538	0.003	0.980
Acromial width, cm	3.332	0.469	3.111	0.414	0.221	0.020
Distance from lateral margin to glenoid plane, cm						
L1	2.476	0.490	1.993	0.467	0.483	0.000
L2	3.219	0.453	2.961	0.392	0.258	0.005
L3	3.302	0.470	3.089	0.419	0.213	0.026
L4	3.248	0.492	2.971	0.443	0.277	0.006
L5	3.104	0.533	2.779	0.466	0.325	0.003
L6	2.839	0.581	2.529	0.506	0.310	0.009
L7	2.476	0.641	2.159	0.595	0.317	0.017
L8	2.040	0.695	1.859	0.560	0.181	0.197
L9	1.770	0.755	1.516	0.579	0.254	0.140
Distance from medial margin to glenoid plane, cm						
M1	2.369	0.456	1.993	0.467	0.376	0.000
M2	1.573	0.471	1.059	0.370	0.514	0.000
M3	1.211	0.448	0.812	0.342	0.399	0.000
M4	0.967	0.368	0.668	0.283	0.299	0.000
M5	0.695	0.375	0.550	0.265	0.145	0.103
M6	0.583	0.392	0.450	0.151	0.133	0.235
M7	0.527	0.372	0.300	0.179	0.227	0.183
Axial tilt, °	33.765	7.542	23.829	6.473	9.936	0.000
CSA, °	32.630	4.948	30.363	4.115	2.267	0.021
Height of AC joint, cm	1.089	0.282	1.446	0.367	0.357	0.000

CSA, critical shoulder angle; RCT, rotator cuff tears; SD, standard deviation.
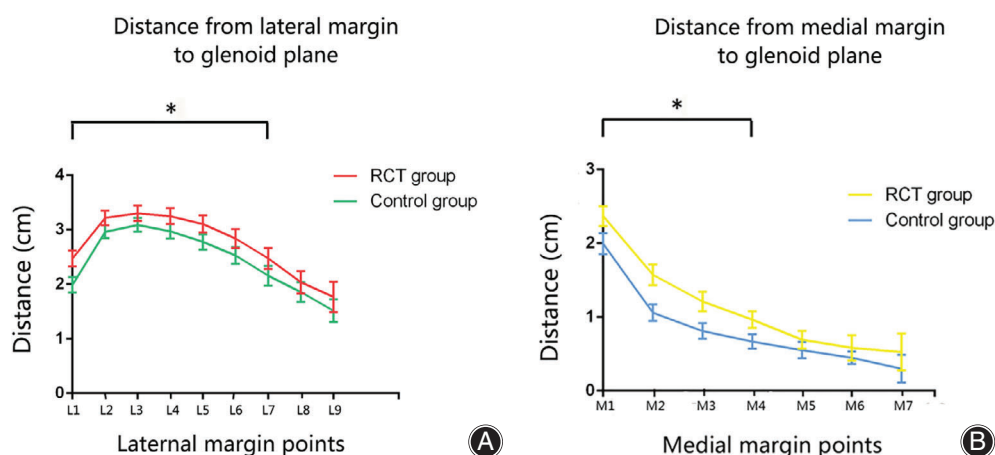
Fig 6 (A) Distance from lateral acromial margin to glenoid plane: statistically significant differences were found in anterior 3 cm (point L1–L7). (B) Distance from medial acromial margin to glenoid plane: statistically significant differences were found in anterior 0.9 cm (point M1–M4). This figure shows the tendency that the anterior acromial margin of shoulder with RCT extends more outwards than that of normal shoulder, no matter it is lateral or medial. (*: $P < 0.05$; Values were shown with the 95% confidence interval).

TABLE 3 Linear regression between the axial tilt and the distance from acromial margin to glenoid plane

Lateral/medial margin	Slope	R^2	P value
L1	0.028	0.199	0.000
L2	0.022	0.191	0.000
L3	0.023	0.183	0.000
L4	0.024	0.177	0.000
L5	0.022	0.127	0.001
L6	0.019	0.081	0.007
L7	0.013	0.033	0.088
L8	0.003	0.002	0.713
L9	0.002	0.000	0.881
M1	0.024	0.171	0.000
M2	0.038	0.435	0.000
M3	0.030	0.320	0.000
M4	0.018	0.161	0.000
M5	0.009	0.037	0.130
M6	0.012	0.063	0.135
M7	0.014	0.106	0.203

$P = 0.000$) in acromial length, 0.986 (95% CI, 0.976–0.992; $P = 0.000$) in acromial width, 0.950 (95% CI, 0.920–0.971; $P = 0.000$) in axial tilt, 0.903 (95% CI, 0.847–0.942; $P = 0.000$) in CSA, 0.988 (95% CI, 0.981–0.993; $P = 0.000$) in L1, 0.980 (95% CI, 0.968–0.989; $P = 0.000$) in L2, 0.985 (95% CI, 0.975–0.991; $P = 0.000$) in L3, 0.986 (95% CI, 0.978–0.992; $P = 0.000$) in L4, 0.988 (95% CI, 0.980–0.993; $P = 0.000$) in L5, 0.988 (95% CI, 0.981–0.993; $P = 0.000$) in L6, 0.992 (95% CI, 0.987–0.995; $P = 0.000$) in L7, 0.991 (95% CI, 0.985–0.995; $P = 0.000$) in L8, 0.991 (95% CI, 0.984–0.995; $P = 0.000$) in L9, 0.989 (95% CI, 0.982–0.994; $P = 0.000$) in M1, 0.981 (95% CI, 0.968–0.989; $P = 0.000$) in M2, 0.982 (95% CI, 0.971–0.990; $P = 0.000$) in M3, 0.977 (95% CI, 0.960–0.988; $P = 0.000$) in M4, 0.979 (95% CI, 0.959–0.990; $P = 0.000$) in M5, 0.932 (95% CI, 0.845–0.976; $P = 0.000$) in M6, 0.969 (95% CI, 0.883–0.995; $P = 0.000$) in M7, and 0.976 (95% CI, 0.959–0.990; $P = 0.000$) in the height of AC joint.

Linear Regression
A simple linear regression model was calculated to predict the distance from acromial margin to glenoid plane based on the axial tilt. Significant association was revealed between the axial tilt and the distance from anterior two thirds of lateral acromial margin to glenoid plane (L1–L6: slope, 0.019–0.028; R^2, 0.081–0.199, all $P < 0.05$). Similar association was also found in the anterior half of medial margin (M1–M4: slope, 0.018–0.038; R^2, 0.161–0.435, all $P < 0.05$). No Significant association was found in points L7–L9 (slope, 0.002–0.013; R^2, 0.000–0.033, all $P > 0.05$) or M5–M7 (slope, 0.009–0.014; R^2, 0.037–0.106, all $P > 0.05$). Details are shown in Table 3. Among these points associated significantly with the axial tilt, L1 and M2 had the maximum slopes in lateral and medial margin respectively (L1: slope = 0.028, R^2 = 0.199, $P = 0.000$; M2: slope = 0.038, R^2 = 0.435, $P = 0.000$) (Fig. 7).

0.981–0.994; $P = 0.000$), L4 (0.988; 95% CI, 0.981–0.993; $P = 0.000$), L5 (0.990; 95% CI, 0.984–0.994; $P = 0.000$), L6 (0.990; 95% CI, 0.984–0.994; $P = 0.000$), L7 (0.991; 95% CI, 0.985–0.995; $P = 0.000$), L8 (0.994; 95% CI, 0.989–0.996; $P = 0.000$), L9 (0.995; 95% CI, 0.992–0.998; $P = 0.000$), M1 (0.989; 95% CI, 0.982–0.993; $P = 0.000$), M2 (0.993; 95% CI, 0.989–0.996; $P = 0.000$), M3 (0.988; 95% CI, 0.980–0.993; $P = 0.000$), M4 (0.987; 95% CI, 0.978–0.992; $P = 0.000$), M5 (0.989; 95% CI, 0.982–0.994; $P = 0.000$), M6 (0.989; 95% CI, 0.979–0.995; $P = 0.000$), M7 (0.991; 95% CI, 0.977–0.997; $P = 0.000$), and the height of AC joint (0.988; 95% CI, 0.980–0.994; $P = 0.000$) showed great reliability of our measurements.

In the normal group, the results were also reliable and repeatable, with the ICC being 0.992 (95% CI, 0.986–0.995;
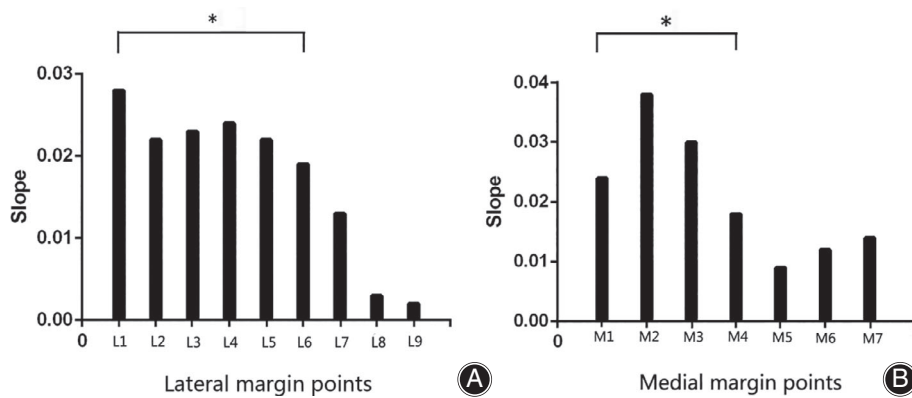
Fig 7 The slopes calculated by linear regression analysis between the axial tilt and the distance from acromial margin to glenoid plane. (A) For the lateral margin, L1 had the maximum slope, followed by L4, L3, L2, L5, and L6 in sequence. (B) For the medial margin, M2 had the maximum slope, followed by M3, M1, and M4 in order. (*, P < 0.05).

Discussion

Since Neer proposed the subacromial impingement theory in 1972 and Bigliani *et al.* classified acromion shapes into three types (flat, curved, or hooked) in 1986[3,22], the relationship between RCT and morphology of acromion has been investigated for a long time. So far, research has mainly focused on parameters based on two-dimensional (2D) images such as the acromion angle[23], the lateral acromion angle[24], the acromion index[25], and the CSA[5]. However, only a few studies discussed this relationship by using 3D images. As a highlight of our research, all measurements were performed on 3D models, making some special measurements impossible in 2D images become possible and much easier.

There existed no obvious differences between the two groups in terms of age of the patients, with a mean value of 60.0 years *vs* 58.3 years. Aging is considered an important intrinsic factor of RCT, and older people are more likely to suffer from RCT than younger people[3]. In this research, the similarity in age of the patients reduced the bias produced by aging and made the results more reliable.

Acromial Roof and Relative Surgical Procedures

Acromial roof of the shoulder with RCT had a larger width (+0.221 cm) than that of the normal group, though no significant difference was found in the length. Furthermore, the CSA was also larger in the RCT group (+2.267°). These results are in accordance with the study by Beeler *et al.*[19], which indicated that a shoulder with RCT has an acromial roof with greater lateral extension. The anterior 3 cm (approximately anterior 70%) of lateral acromial margin and anterior 0.9 cm (approximately anterior 50%) of medial acromial margin were significantly different between the two groups, suggesting to us that these areas may be crucial for the progression of RCT – the mechanism of which could be explained by the following. In the RCT group, the anterior 3 cm of lateral acromial margin and anterior 0.9 cm of medial acromial margin extend more laterally, making these areas much closer to the humeral head. As a result, during the process of elevating arms, these areas have higher possibility to impinge the greater tuberosity of the humerus, facilitating inflammation and edema of the soft tissues around these

structures, and finally leading to tears of the tendons. The posterior 30% of lateral acromial margin and posterior 50% of medial acromial margin are not significantly different and seem not to be involved in the development of RCT.

Nowadays acromioplasty and subacromial decompression are very common to treat SIS, but procedures differ according to surgeons' techniques and habits. In most cases, surgeons modify the anterior aspect of acromion when performing acromioplasty[3], and debride the bursa, resect the anterior acromion, and release the coracoacromial ligament when performing subacromial decompression[12,26–28]. There is no doubt that the anterior acromion should be resected during operation, but it is still under debate as to which part of anterior acromion deserves resection. In most studies[7–10,12,26–28], the authors described the operation areas as "the anterior acromion," which is an ambiguous concept and has limited values on standardizing the surgical procedures or directing us to perform the operation precisely. Based on the results, we believe the anterior 3 cm (anterior 70%) of lateral margin and anterior 0.9 cm (anterior 50%) of medial margin of the acromion play important roles in the progression of RCT. Therefore, we strongly recommend that the surgical procedures should include resecting bone from lateral side of the acromion to reduce CSA to a normal level and removing bone from the undersurface of the anterior 3 cm (anterior 70%) of lateral acromial margin and anterior 0.9 cm (anterior 50%) of medial acromial margin to form a flat acromion (type I), leading to full decompression of the soft tissues in the area and preventing the impingement. As a highlight of this study, we defined the operation areas accurately to the nearest centimeter, which is intuitive and helpful for standardizing the surgical procedures. Although the finding is dramatic, the effects of the standardized operation procedures need to be confirmed by long-term follow-up. The differences found at the medial acromial margin are still controversial. Fujisawa *et al.* did their research by using 3D models and came to the conclusion that changes at medial margin of acromion were not significantly different between the RCT group and the normal group[29]. Our opinion is not in agreement with Fujisawa *et al.*, and further research is still necessary.

Significant differences were also found in the axial tilt, with a tendency of a larger axial tilt in the RCT group and a smaller axial tilt in the normal group. According to the linear regression analysis between the axial tilt and the distance from lateral (or medial) acromial margin to glenoid plane, the points L1 and M2 had maximum slopes in the lateral margin and the medial margin, respectively. This result suggests us that when increasing the axial tilt of acromion (e.g., a normal shoulder progresses to RCT), the areas near L1 and M2 will have the biggest lateral moving distance compared with other points, making these areas the closest to humeral head, which means the highest risk for impingement. We emphasize that these areas deserve more attention and should be fully decompressed in operation. The mechanism of how anterolateral and anteromedial acromial margin facilitates SIS is complex and still unclear, which requires further biomechanical analysis for a better understanding.

Acromioclavicular Joint and Relative Surgical Procedures

The height of AC joint, which was designed to evaluate the spatial volume under AC joint, was significantly smaller in the RCT group. Previous studies found spurs and osteophytes in the AC joint linked to rotator cuff pathology[30]. Watson proposed that a bulging coracoacromial ligament, forced down by the swollen overlying degenerated AC joint, could impinge against the rotator cuff in refractory cases of painful arc syndrome[31]. Based on these theories, some surgeons preferred to remove spurs and osteophytes at the undersurface of the AC joint (coplaning) to enlarge the space and decompress the tendons under the AC joint, the long-term outcomes of which were satisfactory[15,16]. However, other studies pointed out that AC joint symptoms and instability may be problems after coplaning and secondary operation to resect distal clavicle was necessary to relieve pain of AC joint[13,17,18]. As a result, whether coplaning is necessary and to what extent the intervention should be done are still under debate. In our study, the height of AC joint in the RCT group is obviously smaller than that in the normal group, indicating the fact that the spurs at the undersurface of AC joint could significantly narrow the space where rotator cuff passes and causes more pressure on rotator cuff, which accelerates the development of RCT. To our knowledge, previous research about AC joint was mainly performed by 2D images, while 3D analysis was relatively rare. In this study, by performing the 3D reconstruction of scapula and clavicle, we can get a standard anteroposterior view of shoulder joint and define the inferior edge of AC joint precisely, making the measurement more accurate and reliable compared to 2D analysis. Nowadays the management for AC joint during operation is the alternative[12]. According to the results, the difference found at AC joint should not be ignored and the intervention is necessary and should be performed in every patient with prominent spurs or osteophytes at the undersurface of AC joint. Aydın et al. conducted a follow-up study over than 3 years and concluded that excision of the inferior side of the lateral clavicle to the level of the acromion with minimal disruption of the joint capsule does not develop AC joint symptoms[32]. Therefore we recommend that spurs and osteophytes at the undersurface of AC joint should be removed as much as possible to enlarge the space for rotator cuff under the premise of not violating the joint capsule to prevent AC joint symptoms or instability after surgery. It is worth noting that prominent spurs and osteophytes at AC joint were observed both in the RCT group and the normal group, suggesting us that the isolated spurs or osteophytes at the undersurface of AC joint are not sufficient to cause RCT. The formation of RCT is a result of multiple factors working together.

There are some limitations in our research. First, the undersurface of acromion is also an important part for the formation of SIS, but we did not evaluate the undersurface by the limitation of research methods. We aim to find other suitable methods to evaluate the entire acromion in our next work. Second, the significantly different gender ratio between the two groups may cause bias because the scapula size differs according to sex[33]. Third, measurement inaccuracy could appear because of manual operation or adjustment inaccuracy of 3D images, so we used repeated calculations to reduce the error. Last, our conclusion is inferred from the values measured in 3D images and further research is needed to reveal the mechanisms and confirm our inference.

Conclusion

The acromial width and the lateral extension (CSA) are larger but the space under AC joint is smaller in shoulders with RCT compared to those in normal shoulders. The anterior 3 cm (approximately anterior 70%) of lateral margin and anterior 0.9 cm (approximately anterior 50%) of medial margin of acromion are important areas for the formation of SIS. Therefore, we recommend that the surgical procedures to treat SIS should include resecting bone from lateral side of the acromion to reduce CSA to a normal level, and removing bone from the undersurface of the anterior 3 cm (anterior 70%) of lateral margin and anterior 0.9 cm (anterior 50%) of medial margin (especially the areas near L1 and M2) to form a flat acromion (type I), which fully decompresses the soft tissues around and prevents the impingement. Besides, the spurs and osteophytes at the undersurface of AC joint must be removed as much as possible under the premise of not violating the joint capsule.

Authorship Declaration

All authors listed meet the authorship criteria and all authors are in agreement with the manuscript.

Author Contributions

Q.M. contributed to collection of data, analysis of results, and writing of manuscript. C.S., R.D., P.L., S.W., W.Z., L.F., and X.C. contributed to the design of the work.

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