Original Article

Added value of combined acromiohumeral distance and critical shoulder angle measurements on conventional radiographs for the prediction of rotator cuff pathology

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HIGHLIGHTS

- Acromiohumeral distance (AHD) and critical shoulder angle (CSA) do not depend on age or sex.
- CSA and AHD are significantly different in healthy and pathologic rotator cuffs.
- Combining CSA and AHD into one index ($PI_{AHD-CSA}$) increases overall diagnostic performance.
- A high PIAHD-CSA increases the risk of full thickness rotator cuff tear and critical fatty degeneration.

ARTICLE INFO

ABSTRACT

Purpose: To investigate the role of acromiohumeral distance (AHD) and critical shoulder angle (CSA) measurements from conventional radiographs (CR) in isolation and combined (prognostic index $PI_{AHD-CSA}$) as predictors of full thickness rotator cuff tendon tears (RCT) and critical fatty degeneration (CFD; i.e. as much fat as muscle).
Method: In this retrospective study AHD and CSA were measured in 127 CR. MR arthrograms served as reference standard and were screened for RCT and CFD. Statistical analysis for inter-reader agreement, Spearman's rank correlation, linear stepwise regression and logistic regression for AHD and CSA with ROC analyses including $PI_{AHD-CSA}$ were performed.
Results: In 90 subjects (17 females, mean age 36.1 ± 14.1) no RCT were found on MR imaging and served as control group. In 37 patients (13 females, mean age 58.7 ± 13.2) ≥ one RCT was found. Inter-reader agreements rated between κ = 0.42–0.82 for categorical and 0.91–0.96 for continuous variables. No significant correlation of AHD and CSA with either age or sex was seen (p = 0.28 and p = 0.74, respectively). Case group had significantly smaller mean AHD (8.7 ± 3.2 vs. 10.8 ± 2.2 mm; p < 0.001) and larger mean CSA (36.5 ± 4.5° vs. 33.1 ± 4.0°; p < 0.001). $PI_{AHD-CSA}$ increased diagnostic performance for prediction of RCT and CFD (AUC = 0.78 and 0.71), compared to isolated AHD (0.74 and 0.71) and CSA (0.71 and 0.66).
Conclusions: AHD and CSA do not depend on age or sex but differ significantly between healthy and pathologic rotator cuffs. A decreased AHD is most influenced by infraspinatus muscle atrophy and fatty degeneration. Combined $PI_{AHD-CSA}$ increases diagnostic performance for predicting RCT and CFD.

1. Introduction

The acromiohumeral distance (AHD) describes the gap between the cranial humeral head contour and the opposing inferior aspect of the acromion and normally measures around 10 mm [1]. Reduction of AHD is, as a result of imbalance of tractional and adhesive forces about the glenohumeral joint. It follows full thickness rotator cuff tendon tears (RCT) mainly caused by subacromial impingement of the supraspinatus

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or infraspinatus muscle tendon as well as chronic degeneration and trauma, leading to muscle atrophy and fatty degeneration [2]. Eventually RCT and degeneration leads to ascension of the humeral head towards the acromion with reduction of the AHD [3]. Fatty degeneration of RCT muscles is traditionally graded according to Goutallier classification [4] (0 – normal, 1 – fatty streaks, 2 – less fat than muscle, 3 – as much fat as muscle, 4 – more fat than muscle), whereas grades ≥ 2 are associated with compromised postoperative outcome after RCT repair surgery and considered as critical fatty degeneration (CFD) [5,6].

Conventional radiographs (CR) or ultrasound are usually performed as a first line modality for evaluation of shoulder joint pathology and RCT integrity. AHD can thereby easily be measured [7]. Various studies have shown comparably high intra-reader, inter-reader and inter-modality reproducibility of AHD measurements in these modalities [8,9]. It may thus serve as a rough predictor of rotator cuff integrity before additional computed tomography (CT) or magnetic resonance (MR) arthrogram imaging is performed in order to assess joint structures in more detail.

In addition to the AHD, the critical shoulder angle (CSA) has gained increasing attention in recent years. It allows merging two known factors from radiographs for rotator cuff disease - inclination of the glenoid fossa and the acromion coverage into one biomechanical parameter. Increasing CSA increases the risk of RCT and vice versa [10,11]. A small AHD and large CSA are thus predisposing factors for subacromial impingement and consecutive RCT with CFD.

Recent studies have investigated the impact of each measure in order to assess rotator cuff tendon integrity of the shoulder joint. However, literature is scarce when considering possible synergy from both measures combined. We hypothesized that combining AHD and CSA measurements may have added value to isolated measurements and increase pretest-probability of relevant RCT and consecutive CFD, in order to help referring physicians and prevent patients from unnecessary MR examinations.

2. Materials and methods

2.1. Patient demographics

This retrospective study was approved by the local ethics committee (*blinded*). In a retrospective analysis of our institution's database, standardized MR arthrograms of the full past four calendar years (2016–2019) were reviewed. Out of 531 examinations, 128 subjects were identified to meet the study inclusion (age ≥ 18 years, available CR and MR arthrogram for characterization of unspecific shoulder pain) and exclusion criteria (following findings on MR arthrogram isolated partial rotator tendon cuff tears, neurologic disorders, severe labrum and total biceps tendon subluxations or tears, previous shoulder surgery, delay of more than 90 days between CR and MR arthrogram). One additional subject was excluded due to insufficient image quality for MR caused by severe patient-related motion artifacts. Based on MR imaging findings, subjects were grouped in a control group without detection of any, either partial or transmural rotator cuff tendon tear and a case group with at least one RCT. Due to limited availability of young subjects suitable for the case group without history of trauma, we did choose not to aim for an age-matched study design.

2.2. Imaging protocol

Routine and daily patients' image acquisitions of all imaging modalities were standardized according to the institution's quality management guidelines in order to facilitate an appropriate imaging data bank for retrospective studies.

2.2.1. Conventional radiography (CR)

All radiographs were obtained according to our standardized protocol, observing an anteroposterior oblique projection (also known as Grashey view) in an upright, angled shoulder position (35–45° to the image receptor) with the arm abducted and internally rotated. In addition, the orientation of the beam was tilted 20° craniocaudally for optimal visualization of the subacromial space.

2.2.2. MR arthrograms

Fluoroscopically guided shoulder joint injections were performed according to our internal protocol using 1 ml of local anesthetic followed by 1 ml of iodinated contrast agent to confirm correct needle position (iopromide, Ultravist® 300 mg iodine/ml Bayer Healthcare, Berlin, Germany), followed by 5–8 ml of gadolinium contrast agent (gadoteric acid, Artirem® 0.0025 mmol/ml, Guerbet, Roissy, France).

MR images were then acquired on either a 1.5 T (103 patients) MR unit (Signa Excite HD, GE Healthcare, Wauwatosa, WI, USA), or a 3.0 T MR unit (24 patients; MAGNETOM Skyra Siemens Healthcare, Forchheim, Germany) due to a scanner upgrade during the study period. MR imaging on the 1.5 T unit was performed with a dedicated 8-channel coil with T1-weighted fast spin echo (FSE) acquisition in sagittal oblique plane (repetition time/echo time (TR/TE in milliseconds): 600/8; section thickness: 3 mm; field of view (FOV): 140 mm; matrix: 416 × 256), T1-weighted FSE fat-saturated (fs) in coronal oblique plane (TR/TE: 4200/90; section thickness: 3 mm; FOV: 140 mm; matrix: 256 × 224), proton-density (PD) weighted fs in coronal oblique plane (TR/TE: 2250/35; section thickness: 3 mm; FOV: 140 mm; matrix: 352 × 256), PD FSE fs in axial plane (TR/TE: 3000/40 ms; section thickness: 3 mm; FOV: 140 mm; matrix 256 × 224). MR imaging protocol in the 3.0 T unit included using a dedicated 16-channel coil, and the following sequences: T1-weighted FSE in sagittal oblique plane (TR/TE: 642/11; section thickness: 2.5 mm; FOV: 140 mm; matrix: 384 × 326), T1-weighted turbo spin echo (TSE) fs in coronal oblique plane (TR/TE: 756/11; section thickness: 2.5 mm; FOV: 140 mm; matrix: 384 × 326), PD TSE fs in coronal oblique plane (TE/TR: 3830/34; section thickness: 2.5 mm; FOV: 140 mm; matrix size: 384 × 326), PD TSE fs in transaxial plane (TE/TR: 5000/36; section thickness: 2.0 mm; FOV: 140 mm; matrix size: 384 × 326).

2.2.3. Image analysis

All measurements on CR and MR arthrograms were obtained with a standard picture archive and communication system (IMPAX Version 6.6.1, AGFA HealthCare, Mortsel, Belgium).

For AHD the space between the inferior cortical bony part of the acromion and the most cranial cortical bone of the humeral head was measured on CR [1,12]. To determine the CSA on CR, first a line was drawn through the inferior and superior margin of the glenoid, which implies the inclination of the glenoid fossa. Then, a second line was drawn from the inferior margin of the glenoid to the most lateral aspect of the acromion [11,13] (Fig. 1a).

Graduation of fatty muscle degeneration of the rotator cuff muscles on a 5 point Likert scale according to Goutallier [4] was performed on sagittal T1-weighted MR arthrogram images at the Y-position as described by Zanetti et al. [14] and in addition the cross-sectional (cs)-area (cs-area) of each muscle (in cm²) was measured by placing regions of interest (ROI) neatly encircling respective muscle borders (Fig. 1b).

All measurements and Goutallier ratings were performed by one musculoskeletal (MSK)-fellowship trained radiologist (R1) blinded to the patient's group status. In a subset of 35 subjects, measurements and ratings were repeated after a delay of four weeks by the same reader and a second MSK-fellowship trained junior reader (R2) (both two years of experience in MSK imaging) in order to assess intra- and inter-reader agreement, respectively.

The shoulder MR arthrograms that served as reference standard were read by an expert radiologist (R3) with 10 years of experience in MSK imaging blinded to other readers and patient data. R3 qualified rotator cuff tendon integrity, i.e., intact tendon, partial or RCT and muscle quality according to the Goutallier classification. In cases of
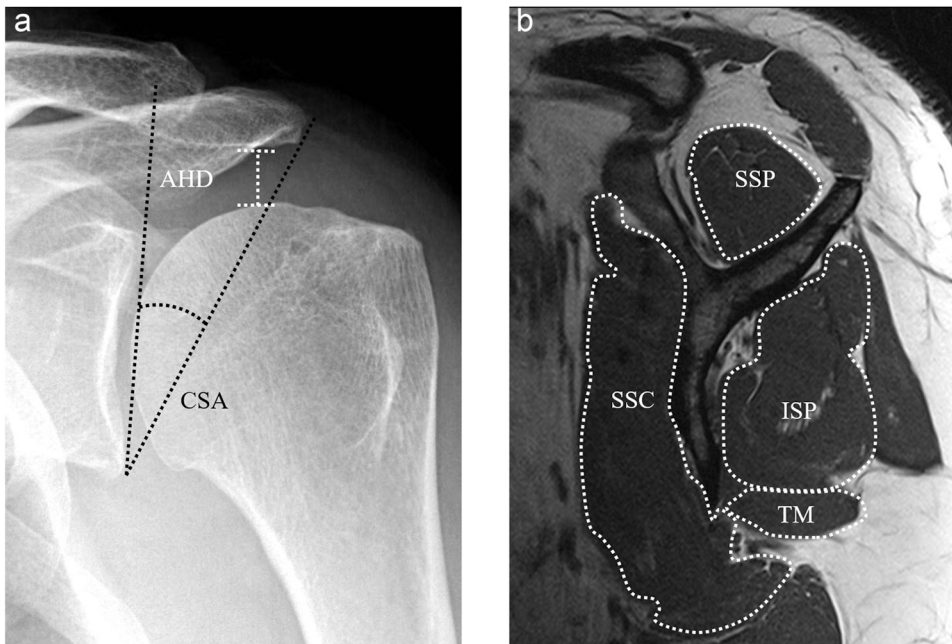
Fig. 1. 65-year-old female complaining about non-traumatic shoulder pain on the left side. **(a)** AHD and CSA measurements are illustrated on anteroposterior oblique radiograph of the left shoulder. AHD is measured by drawing a line from the inferior cortical aspect of the acromion to the most cranial aspect of the cortical bone of the humeral head (here AHD=10 mm). CSA is measured by drawing a line from the superior to the inferior margin of the glenoid fossa and an additional line from the inferior glenoid fossa to the most lateral extension of the acromion (here CSA = 28°). No RCT or CFD of the rotator musculature was described. **(b)** Illustrates the Y-position of the scapula on a sagittal oblique T1-weighted MR image that is defined by a Y-shaped appearance of the corpus and the spina scapulae. At this slice position qualitative Goutallier ratings and cs-area measurements of all four rotator cuff muscles were performed. SSP = supraspinatus; ISP = infraspinatus; TM = teres minor; SSC = subscapularis.

disagreement on muscle quality between junior readers, ratings from R3 were used.

2.3. Image analysis

Independent-sample student's *t*-test was used comparing means between groups for normally distributed data. For intra- and inter-reader agreements intra-class correlation coefficients (ICCs) were calculated for continuous variables and kappa-values for categorical values. An agreement between 0.81 and 1.00 was rated as perfect, between 0.61 and 0.80 as good, between 0.41 and 0.60 as moderate, between 0.21 and 0.40 as fair and less than 0.20 as poor [15,16]. Spearman rank correlation was used for continuous variables and Pearson Chi-Square was used for categorical variables.

Stepwise linear regression was used for correlation of different variables from MR arthrograms with AHD or CSA measurements from CR. Multivariate logistic regression (LR) was performed to calculate odds ratios (OR) of AHD, CSA and a prognostic index ($PI_{AHD-CSA}$) combining AHD and CSA for prediction of RCT and CFD. The $PI_{AHD-CSA}$ was calculated based on predicted probabilities from LR analysis. Area under curve (AUC) with 95% confidence intervals (CI) from receiver operator characteristic (ROC) curves were used for assessing diagnostic performance of each variable and compared by using DeLong Test. Sensitivity and specificity at optimal cut-off values for each variable were calculated. Statistical analysis was performed using SPSS software (version 22.0.0.1). In order to perform ROC curve analysis, we dichotomized the Goutallier classification. By definition a patient was considered having CFD of the rotator cuff if either SSP or ISP were scored ≥ 2 in the Goutallier.

3. Results

Intra-reader and inter-reader agreements on radiographs were considered excellent: for AHD 0.96 (95%-CI 0.82–0.99) and 0.91 (95% CI-0.82–0.96), respectively; for CSA 0.96 (95%-CI: 0.84–0.99) and 0.96 (95%-CI: 0.87–0.99); for cs-area: 0.94 (95%-CI: 0.76–0.99) and 0.92 (95%-CI: 0.60–0.98). The intra- and inter-reader agreement for Goutallier grading was moderate ($\kappa = 0.49$ and 0.42, respectively). Using dichotomized CFD data the intra- and inter-reader agreement was perfect ($\kappa = 0.82$ and 0.76, respectively).

3.1. Control group

3.1.1. Quantitative data

90 subjects (17 female (19%) mean age 46.9; range 21–70, 73 males (81%); mean age 33.6; range 16–72) were considered as healthy without partial or RCT. Measured on CR mean AHD was 10.8 ± 2.2 mm and mean CSA was $33.1 \pm 4.0°$ (Table 1(1.1)). Mean cs-area measurements are demonstrated in Table 1 (1.2).

No significant correlation of AHD or CSA with age or sex was found ($p = 0.245$ and $p = 0.340$ for age; $p = 0.727$ and $p = 0.265$ for sex,

Table 1
Descriptive statistics.

1.1: Study population

	Control group (n = 90)	Case group (n = 37)	Difference (*p*-value)
age [y; SD]	36.1 ± 14.1	58.7 ± 13.1	+ 22.6 ($p < 0.001$)
sex [n of female, %]	17; 19%	13; 35%	+ 16% ($p = 0.05$)
AHD [mm; SD]	10.8 ± 2.2	8.7 ± 3.2	-2.2 ($p < 0.001$)
CSA [°; SD]	33.1 ± 3.9	36.5 ± 4.5	+ 3.4 ($p < 0.001$)
total cs-area [mm²; SD]	4191 ± 971	2'858 ± 996	-1333 ($p < 0.001$)
CFD [n; percentage]	4; 4%	22; 59%	+ 55% ($p < 0.001$)

1.2: Overview of mean cs-area of individual muscles of the rotator cuff

	Control group (n = 90)	Case group (n = 37)	Isolated SSP tear (n = 21)
SSP [mm²; SD]	773 ± 192	**438 ± 231**	450 ± 269
ISP [mm²; SD]	957 ± 248	**677 ± 326**	690 ± 371
TM [mm²; SD]	448 ± 188	412 ± 187	442 ± 224
SSC [mm²; SD]	2013 ± 636	**1330 ± 599**	1395 ± 670
All [mm²; SD]	4'191 ± 971	2'858 ± 996	**2978 ± 1188**

1.3 Distribution of RCT and CFD in case group [n,%]

	SSP	ISP	TM	SSC
RCT	32; 86.5%	8; 21.6%	1; 2.7%	10; 27.0%
CFD	19; 51%	20; 54%	12; 32%	17; 46%

Acromiohumeral distance (AHD), critical shoulder angle (CSA), full-thickness rotator cuff tendon tear (RCT), critical fatty degeneration (CFD), cross-sectional area (cs-area), supraspinatus (SSP), infraspinatus (ISP), teres minor (TM), subscapularis (SSC). Numbers in **bold** show significant differences at p < 0.001 (2-tailed) for comparisons of either case group or isolated SSP tear group to control group.

respectively). There was a significant difference of cs-area of rotator cuff muscles between male and female subjects (p < 0.001).

3.1.2. Qualitative data

By definition no RCT were found. CFD was found in 4/90 subjects (4%), see Table 1 (1.1), in 2/90 subjects of the supraspinatus muscles, in 3/90 subjects of the infraspinatus muscles, and in 2/90 subjects of the teres minor muscles. None of the subscapularis muscles were rated as CFD.

3.2. Case group

3.2.1. Quantitative data

37 patients (13 women (35%), mean age 61, range 37–90; 24 men (65%), mean age 57.4, range 24–84) were identified to show at least one RCT.

Measured on CR mean AHD was 8.6 ± 3.2 mm. Mean CSA was 36.5 ± 4.5° (Table 1 (1.1), Figs. 2a and 3a). Mean cs-areas are demonstrated in Table 1 (1.2).

There was a slightly non-significant larger proportion of females in the case group (17 female, 19% in control vs. 13 female, 38% in case group; $p = 0.05$). Mean AHD was significantly smaller (difference − 2.2 mm, p < 0.001), mean CSA significantly larger (difference + 5.4°, p < 0.001), and mean cs-area of rotator cuff muscles significantly smaller compared to control group (difference − 1333 mm^2, p < 0.001).

3.2.2. Qualitative data

In total 51 RCT (Fig. 2b) and 69 CFD (Fig. 3b) were detected with the large majority affecting SSP and ISP tendons/muscles. The corresponding distributions of RCT and CFD among different muscles are demonstrated in Table 1 (1.3). 7 of the 8 ISP-RCTs occurred in patients also showing a SSP-RCT. 19 patients with a RCT showed a CFD of the SSP and 20 showed a CFD of the ISP.

There was a significantly higher proportion of CFD in the case group (+ 55%, p < 0.001), Table 1 (1.1).

Stepwise multi regression detected that AHD is most influenced by fatty degeneration and cs-area of the ISP muscle ($R = 0.466$,

$p < 0.0001$; $R = 0.497$, $p = 0.027$, respectively). CSA has a weak but significant influence on cs-area of the ISP muscle ($R = 0.341$, $p = 0.039$).

3.2.3. Logistic regression and ROC-analyses

From logistic regression analysis (LR) respective ORs of both covariates were calculated and are shown in Table 2, including PI$_{AHD-CSA}$. Respective rounded LR derived-equations were $CSA − 2x\ AHD$ for predicting RCT, and $CSA − 5x\ AHD$ for predicting CFD. Cut-off values of PI$_{AHD-CSA}$ were 16 for RCT and − 10 for CFD (exemplarily estimating RCT and CFD for a patient with AHD = 8 mm and CSA = 34° → $RCT = 34 − 2x8 = 18$; $CFD = 34 − 5x8 = − 6$; probability having RCT and CFD is above average). AUC values with 95% CI from ROC analyses for AHD, CSA, and PI$_{AHD-CSA}$ according to dichotomized RCT and CFD data are summarized in Table 3. Using respective PI$_{AHD-CSA}$ for combining AHD and CSA measurements led to non-significantly increased AUC for RCT and CFD (0.78 and 0.73, p = 0.13 and 0.17 respectively), compared to isolated AHD measurements (Table 2). Diagnostic statistics such as sensitivity, specificity and respective optimal cut-off values are listed in Table 4.

Fig. 4a shows larger AUC for isolated AHD than isolated CSA measurements for prediction of RCT (0.74 vs. 0.71; DeLong Test p = 0.58) and also for prediction of CFD (0.69 and 0.66; p = 0.65), as seen in Fig. 4b, especially in the range below 70% sensitivity. Fig. 4c and d illustrate jittered scatter plots for distribution of AHD and CSA values of different individuals, showing a clear trend of small AHD with large CSA in combination for either RCT and/or CFD. At optimal cut-off values of 16 for RCT and − 10 for CFD, resulting sensitivities were 68%/62% with specificities of 78%/72%.

4. Discussion

The aim of this study was to investigate the potential of AHD and CSA measurements from CR in isolation and combined to predict RCT and/or CFD of rotator cuff musculature using MRI as reference standard.

In the healthy control group without RCT there was no significant correlation of AHD or CSA with either age or sex. This is important, as
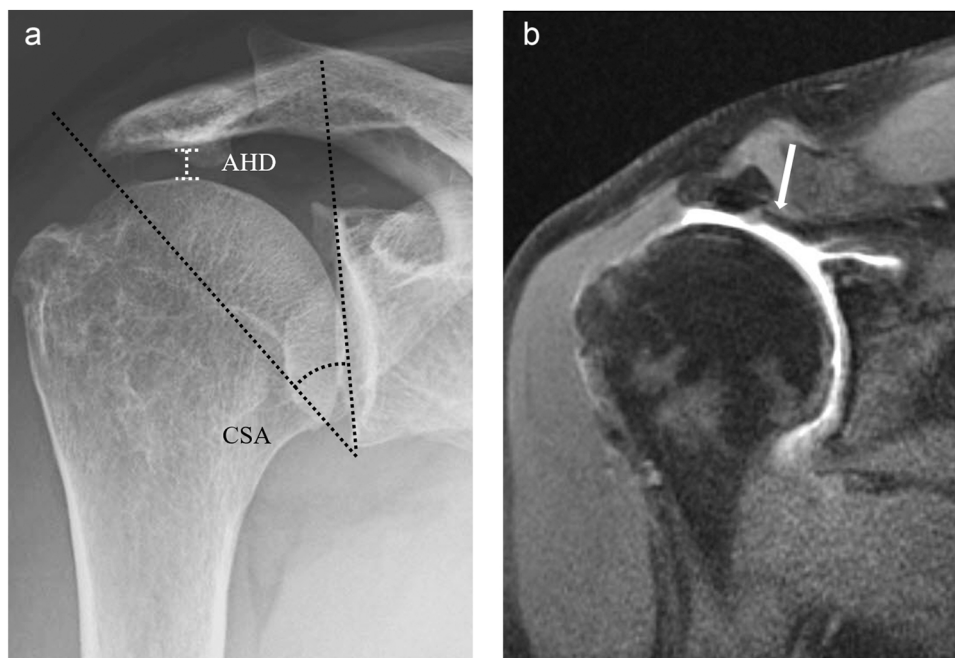

Fig. 2. 53-year-old male complaining about right-sided traumatic shoulder pain. **(a)** Anteroposterior oblique radiograph shows AHD = 7 mm and CSA = 38°, indicating a RCT with 99% specificity by the equation CSA – 2xAHD = 24 (Table 4). **(b)** Coronal T1-weighted fat-saturated MR arthrogram. A large RCT of the SSP with retraction of lateral tendon end (white arrow) medial to the superior humeral head was detected.
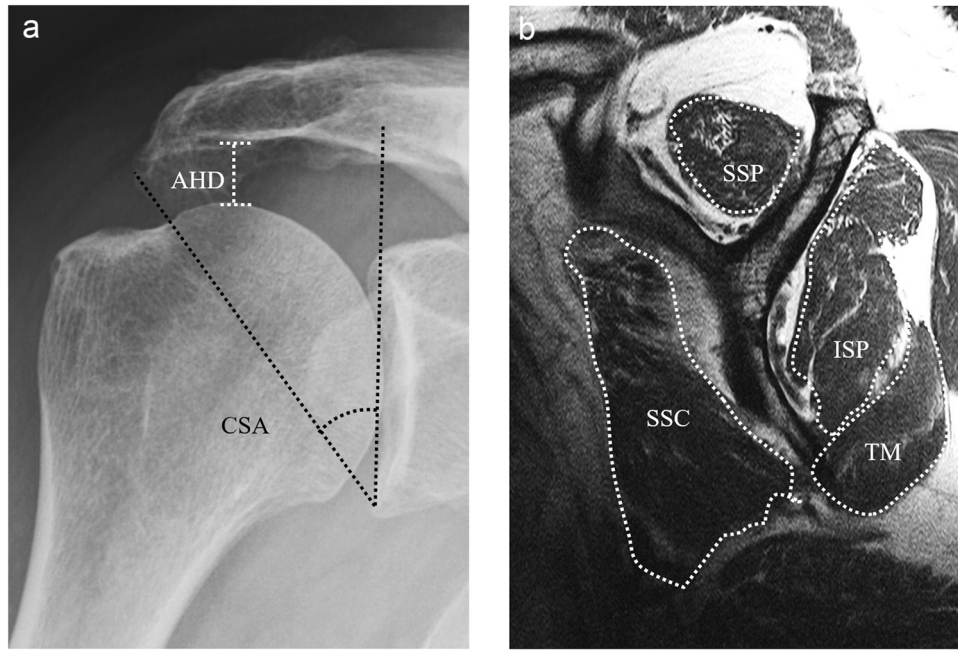
Fig. 3. 60-year-old man complaining about chronic right sided shoulder pain. **(a)** Anteroposterior oblique radiograph illustrates AHD = 9 mm and CSA = 37°, both indicating CFD with 94% specificity. **(b)** Sagittal oblique T1-weighted MR image illustrates rotator cuff muscle quality at the Y-figure position of the scapula. Marked atrophy of the SSP muscle and CFD (Goutallier 2) for SSP and ISP muscle was described.

Table 2

Odds ratios for prediction of RCT and CFD.

	Odds ratio	95%-CI	p-value
RCT			
AHD	1.39	1.22–1.72	**< 0.001**
CSA	1.16	1.04–1.30	**< 0.001**
PI$_{AHD-CSA}$	1.17	1.09–.26	**< 0.001**
CFD			
AHD	1.41	1.13–1.75	**< 0.001**
CSA	1.07	0.96–1.20	**0.011**
PI$_{AHD-CSA}$	1.07	1.03–1.11	**< 0.001**

Acromiohumeral distance (AHD), critical shoulder angle (CSA), prognostic index of AHD and CSA combined (PI$_{AHD-CSA}$), full-thickness rotator cuff tendon tear (RCT), critical fatty degeneration (CFD). **Note:** for comparability purposes AHD values are inverted.

these two factors may not significantly influence on comparability among different patient populations. We used standardized image acquisition parameters in both CR and MR according to our institutions quality management guidelines (i.e., patient posture and shoulder position) in order to allow reproducible measurements and keep variability minimal. This is also reflected in the high intra- and inter-reader agreements for both AHD- and CSA- as well as cs-measurements in our study. Inter-reader agreements for Goutallier-classifications of fatty

degeneration were moderate, supporting previous work. However, dichotomization of ratings and calculation of CFD resulted in high inter-reader agreements. This approach may be more relevant, as beyond a cut-off of Goutallier 2 postoperative outcome after RCT repair decreases markedly [5,6].

cs-areas as measured on MR arthrograms may be construed as surrogates for muscle power [17,18]. There was a significantly reduced cs-area in the case group compared to the control group for SSP, ISP and SSC muscles. This may be explained in part by the larger, though

Table 4

Diagnostic performance at optimal cut-off values from receiver operator characteristic (ROC) analyses.

	RCT			CFD		
	Cut-off	Sens. (%)	Spec. (%)	Cut-off	Sens. (%)	Spec. (%)
AHD	10 mm	60	74	9 mm	39	83
CSA	34°	76	51	34°	73	48
PI$_{AHD-CSA}$	16	68	78	-10	62	77

Acromiohumeral distance (AHD), critical shoulder angle (CSA), prognostic index of AHD and CSA combined (PI$_{AHD-CSA}$), full-thickness rotator cuff tendon tear (RCT), critical fatty degeneration (CFD).

Table 3

Area under curve (AUC) from receiver operator characteristic (ROC) analyses.

	All muscles	Isolated SSP	Isolated ISP	Isolated TM	Isolated SSC
RCT					
AHD	0.74 (0.64–0.84)	0.73 (0.62–0.84)	0.68 (0.52–0.83)	0.72 (0.61–0.83)	0.61 (0.46–0.75)
CSA	0.71 (0.61–0.81)	0.71 (0.60–0.81)	0.77 (0.58–0.95)	0.22 (0.13–0.32)	0.56 (0.38–0.74)
PI$_{AHD-CSA}$	0.78 (0.69–0.87)	0.78 (0.67–0.88)	0.79 (0.63–0.95)	0.47 (0.39–0.56)	0.62 (0.45–0.78)
CFD					
AHD	0.69 (0.58–0.81)	0.70 (0.57–0.83)	0.74 (0.62–0.85)	0.66 (0.52–0.81)	0.73 (0.60–0.86)
CSA	0.66 (0.55–0.78)	0.63 (0.49–076)	0.72 (0.61–0.83)	0.71 (0.58–0.85)	0.66 (0.52–0.80)
PI$_{AHD-CSA}$	0.73 (0.62–0.84)	0.72 (0.58–0.85)	0.79 (0.69–0.89)	0.73 (0.59–0.86)	0.75 (0.63–0.88)

Acromiohumeral distance (AHD), critical shoulder angle (CSA), prognostic index of AHD and CSA combined (PI$_{AHD-CSA}$), full-thickness rotator cuff tendon tear (RCT), critical fatty degeneration (CFD), 95% confidence intervals in parentheses.
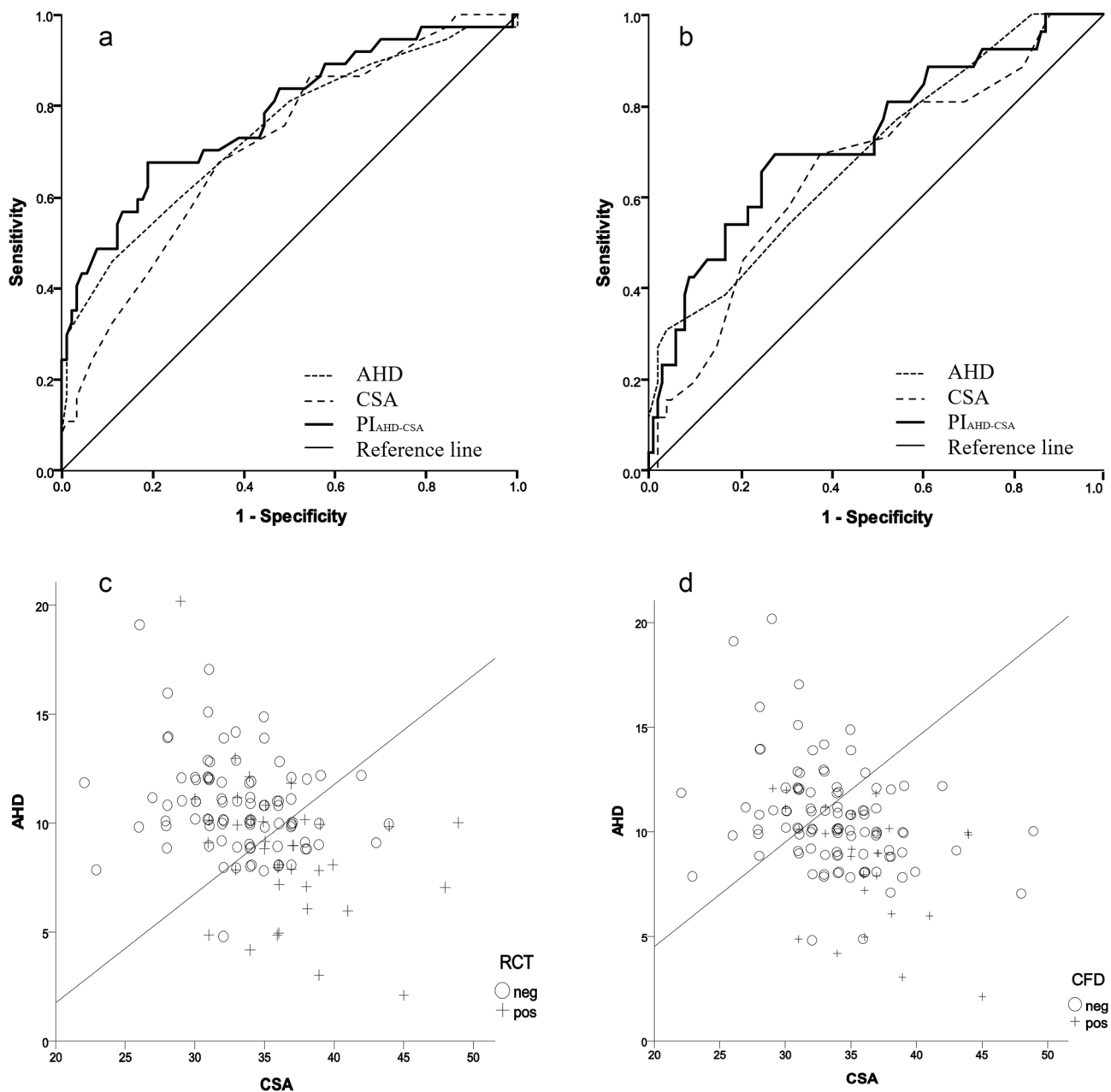
Fig. 4. ROC curves of AHD, CSA and combined AHD-CSA measurements ($PI_{AHD-CSA}$) for RCT (Fig. 4a) and CFD (Fig. 4b). Note larger AUC for $PI_{AHD-CSA}$ compared to isolated AHD and CSA measurements, especially in the range of modest diagnostic performance with sensitivity below 80%. Distribution of control and case group in jittered scatter plots for diagnosis of RCT (Fig. 4c) and CFD (Fig. 4d). Respective straight lines in plots illustrate optimal cut-off values from ROC analyses for combined AHD and CSA variables ($PI_{AHD-CSA}$). These variables were calculated by logistic regression derived equations, i.e. $PI_{AHD-CSA} = CSA-2xAHD$ for predicting RCT, and $PI_{AHD-CSA} = CSA-5xAHD$ for predicting CFD. At optimal cut-off values of 16 for RCT and − 10 for CFD resulting sensitivities were 68%/62% and specificities 78%/72%. Note: patients positive for RCT and/or CFD tend to have smaller AHD and larger CSA values, however with marked overlap with negative controls.

non-significant (p = 0.05) proportion of females in the case group (19 vs. 35%). Certainly, the reduced cs-area of the SSP in the case group reflects the large majority of SSP among all RCT (86.5%). It is by far the clinically most frequent and may thus indicate a largely representative patient cohort in this study and 87.5% (7 of 8) of the ISP-RCTs were found in patient who also showed an SSP-RCT. Interestingly however, AHD was most influenced by fatty degeneration and cs-area of the infraspinatus muscle. This finding corroborates findings from Saupe et al. [11,12], identifying the integrity of the ISP muscle as a decisive structure for maintaining muscular traction balance about the shoulder joint.

Reduced AHD is known to be associated with RCT, CFD of the supraspinatus and infraspinatus muscle and poor outcome after surgery

[19,20] and therefore thus frequently used preoperatively as a surrogate marker for rotator cuff integrity and/or postoperative outcome after RCT repair and can help physicians to decide if additional imaging is required. Multivariate LR analysis showed that AHD can significantly predict RCT or CFD with an OR of 1.39 and 1.41 (p < 0.001). According to additional ROC analyses increasing AHD as an isolated parameter was associated with increasing sensitivity but decreasing specificity for the detection of RCT or CFD. Isolated AHD measurements larger than e.g., 8 mm may still include a marked number of false negatives and hence cannot be considered reliable for ruling out significant damage to rotator cuff tendons.

CSA on the other hand as a constitutional parameter is independent of soft tissue changes but has major impact on the biomechanics of the

shoulder and glenoid fossa wear with incidence of RCT [11,12]. LR analysis showed that CSA may significantly predict RCT or to a lesser extent CFD with an OR of 1.16 (p < 0.001) and 1.07 (p < 0.011) respectively. Moor et al. reported a sensitivity and specificity of 82% and 92% for RCT choosing a specific cut-off value of CSA > 35° [11]. According to our data a CSA < 32° or > 37° was associated with either comparable sensitivity or specificity but no cut-off value could offer similar performance for both measures. In this study AHD is shown to not correlate with age in the younger and larger control group (mean age 36.1a). However, the case group has a mean age of 58.7 years and certain age associated changes of AHD cannot be excluded with certainty. However, we assume that a potential bias would have mostly affected the direct AHD measurement itself, but only with limited impact on our combined prognostic index, that is indirectly derived from AHD as well.

In order to quantify localization and extent of tendon and muscle damage MR arthrograms of the shoulder joint should be reserved for patients with adequate pretest probability. PI$_{AHD-CSA}$ combines AHD and CSA measurements into one predictor variable, allowing to include both effects of decreasing AHD and increasing CSA on rotator cuff integrity. Resulting ORs for RCT and CFD were significant at 1.17 and 1.07, being smaller than mere AHD and slightly larger than CSA. AUC of ROC analysis showed no significant difference between variables for either RCT or CFD. However, ROC curve analysis of PI$_{AHD-CSA}$ performed markedly superior to AHD and CSA in isolated SSP and ISP pathologies and this effect for all muscles was most accentuated in the lower range of sensitivity below 70%. Hence, at optimal cut-off values PI$_{AHD-CSA}$ allows to maintain good specificity of both AHD and CSA but add substantial sensitivity to the diagnosis of RCT or CFD. With respect to existing literature, this may be the main benefit of a quantitative formula over mere qualitative interpretation of the two different quantitative measures CSA and AHD, as the two parameters have been validated as independent risk factors, but both lack the ability to screen for disease due to the large percentage of false negatives when cut-off values are used that offer a somewhat good specificity [21,22].

This study has some limitations. First, the control group consisted of patients with shoulder pain other than RCT. It may be possible that pain related changes of muscle traction may impact on reduction of the AHD measurements. In addition, certain joint pathologies, e.g. biceps tendon rupture or adhesive capsulitis were exclusion criteria and their impact on AHD and CSA could thus not be assessed. However, as we did not measure the impact on AHD and CSA but used these two parameters in an equation for prediction of RCT and CFD, we are confident that the effect of excluding biceps tendon pathologies and similar is limited with regard to the outcome measures of this investigation. Second, there is a significant difference between case and control group concerning age and marked difference concerning sex. However, in the control group AHD and CSA were not significantly correlated with either of them. Third, the number of patients with RCT was rather small (n = 37). In order to acquire a homogeneous patient cohort, consistent in- and exclusion criteria had to be applied leading to the exclusion of most examinations.

In conclusion, AHD and CSA do not depend on age or sex but differ significantly between healthy and pathologic rotator cuffs. A decreased AHD is most influenced by infraspinatus muscle atrophy and fatty degeneration. AHD and CSA perform almost equal for ruling out RCT or CFD with good sensitivity and specificity. Combining both parameters into a prognostic index helps to integrate both pathologic mechanisms and increase diagnostic performance. The PI$_{AHD-CSA}$ equation for RCT is CSA-2xAHD= 16 and the PI$_{AHD-CSA}$ for CFD is CSA-5xAHD = − 10. If the result of the equation is greater than the given cut-off values, a higher risk of pathology can be assumed.

Declaration of ethics in publishing

The authors declare that they have conducted this research in accordance with the Declaration of Helsinki and with applicable institutional, state, or federal requirements. IRB approval was given for this retrospective analysis, informed consent for use of research data was present for all included subjects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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