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Magnetic resonance imaging features for diagnosing adhesive capsulitis of the shoulder: a systematic review and meta-analysis

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Abstract

Background Various magnetic resonance imaging (MRI) characteristics are frequently employed to aid diagnose adhesive capsulitis of the shoulder (ACS) and offer valuable therapeutic insights. To identify and summarize the diagnostic accuracy of these features, a systematic review and meta-analysis were performed.

Methods Four databases, including PubMed, EMBASE, Web of Science, and Cochrane Library, were searched. Overlapping descriptions used to represent the same imaging in different studies are grouped into one MRI feature. Pooled diagnostic accuracy, including sensitivity and specificity, was calculated using a bivariate random-effects model.

Results The screening identified 21 studies involving 928 ACS patients and 873 non-ACS patients considered eligible for inclusion in this meta-analysis. A total of 106 overlapping descriptions were classified into 7 features, including axillary capsular thickening, axillary capsular hyperintensity, axillary capsular enhancement, fat obliteration of the rotator interval (RI), RI enhancement, RI joint capsule thickening, and coracohumeral ligament (CHL) thickening. All seven features were considered informative for the diagnosis of ACS. Axillary capsular enhancement had the highest pooled sensitivity (95%, 95% CI [91%- 98%]), the highest diagnostic odds ratios (107, 95% CI [32, 357]), and the highest area under the curve(0.96 [0.94—0.97]). All features except fat obliteration of the RI and CHL thickening showed a pooled sensitivity of > 80%. Three of seven (axillary capsular thickening, axillary capsular hyperintensity, and axillary capsular enhancement) showed a pooled specificity of > 80%.

Conclusion Seven informative MRI features were identified in this study, with axillary capsular enhancement and RI joint capsule thickening showing the highest diagnostic accuracy. Clinicians can refer to these MRI features to increase confidence in diagnosing ACS and rule out other confused diagnoses.

Keywords Meta-analysis. Adhesive capsulitis of the shoulder, Frozen shoulder, Diagnostic accuracy, Magnetic resonance imaging (MRI) features

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Introduction

Adhesive capsulitis of the shoulder (ACS), commonly known as frozen shoulder, is a prevalent shoulder condition characterized by shoulder pain, reduced ability to move the shoulder actively and passively in all directions, and limited ability to rotate the arm outward and turn the palm upward [1, 2]. Pathologically, it involves inflammation of the synovium, leading to capsular hypertrophy and subsequent fibrosis [3]. The development of ACS is associated with thyroid dysfunction, autoimmune diseases, diabetes mellitus, and breast cancer treatment [4]. The incidence rate of ACS in the general population varies from 2 to 5%, the majority of whom are women between the ages of 40 and 60, and is more common in the nondominant limb [5, 6].

At present, the diagnosis of ACS is based on the clinical symptoms, signs, and follow-ups after excluding other factors that cause shoulder stiffness, such as rotator cuff tears, calcific tendinitis, trauma, surgical history, or nerve injury. Shoulder arthroscopy is the gold standard for diagnosing ACS, but it is invasive and difficult to confirm the diagnosis as a routine examination [7]. Diagnostic criteria for ACS include stiffness persisting for more than 4 weeks, pain (especially at night), and the absence of other shoulder disorders, such as calcific tendinitis and rotator cuff tears, to explain symptoms [8]. Similar clinical symptoms and signs may reduce the accuracy of the clinical diagnosis of ACS. Imaging modalities such as X-ray, ultrasound, computer tomography (CT), magnetic resonance imaging (MRI), and nuclear medicine are important clinical adjuncts to help confirm the diagnosis. MRI is widely used in the examination of bone and joint muscle injuries, including ACS, for the best soft tissue resolution and good display of tendons and ligaments [9, 10]. Several studies have reported on MRI findings by examining signal changes and morphological changes in different anatomical structures of the affected shoulder [11, 12]. There was a meta-analysis [13] of the overall performance of different MRI features in diagnosing ACS, which included 15 studies and summarized 6 characteristics, but some missed and ignored MRI features in some studies failed to be summarized and analyzed thoroughly, because of these MRI characteristics that were involved in three or fewer studies. The purpose of this systematic review and meta-analysis was to identify additional MRI features in patients with ACS and to comprehensively summarize the diagnostic accuracy of these features.

Materials and methods

Study design

This study followed the guidelines of the Preferred Reporting Items for a Systematic Review and Meta-analysis of Diagnostic Test Accuracy Studies (PRISMA-DTA) statement [14].

Literature search strategy

We performed an online literature search till December 2022 in four databases, including PubMed, Cochrane Library database, EMBASE, and Web of Science, to get pertinent papers on the diagnostic accuracy of MRI characteristics for adhesive capsulitis of the shoulder. The search terms "frozen shoulder" or "adhesive capsulitis" were used in combination with "magnetic resonance imaging" or "magnetic resonance arthrography" as follows: [("adhesive capsulitis"[Title/Abstract] OR "frozen shoulder"[Title/Abstract]) AND ("magnetic resonance imaging"[Title/Abstract] OR "MR imaging"[Title/Abstract] OR "MRI"[Title/Abstract] OR "magnetic resonance arthrography"[Title/Abstract] OR "MR arthrography"[Title/Abstract])]. After removing the repeated articles, two researchers (J-X and XN-Z) independently screened titles and abstracts and excluded articles that did not meet the inclusion criteria, and read the full text of articles that might meet the inclusion criteria to further determine whether they met the inclusion criteria. The search was supplemented by manually searching references to relevant articles and reviews. Any disagreement was resolved through consensus.

Eligibility criteria

The inclusion criteria were as follows: population, original literature that included ACS patients and non-ACS patients; index test, MRI; reference standard, arthroscopy, surgically or clinically confirmed ACS or non-ACS; outcomes, sufficient information to extract the raw data including true-positive (TP), true-negative (TN), false-positive (FP), and false negative (FN) results of MR features for diagnosis ACS; and language—English.

The exclusion criteria were as follows: research not in the field of interest; case reports and series, review articles, editorials, letters, conference proceedings and comments; abstracts of meetings; studies without adequate data for TP, FP, TN, FN results; sample size <10; animal or phantom studies and studies that used duplicate patient datasets.

Data extraction

The following information was extracted from the considered studies using standardized tables: (1) study characteristics, including the first author's surname, publication year, country, study design, reference standard, duration of patient recruitment and blinding of reference standard; (2) patient characteristics, including the total number of patients, number of shoulders with ACS, number of shoulders with no-ACS, age, gender and clinical

characteristics; (3) MRI technique, including the scanner type (brand, model and magnet strength), technical parameters (MR technique and conventional sequence) and interpretations (consensus reading and reader experience); and (4) diagnostic data of MRI features for ACS, included TP, FP, TN, and FN. Two researchers (H-G and XN-Z) extracted data according to the standard, different opinions on the inclusion of existing data were resolved by consensus. Microsoft Excel 2020 will be used to manage the relevant data included in the study.

Quality assessment

The Quality Assessment of Diagnostic Accuracy Studies (QUADAS- 2) tool [15] was used to assess the methodological quality of the included articles independently by two researchers (YQ-L and MQ-L). This tool consists of four domains: (1) patient selection, (2) index test, (3) reference standard, and (4) flow and timing of patients.

Data synthesis and analyses

The patient demographic information and collected factors were summarized using conventional descriptive statistics. Continuous variables were represented by their means and 95% confidence intervals (CIs), whereas categorical variables were represented by frequencies or percentages, unless otherwise specified. Analyzed utilizing a bivariate random-effects model, the diagnostic performance of the detected MRI features, including sensitivity and specificity, was pooled. To derive a summary, the diagnostic performance, including sensitivity and specificity, of each feature was plotted in forest plots. The diagnostic odds ratios (DORs) of the identified MRI features were calculated to determine the significant MRI features for diagnosing ACS [16–18]. In addition, pooled areas under the curve (AUCs), positive likelihood ratios and negative likelihood ratios were calculated. Meta-analysis was not performed if a feature was described and analyzed in fewer than 4 studies or if it was not clearly described or defined.

The I^2 test and Cochran's Q test were used for heterogeneity analysis. Significant heterogeneity was indicated with a P value less than 0.05 or I^2 value greater than 50% [19]. Meta-regression analysis and subgroup analysis were used to explore sources of heterogeneity.

All statistical analyses were performed using Stata Version 15.0, Meta-Disc Version 1.5, and Review Manager Version 5.4, with a significance threshold of $p < 0.05$.

Results

Literature search

683 studies met the criteria for the initial search, out of which 335 were duplicated. Following the elimination of duplicate publications, we examined the titles and abstracts of 348 investigations. Subsequently, we excluded 294 studies that were not relevant and 12 reviews. For the remaining 42 studies, we excluded 21 for the following reasons: conference abstracts ($n = 8$), studies without adequate data for TP, FP, TN, and FN results ($n = 12$), and non-English ($n = 1$). Finally, a total of 21 studies [20–40]with 1801 patients were included in this study. The flow diagram of the literature search and selection is shown in Fig. 1.

Patient and study characteristics

In total, 928 patients with ACS and 873 patients without ACS were included. The mean age of the patients with ACS and non-ACS ranged from 45.6 to 57.9 years and 41 to 62.3 years, respectively. Two studies [25, 29] did not report the number of non-ACS female patients. There were 410 women with ACS. Patient characteristics are shown in Table 1. The study design was retrospective in sixteen studies [20–23, 27–31, 33, 35–40], prospective in four studies [24, 25, 32, 34], and cross-sectional analytic in one study [26]. Three studies [28, 36, 39] used surgical findings as the reference standard, two studies [33, 40] used surgical findings or clinical findings, fifteen studies [20–26, 29–32, 34, 37, 38,] used clinical findings, while one [27] used either clinical or radiologic findings. (Table 2).

MRI characteristics are summarized in Table 3. 11 studies [20–23, 25, 29–31, 35]used non-contrast-enhanced(non-CE), 7 [27, 30, 32, 34, 36–38]studies used both non-CE and contrast-enhanced (CE) MRI, and 3 studies [28, 33, 40] used direct MRA. 8 studies [20–22, 27, 30, 32, 34, 35] used 3-T scanners,10 studies [23, 25, 26, 29, 31, 33, 36, 37, 39, 40] used 1.5-T scanners, one [24] used a 0.5-T scanner, one [38] used a 1.5-T or a 3-T scanner, and one [28] used a 1.5-T or a 1-T scanner.

Categorization of MRI features

Out of the 21 studies, there were a total of 106 MRI descriptors. However, 14 of these MRI descriptors were not included in this particular study because they did not provide enough information to accurately reconstruct the results for true positives (TP), false positives (FP), true negatives (TN), and false negatives (FN). Furthermore, 35 descriptors were excluded because they were only mentioned in less than four pieces of research based on reported MRI findings. Comparable explanations of correlated imaging were consolidated and categorized as a unified MRI characteristic. Finally, 57 descriptions were classified into 7 MRI features: axillary capsular thickening, axillary capsular hyperintensity, axillary capsular enhancement, fat obliteration of the RI, RI enhancement, RI joint capsule thickening, and coracohumeral ligament

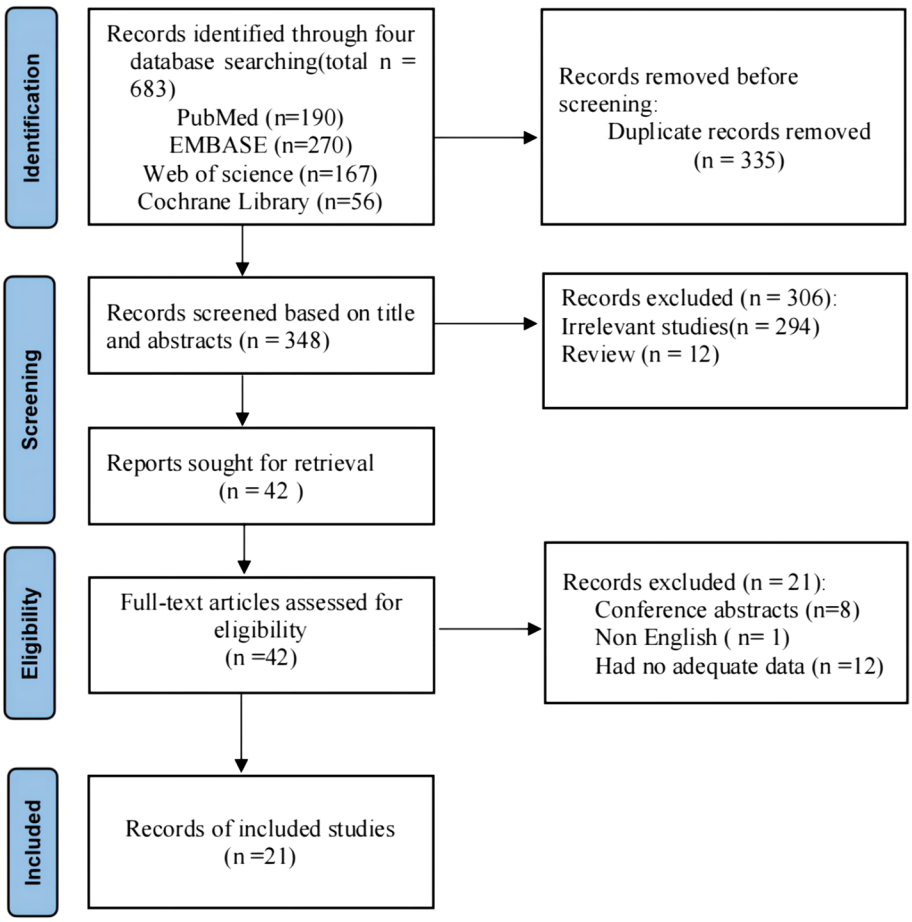

Fig. 1 Flowchart showing the study selection process

(CHL) thickening. Table 4 shows the performance results for individual studies for these seven MRI features**.**

Study quality

Figure 2 shows the risk of bias and concern for applicability of the 21 included studies using the Quality Assessment ofv Diagnostic Accuracy Studies (QUADAS)– 2 tool. Four nonconsecutive enrollment case–control studies [36, 37, 39, 40] were at high risk of bias, while two studies [25, 29] without the sex ratios of the ACS group and non-ACS group were at high applicability concern. Twenty-one studies [20–40] were at insignificant risk of bias because the index tests evaluated after the reference standard were blind to the observers. Sixteen studies [20–27, 29–32, 34, 35, 37, 38] used radiological or clinical criteria rather than arthroscopy or surgery as the reference standard, and 13 studies [22–24, 26, 27, 29–31, 35, 37–40] without a flowchart and time frame between MRI and the reference standard were at an unclear bias risk. Sixteen studies [20–27, 29–32, 34, 35, 37, 38] using uncertain radiological or clinical criteria as reference standards were considered to be of unclear applicability concern.

Overall diagnostic accuracy

The meta-analysis presents the combined diagnostic performance of the seven detected MRI features in Table 5. This includes the pooled sensitivity, specificity, areas under the curve, diagnostic odds ratios, positive likelihood ratios, and negative likelihood ratios. The pooled diagnostic odds ratios (DORs) with 95% confidence intervals (CIs) indicated that all seven MRI characteristics provided valuable information for diagnosing ACS. Forest plots for the seven features are shown in Fig. 3. Of these MRI features, axillary capsular enhancement had the highest pooled sensitivity (95%, 95% CI [91%– 98%]). All features except CHL thickening and fat obliteration of

Table 1 Demographics

study	Total No. of patients	No. of ACS	No. of no-ACS	ACS			no-ACS		
				Mean age (age range)	Male: Female,% of Female	Characteristics	Mean age (age range)	Male: Female,% of Female	Characteristics
Ahn 2015 [30]	103	50	53	53.5 (38–74)	20:30, 60%	Clinically diagnosed ACS	51.7 (22–78)	26:27,50.9%	shoulder pathologies without ACS
Akkaya 2021 [29]	309	193	116	51.48 ± 12.41	NR	Clinically diagnosed ACS	50.09 ± 11.68	NR	shoulder pathologies without ACS
Bang 2019 [20]	104	54	50	56.98 ± 7.16 (41–74)	20:34, 55.5%	Clinically diagnosed ACS	56.44 ± 5.52(44–65)	19:31, 62%	did not have AC-related symptoms
Carbone 2014 [25]	113	48	65	57.9 (43–65)	NR	Clinically diagnosed ACS	62.3 (55–71)	NR	negative for shoulder diseases
Chi 2017 [23]	45	15	30	55.8 (38–72)	10:5, 33.3%	Clinically diagnosed ACS	55.8 (38–72)	20:10, 33.3%	negative for shoulder diseases
Cho 2020 [9]	103	52	51	57.06 ± 7.29 (41–74)	20:32, 61.5%	Clinically diagnosed ACS	56.47 ± 5.47(43–65)	18:33, 64.7%	shoulder pathologies without ACS
Connell 2002 [36]	46	24	22	53.5 (38–72)	7:17, 70.8%	Surgically confirmed ACS	54.5 (NR)	12:10, 45.4%	negative for shoulder diseases
ElSayed 2022 [26]	56	28	28	45.61 ± 11.95 (23–65)	17:11, 39.2%	Clinically diagnosed ACS	47.25 ± 8.97 (27–61)	14:14, 50%	healthy volunteers or shoulder pathologies without ACS
Emig 1995 [39]	25	10	15	50 (23–66)	4:6, 60%	arthrography and surgery diagnosed ACS	41 (28–56)	8:7, 46.7%	healthy volunteers
Gokalp 2011 [37]	21	12	9	48 (22–55)	2:7, 77.8%	Clinically diagnosed ACS	48 (40–60)	5:7, 58.3%	negative for shoulder diseases
Teixeira 2012 [38]	66	32	34	49.7 (NR)	14:18, 56.2%	Clinically diagnosed ACS	48 (NR)	16:18, 52.9%	shoulder pathologies without ACS
Jung 2019 [31]	200	100	100	54.3 (37–42)	39:61, 61%	Clinically diagnosed ACS	54.6 (38–80)	40:60, 60%	shoulder pathologies without ACS
Jung 2006 [40]	28	14	14	54 (46–63)	3:11,78.6%	Clinically diagnosed ACS	46 (24–66)	11:3, 21.4%	shoulder pathologies without ACS
Lee 2012 [33]	80	40	40	52.8 (34–68)	18:22, 55%	Clinically diagnosed ACS	52.8 (34–68)	18:22, 55%	NR

Table 1 (continued)

study	Total No. of patients	No. of ACS	No. of no-ACS	ACS			no-ACS		
				Mean age (age range)	Male: Female,% of Female	Characteristics	Mean age (age range)	Male: Female,% of Female	Characteristics
Mengiardi 2004 [28]	44	22	22	54.7(31–77)	16:6, 27.2%	Surgically confirmed ACS	54.9 (28–77)	16:6, 27.3%	shoulder pathologies without ACS
Park 2019 [35]	49	29	20	51 (30–73)	12:17, 58.6%	Clinically diagnosed ACS	49 (23–63)	10:10, 50%	shoulder pathologies without ACS
Pessis 2020 [21]	84	42	42	53.1 ± 7.68 (35–68)	13:29, 69%	Clinically diagnosed ACS	50.6 ± 12.96 (18–82)	10:32, 76.2%	shoulder pathologies without ACS
Sasanuma 2017 [34]	21	16	5	54.4 (39–79)	6:10, 62.5%	Clinically diagnosed ACS	47.6 (30–65)	5:0, 0%	healthy volunteers
Song 2011 [27]	80	35	45	50.1 (NR)	14:21, 60%	Clinically/radiologically diagnosed ACS	48.9 (NR)	22:23, 51.1%	negative for shoulder diseases
Yoon 2017 [32]	104	52	52	55.1 ± 9.0	15:37, 71.2%	Clinically diagnosed ACS	53.1 ± 10.7	23:29, 55.8%	healthy volunteers
Zhao 2012 [24]	120	60	60	50.2 (36–74)	24:36, 60%	Clinically diagnosed ACS	46.9 (NR)	24:36, 60%	rotator cuff tears

No number, *ACS* adhesive capsulitis of the shoulder, *NR* not reported

Table 2 Characteristics of the studies

study	country	Study design	Study period	Reference standard	Blinding from reference standard
Ahn 2015 [30]	South Korea	Retrospective	2011.1–2011.10	clinical symptoms and signs	Blinding
Akkaya 2021 [29]	Turkey	Retrospective	2018.1–202.4	clinician based on the clinical examination	Blinding
Bang 2019 [20]	Korea	Retrospective	2015.11–2017.11	clinical symptoms follow-up data	Blinding
Carbone 2014 [25]	Italy	Prospective	2010–2013	clinical symptoms follow-up data	Blinding
Chi 2017 [23]	USA	Retrospective	2010.1–2011.12	clinical symptoms and signs	Blinding
Cho 2020 [9]	Korea	Retrospective	2015.12–2018.7	clinical symptoms and signs	Blinding
Connell 2002 [36]	Australia	Retrospective	1998.9—2001.7	surgical finding	Blinding
ElSayed 2022 [26]	Egypt	Cross sectional study	2021.9–2022.2	suggestive history and clinical symptoms and signs	Blinding
Emig 1995 [39]	USA	Retrospective	NR	arthrography/Surgical finding	Blinding
Gokalp 2011 [37]	Turkey	Retrospective	NR	clinical symptoms and signs	Blinding
Teixeira 2012 [38]	France	Retrospective	2008.1–2010.12	clinical symptoms and signs	Blinding
Jung 2019 [31]	South Korea	Retrospective	2014–2015	clinical symptoms and signs	Blinding
Jung 2006 [40]	South Korea	Retrospective	NR	surgical/clinical symptoms and signs	Blinding
Lee 2012 [33]	South Korea	Retrospective	2005.5–2011.5	surgical/clinical symptoms and signs	Blinding
Mengiardi 2004 [28]	Switzerland	Retrospective	1998.1–2003.4	surgical finding	Blinding
Park 2019 [35]	South Korea	Retrospective	2016.1–2016.12	clinical symptoms and signs	Blinding
Pessis 2020 [21]	France	Retrospective	2013.4–2016.6	clinical symptoms and signs	Blinding
Sasanuma 2017 [34]	Japan	Prospective	2015.1–2015.9	clinical symptoms and signs	Blinding
Song 2011 [27]	South Korea	Retrospective	2008.1–2009.12	clinical symptoms and signs/radiographic finding	Blinding
Yoon 2017 [32]	South Korea	Prospective	2011–2014	clinical symptoms and signs	Blinding
Zhao 2012 [24]	China	Prospective	2006.7–2009.6	clinical symptoms and signs	Blinding

NR: not reported

the RI showed a pooled sensitivity of > 80%. In fact, three of seven features showed a pooled sensitivity of > 90%. Axillary capsule enhancement had the highest pooled DORs. All features except fat obliteration of RI showed a pooled specificity of > 70%, with two of seven features showing a pooled specificity of > 80%.

Figure 4 shows the summary receiver operating characteristic (SROC) curves for these seven MRI features. According to the area under SROC, axillary capsular enhancement had the highest diagnostic accuracy, while fat obliteration of the RI did not perform well in diagnosing ACS.

Significant heterogeneity was not observed in axillary capsular enhancement. Six features were considered significant heterogeneity: axillary capsular thickening, hyperintensity, fat obliteration of the RI, RI enhancement, RI joint capsule thickening and CHL thickening. Meta-regression analysis was performed based on study design, number of patients, magnet strength and reader consensus. The results of the meta-regression analysis are shown in Table 6. In the meta-regression analysis, for Axillary capsular thickening, the Study design ($P < 0.05$) and Number of patients ($P < 0.05$) caused heterogeneity. For Coracohumeral ligament thickening, the number of patients ($P < 0.05$) caused heterogeneity.

Discussion

ACS is a common shoulder disorder characterized by a decrease in the active and passive range of motion (ROM) of the shoulder along with pain. However, some diseases, such as rotator cuff tears and calcific tendinitis, also have similar clinical symptoms and signs, thus reducing the accuracy of the clinical diagnosis of ACS. Clinical symptoms alone are sometimes insufficient to differentiate ACS from other shoulder disorders, such as rotator cuff tears [41]. MRI possesses the property of high soft tissue resolution and the unique advantage of sensitivity to edema for ACS diagnosis. Various MRI findings have been reported by several studies.

There was a meta-analysis [13] of the overall performance of different MRI features in diagnosing ACS. Suh et al. [13] included 15 studies and identified six MRI features that aid in the diagnosis of ACS and summarized the diagnostic accuracy of these identified features. The strength of our study is pooling estimates of a larger number of studies ($n = 21$) and summarizing more MRI features ($n = 7$), we included six additional studies and one additional imaging feature (Rotator interval joint capsule thickening). And Coupled forest plots of pooled sensitivity and specificity are more

Table 3 Magnetic resonance imaging (MRI) or magnetic resonance arthrography (MRA) characteristics

study	Scanner		Technical parameters			Interpretation		
	Brand	Model	Magnet strength	MR technique	Conventional sequence	No readers	Consensus reading	Reader experience (years)
Ahn 2015 [30]	Siemens/Philips	TrioTim/Achieva	3.0 T	Non-CE MRI、CE MRI	T1 WI, T2 FS, PDFS, FS-T1 CE	2	NO	11/5
Akkaya 2021 [29]	Philips	Ingenia	1.5 T	Non-CE MRI	PDFS, T1 WI	3	Yes	30/16/4
Bang 2019 [20]	Siemens/Philips	Magnetom Skyra/Ingina	3.0 T	Non-CE MRI	T2 WI	NR	NR	NR
Carbone 2014 [25]	Siemens	Avanto	1.5 T	Non-CE MRI	T2 WI	2	Yes	13/5
Chi 2017 [23]	Siemens	Magnetom	1.5 T	Non-CE MRI	T1 WI, T2 WI, T2 FS, PDFS	2	No	13/5
Cho 2020 [9]	Siemens/Philips	Magnetom Skyra/Ingenia	3.0 T	Non-CE MRI	T2 WI	1	Yes	NR
Connell 2002 [36]	GE	Signa Horizon	1.5 T	Non-CE MRI、CE MRI	T2 WI, T2 FS, FS-T1 CE	2	Yes	NR
ElSayed 2022 [26]	Philips	Achieva	1.5 T	Non-CE	T1 WI, T2 WI, T2 FS, PDFS, SPAIR	2	No	≥ 10
Emig 1995 [39]	GE	Signa	1.5 T	Non-CE MRI	T2 WI, T2 FS	2	Yes	NR
Gokalp 2011 [37]	Siemens	Magnetom Visio	1.5 T	Non-CE MRI、CE MRI	T1 FS, T2 FS, PDFS, FS-T1 CE	2	Yes	NR
Teixeira 2012 [38]	GE	Signa HDx/Signa HDxt	1.5 T/3.0 T	Non-CE MRI、CE MRI	T1 WI, T2 FS, FS-T1 CE	2	No	3
Jung 2019 [31]	Siemens	Avanto	1.5 T	Non-CE MRI	T2 FS, PDFS	2,	No	9/13
Jung 2006 [40]	GE	Twin Speed	1.5 T	Direct MRA	T1 FS, T2 WI, intermediate-WI	2	Yes	NR
Lee 2012 [33]	Siemens/GE	Magnetom Vision Plus/Signa Excite	1.5 T	Direct MRA	T1 FS, T2 WI	3	Yes	15/2
Mengiardi 2004 [28]	Siemens	Expert/Symphony	1/1.5 T	Direct MRA	T1 WI/T2 WI/T1 FS/intermediate-WI	2	Yes	10/5
Park 2019 [35]	Philips	Intera Achieva	3 T	Non-CE MRI	T1 WI, T2 WI, T2 FS, PDFS, SPAIR	3	Yes	> 9
Pessis 2020 [21]	Siemens	Skyra	3 T	Non-CE MRI	T1 WI, T2 WI, T2 FS, FS-T1 CE	2	No	1/21
Sasanuma 2017 [34]	Siemens	Skyra	3 T	CE MRI	weighted image, opposed phase image, water-only image, and fat-only image	1	No	> 15
Song 2011 [27]	Philips	Gyroscan Intera Achieva	3 T	CE MRI	T1 FS, T2 WI	2	No	8/9
Yoon 2017 [32]	GE	Signa HDxt/Discovery MR750w	3 T	CE MRI、Non-CE MRI	T1 FS, T1 WI, T2 WI, FS-T1 CE	2	Yes	> 5
Zhao 2012 [24]	GE	Signa Contour	0.5 T	Non-CE MRI	T1 FS, T1 WI, T2 FS, STIR	2	No	NR

MR magnetic resonance, *CE* contrast enhanced, *WI* weighted image, *FS* fat suppression, *PD* proton density, *T1 CE* T1 contrast enhancement, *STIR* short tau inversion recovery, *NR* not reported

comprehensive. We also performed several subgroup analyses to explore pertinent factors that can optimize the diagnostic performance of these MRI features.

This study focused on identifying the seven most frequently observed MRI characteristics of ACS. These include axillary capsular thickening, axillary capsular

Table 4 Pooled sensitivity, specificity, diagnostic odds ratio (DORs), area under the curve, and likelihood ratio (LR) of individual MR features

MR features	No. of studies	Sensitivity	Specificity	Positive Likelihood Ratio	Negative Likelihood Ratio	Diagnostic Odds Ratios	AUROC	Threshold effect
Axillary capsular thickening	12	0.82 [0.68, 0.91]	0.85 [0.75,0.92]	5.6 [3.3, 9.3]	0.21 [0.12,0.37]	27 [13,52]	0.91 [0.88—0.93]	0.53
Axillary capsular hyperintensity	6	0.84[0.67, 0.93]	0.84 [0.75,0.91]	5.4 [3.2,9.0]	0.19 [0.09,0.42]	28 [10,82]	0.90 [0.87—0.92]	0.01
Axillary capsular enhancement	5	0.95 [0.91, 0.98]	0.84 [0.68, 0.93]	5.9 [2.8, 12.6]	0.06 [0.03, 0.11]	107 [32, 357]	0.96 [0.94—0.97]	1
Fat obliteration of the rotator interval	12	0.76 [0.55, 0.89]	0.67 [0.52, 0.79]	2.3 [1.5, 3.5]	0.36 [0.18, 0.72]	6 [2, 17]	0.76 [0.72—0.80]	0.07
Rotator interval enhancement	5	0.90 [0.71, 0.97]	0.74 [0.54, 0.88]	3.5 [1.9, 6.5]	0.14 [0.05, 0.39]	25 [8, 75]	0.89 [0.86—0.91]	0.48
Rotator interval joint capsule thickening	4	0.92 [0.57, 0.99]	0.79 [0.69, 0.87]	4.5 [2.8, 7.1]	0.10 [0.01, 0.73]	44 [5, 408]	0.86 [0.83—0.89]	0.00
Coracohumeral ligament thickening	10	0.73 [0.50, 0.89]	0.76 [0.63, 0.86]	3.1 [2.1, 4.8]	0.35 [0.17, 0.10]	9 [3, 23]	0.81 [0.77—0.84]	0.29

MR magnetic resonance, *AUROC* area under the curve, *No* number

thickening hyperintensity, axillary capsular thickening enhancement, Rotator interval enhancement, Rotator interval joint capsule thickening and Coracohumeral ligament thickening. Additionally, this study summarized the diagnostic accuracy of these features. Enhancement of the axillary capsule had the highest sensitivity, axillary capsular thickening had the highest specificity, and the summary SROC curves of axillary capsular enhancement among the seven MRI features showed the highest diagnostic accuracy. A previous study summarized 6 features and concluded that RI enhancement has the highest sensitivity and CHL thickening has the highest specificity [13]. This result differs from our study, possibly because our study included 6 additional studies. Overall, MRI features could accurately identify ACS and assist clinicians in early intervention and selection of an appropriate treatment, such as an intra-articular steroid injection or physical therapy, and further reduce the duration of joint stiffness and incidence of morbidity [42].

The MRI features we summarized can not only help clinical diagnosis but also reflect clinical impairment. Several studies [21, 43] have investigated the relationship between MRI features and pain intensity. Pain intensity was positively correlated with RI thickness, joint capsule enhancement and thickness and negatively correlated with enhancement of RI. Regarding the correlation between MRI features and rotational motion, several studies [31–33] suggested that the limitations of external rotation and internal rotation in patients with ACS were most related to the thickness of the CHL and capsular thickness of the axillary recess and RI. The severity of clinical symptoms but not ROM was associated with enhancement of the axillary recess [32]. This might suggest that MRI features reflect pathologic findings such as inflammatory fluid expansion and neo angiogenesis and help diagnose frozen shoulder with confidence. High signal intensity in the axillary capsule reflected synovial inflammation, leading to reactive capsular fibrosis in ACS [30, 43].

MRI findings can also reflect clinical stages based on arthroscopy and physical examination of the affected joints [44]. ACS is classified into four stages [45]: stage 1 (duration of symptoms 0–3 months), stage 2 (duration of symptoms 3–9 months), stage 3 (duration of symptoms 9–15 months), and stage 4 (duration of symptoms 15–24 months). High concentrations of cystic signals were most strongly associated with stage 2, and the mean thickness of the axillary pouch in stage 2 was significantly thicker than that in other stages [46]. Rotors inter scarring is a nonspecific sign of ACS and is not correlated with clinical staging; in contrast, a shorter duration of clinical symptoms showed higher enhancement of the RI joint capsular [21]. The anterior band of IGHL thickening was most significantly correlated with the clinical stages [47].

These features can also be useful in differentiating ACS from other causes of shoulder pain. One study [36] summarized the MRI findings of patients with ACS, which

Fig. 2 Grouped bar charts showing the risk of bias and concern for applicability of the 21 included studies using the QUADAS- 2 tool

can identify changes in the shoulder joint that correspond to abnormalities found at surgery and concluded that axillary capsular thickening and enhancement and RI enhancement can distinguish other diseases causing shoulder joint pain, such as rotator cuff tears. RI fat obliteration has been considered a specific MRI finding of ACS, and it is always correlated with clinical symptoms [48]. As the most common cause of shoulder pain and disability, rotator cuff tears are characterized by increased tendon signals on MRI, particularly the supraspinatus tendon. The increased signal within the capsule may lead to an increased false-positive rate for

Table 5 Results of meta-regression analyses

Covariate		No. of studies	Sensitivity(95%CI)	*p* value	Specificity(95%CI)	*p* value
Axillary capsular thickening						
Study design				0.03		0.05
	Retrospective	9	0.76[0.64–0.88]		0.89[0.82–0.95]	
	Prospective	2	0.99[0.95–1.00]		0.53[0.20–0.86]	
No. of patients				0.14		0.01
	≥ 100	3	0.95[0.91–1.00]		0.70[0.49–0.90]	
	< 100	9	0.72[0.61–0.83]		0.89[0.82–0.96]	
Magnet strength				0.69		0.05
	≥ 3T	6	0.87[0.75–0.99]		0.80[0.66–0.94]	
	< 3T	6	0.76[0.57–0.95]		0.89[0.80–0.98]	
Reader consensus				0.84		0.82
	YES	5	0.86[0.72–1.00]		0.88[0.75–1.00]	
	NO	7	0.79[0.63–0.96]		0.85[0.73–0.96]	
Fat obliteration of the rotator interval						
Study design				0.14		0.30
	Retrospective	8	0.71[0.51–0.91]		0.59[0.39–0.78]	
	Prospective	3	0.92[0.78–1.00]		0.75[0.50–1.00]	
No. of patients				0.88		0.76
	≥ 100	4	0.78[0.52–1.00]		0.65[0.39–0.90]	
	< 100	8	0.75[0.53–0.97]		0.66[0.46–0.85]	
Magnet strength				0.10		0.90
	≥ 3T	5	0.89[0.78–1.00]		0.67[0.44–0.90]	
	< 3T	7	0.59[0.37–0.81]		0.64[0.44–0.84]	
Reader consensus				0.93		0.22
	YES	6	0.77[0.54–1.00]		0.57[0.35–0.79]	
	NO	6	0.74[0.50–0.99]		0.72[0.55–0.90]	
Coracohumeral ligament thickening						
Study design				0.18		0.27
	Retrospective	8	0.77[0.56–0.98]		0.75[0.63–0.88]	
	Prospective	1	0.43[– 0.39–1.00]		1.00[1.00–1.00]	
No. of patients				0.01		0.26
	≥ 100	2	0.95[0.87–1.00]		0.67[0.42–0.92]	
	< 100	8	0.62[0.41–0.84]		0.78[0.66–0.90]	
Magnet strength				0.55		0.33
	≥ 3T		0.67[0.36–0.98]		0.74[0.57–0.91]	
	< 3T		0.79[0.55–1.00]		0.77[0.63–0.92]	
Reader consensus				0.26		0.91
	YES	2	0.83[0.64–1.00]		0.80[0.68–0.92]	
	NO	8	0.60[0.28–0.92]		0.70[0.53–0.86]	

No.: number

radiologists in diagnosing rotator cuff tears because ACS is also commonly associated with rotator cuff tear pathology. However, when the intra-tendinous signal intensity approaches the fluid signal, a tear can be diagnosed with confidence [49].

Significant changes in sensitivity and specificity were seen when different diagnostic cutoff values were used for axillary joint capsule thickening, RI joint capsule thickening, and CHL thickening. The abnormal thickening of axillary capsular, CHL, and RI joint capsular showed moderate variation (2–5.8 mm), narrow variation (1.7–4.6 mm), and wide variation (1.7–6 mm), respectively, with the most commonly used cutoff values of more than 3 mm (seven of twelve studies), 3 mm (six of nine studies), and greater than 3.5 mm (three of five studies).

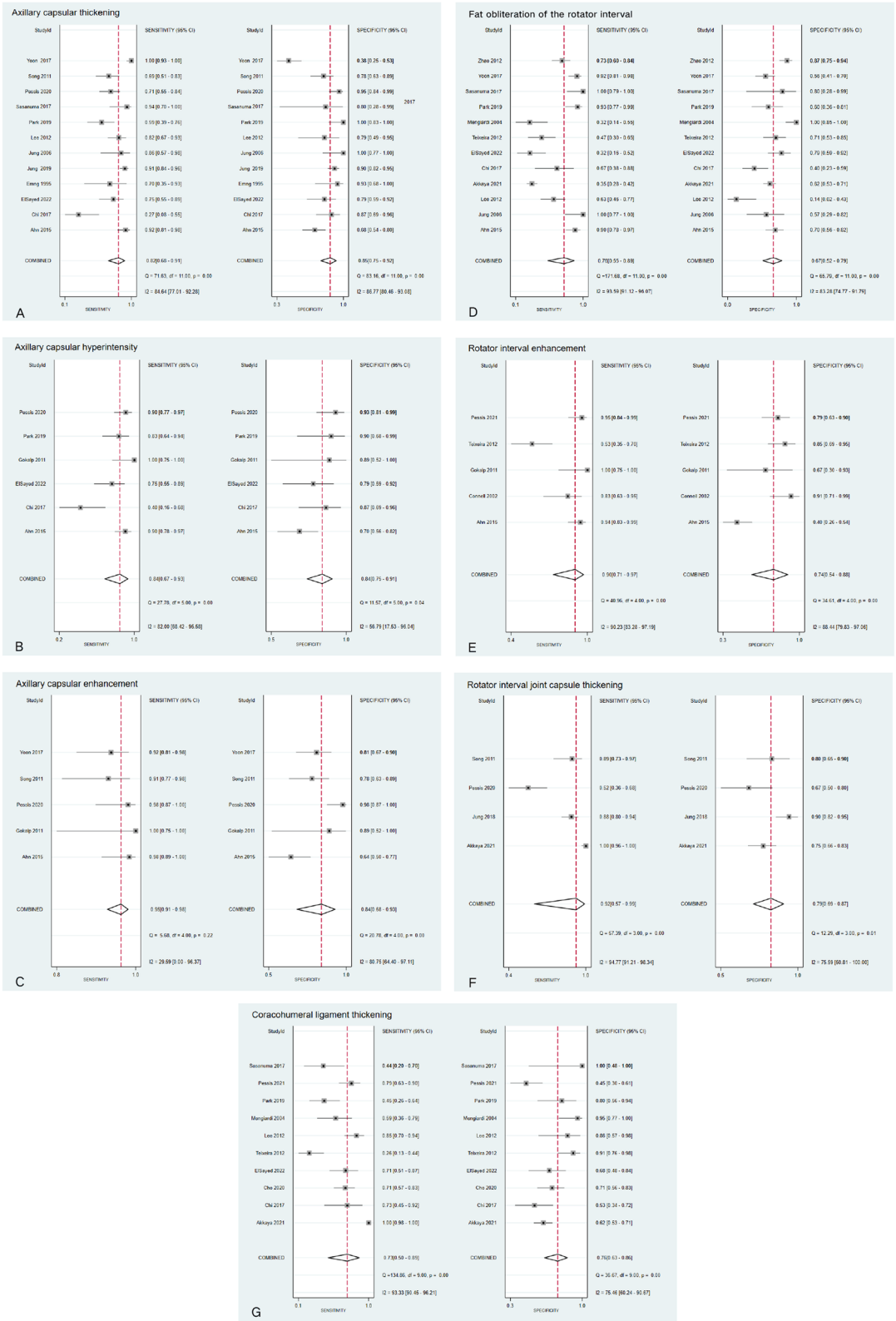

Fig. 3 Coupled Forest plots of pooled sensitivity and specificity showing MR features

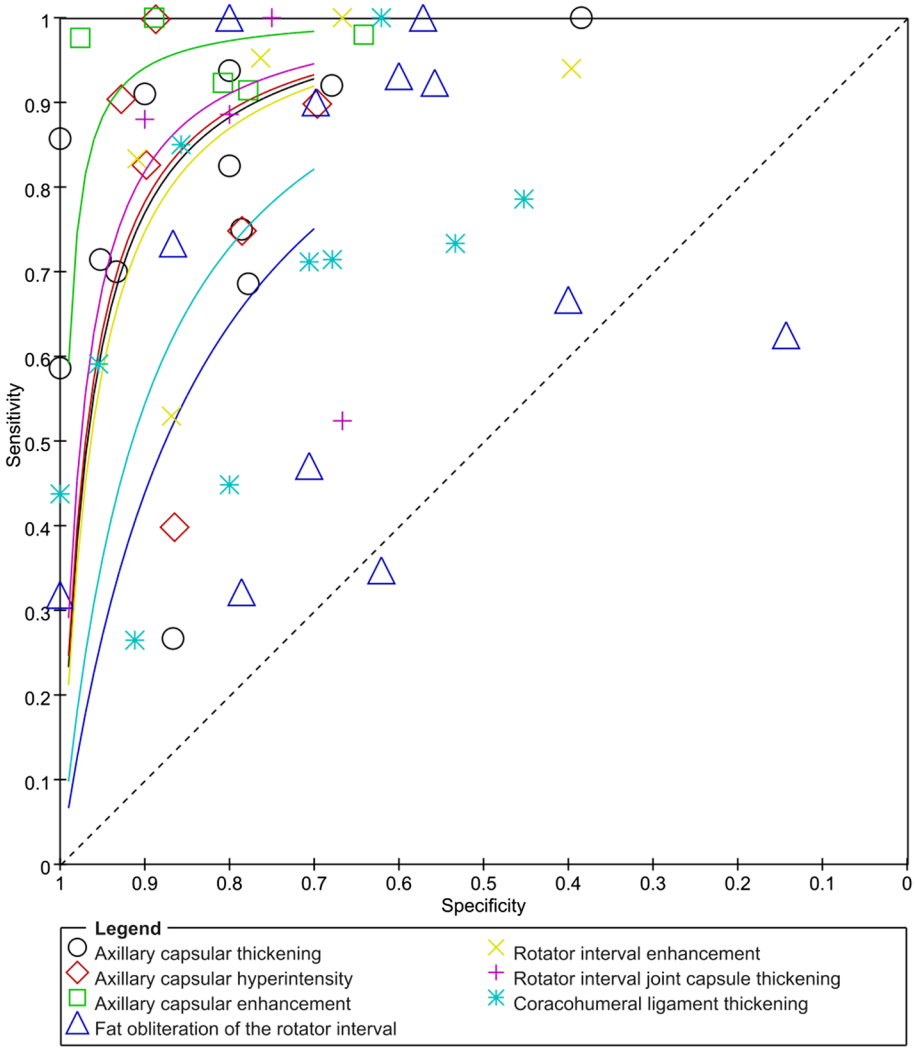

Fig. 4 Areas under the ROC curve (AUCs) of seven MR features for diagnosing adhesive capsulitis of the shoulder

This study has some limitations. First, some imaging features used in 21 studies were excluded from this meta-analysis due to inadequate information, such as sensitivities and specificities, or being mentioned in less than 4 studies. The statistical significance of these excluded MRI features cannot be assessed despite the usefulness of these MRI features in diagnosing ACS. Secondly, the diagnosis of AC is based on clinical presentation, medical history and physical examination. Atypical clinical symptoms and signs may reduce the accuracy of the clinical diagnosis of ACS. Therefore, sixteen studies [20–27, 29–32, 34, 35, 37, 38] used clinical or imaging as the gold standard in the examinations, and we believe that the issue of clinical applicability is uncertain. This was inevitable because of the disease characteristics. The unclear applicability concern caused by the disease's characteristics did not undermine the reliability of our results. Thirdly, the effect of different diagnostic thresholds on heterogeneity could not be adequately analyzed because of the lack of a unified measurement standard and detailed definition of MRI features assessed in each study. Additionally, we were unable to assess the diagnostic accuracy of combinations of multiple MRI features. In fact, the diagnosis of ACS relies on multiple MRI features combined with clinical findings in clinical practice.

In conclusion, seven valuable MRI characteristics were identified that could assist in the diagnosis of ACS: axillary capsule enhancement, axillary capsular hyperintensity, axillary capsule thickening, fat obliteration of the RI, RI enhancement, RI joint capsule thickening, and CHL

Table 6 Performance results for individual studies

Axillary capsular thickening				
Study	**TP**	**FP**	**FN**	**TN**
Ahn 2015 [30]	46	17	4	36
Chi 2017 [23]	4	4	11	26
ElSayed 2022 [26]	21	6	7	22
Emig 1995 [39]	7	1	3	14
Jung 2019 [31]	91	10	9	90
Jung 2006 [40]	12	0	2	14
Lee 2012 [33]	33	3	7	11
Park 2019 [35]	17	0	12	20
Sasanuma 2017 [34]	15	1	1	4
Pessis 2020 [21]	30	2	12	40
Song 2011 [27]	24	10	11	35
Yoon 2017 [32]	52	32	0	20
Axillary capsular hyperintensity				
Study	TP	FP	FN	TN
Ahn 2015 [30]	45	16	5	37
Chi 2017 [23]	6	4	9	26
ElSayed 2022 [26]	21	6	7	22
Gokalp 2011 [37]	13	1	0	8
Park 2019 [35]	24	2	5	18
Pessis 2020 [21]	38	3	4	39
Axillary capsular enhancement				
Study	TP	FP	FN	TN
Ahn 2015 [30]	49	19	1	34
Gokalp 2011 [37]	13	1	0	8
Pessis 2020 [21]	41	1	1	41
Song 2011 [27]	32	10	3	35
Yoon 2017 [32]	48	10	4	42
Fat obliteration of the rotator interval				
Study	TP	FP	FN	TN
Ahn 2015 [30]	45	16	5	37
Jung 2006 [40]	14	6	0	8
Lee 2012 [33]	25	12	15	2
Akkaya 2021 [29]	67	44	126	72
Chi 2017 [23]	10	18	5	12
ElSayed 2022 [26]	9	6	19	22
Teixeira 2012 [38]	16	10	18	24
Mengiardi 2004 [28]	7	0	15	22
Park 2019 [35]	27	8	2	12
Sasanuma 2017 [34]	16	1	0	4
Yoon 2017 [32]	48	23	4	29
Zhao 2012 [24]	44	8	16	52
Rotator interval enhancement				
Study	TP	FP	FN	TN
Ahn 2015 [30]	47	32	3	21
Connell 2002 [36]	20	2	4	20
Gokalp 2011 [37]	13	3	0	6
Teixeira 2012 [38]	18	5	16	29
Pessis 2020 [21]	40	9	2	33

Table 6 (continued)

Axillary capsular thickening				
Study	**TP**	**FP**	**FN**	**TN**
Rotator interval joint capsule thickening				
Study	TP	FP	FN	TN
Akkaya 2021 [29]	100	29	0	87
Jung 2018	88	10	12	90
Pessis 2020 [21]	22	14	20	28
Song 2011 [27]	31	9	4	36
Coracohumeral ligament thickening				
Study	TP	FP	FN	TN
Akkaya 2021 [29]	193	44	0	72
Chi 2017 [23]	11	14	4	16
Cho 2020 [9]	37	15	15	36
ElSayed 2022 [26]	20	9	8	19
Teixeira 2012 [38]	9	3	25	31
Lee 2012 [33]	34	2	6	12
Mengiardi 2004 [28]	13	1	9	21
Park 2019 [35]	13	4	16	16
Pessis 2020 [21]	33	23	9	19
Sasanuma 2017 [34]	7	0	9	5

thickening. Axillary capsular enhancement had the highest pooled sensitivity, pooled specificity, and DORs. MRI is a noninvasive and effective tool for diagnosing shoulder disease, and the MRI features summarized in this meta-analysis are informative and will be helpful for the diagnosis and management of ACS in clinical practice.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Not applicable.

Registration and protocol
This systematic review and meta-analysis was not registered.

Authors' contributions
J Xiang and K Zhang conceived and supervised the study. H Gao and X Zhou carried out the search process and data collection. Y Liu and M Luo assessed the quality of the study, and J Xiang drafted the manuscript. K Zhang and W Liu revised and polished manuscript. All the authors have read and approved the final manuscript.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Since this is a systematic review and meta-analysis, Ethics approval and consent to participate are not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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