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REVIEW ARTICLE

The role of ultrasound imaging in adult patients with testicular torsion: a systematic review and meta-analysis

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Abstract

Purpose Our aim was to determine the accuracy of ultrasound (US) examination-based testicular torsion diagnosis in adult patients with acute scrotal pain.

Methods A comprehensive electronic search was performed using internet retrieval systems up to 5 August 2018 in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. The quality of eligible studies was assessed using Quality Assessment for Studies of Diagnostic Accuracy (QUADAS-2). The diagnostic value of ultrasound in patients with testicular torsion was evaluated using pooled estimates of sensitivity, specificity, likelihood ratio, and diagnostic odds ratio, as well as the summary receiver operating characteristics curve.

Results Twenty-six studies with 2116 patients were included in the study. Overall diagnostic sensitivity was 0.86 [95% confidence interval (CI) 0.79–0.91] and specificity was 0.95 (95% CI: 0.92–0.97). Subgroup analysis of prospective studies showed pooled sensitivity of ultrasound for testicular torsion was 0.94 (95% CI 0.83–0.98), and pooled specificity was 0.98 (95% CI 0.94–1.00). Recent studies after 2010 showed diagnostic sensitivity of 0.95 (95% CI 0.84–0.99) and specificity of 0.98 (95% CI 0.93–0.99).

Conclusions This meta-analysis demonstrated that ultrasound represents an effective imaging modality for diagnosing testicular torsion in adult patients with acute scrotal pain.

Keywords Testicular torsion · Color Doppler ultrasound · Meta-analysis · Systematic review · Adult patient

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Introduction

Acute scrotal pain is relatively common among children and early adolescents [1, 2], and is a challenging clinical problem that requires prompt diagnosis for appropriate treatment. The most common cause of nontraumatic acute scrotal pain in adults is acute epididymitis (or epididymo-orchitis: EO) [3]. Testicular torsion is relatively rare in adult patients, but should be considered because of the risks associated with delaying surgical intervention; testicular torsion can lead to organ loss from ischemia, cosmetic deformity, and compromised fertility [2–4]. Ultrasound (US) has been an indispensable imaging modality in the clinical assessment of patients with acute scrotal pain. Color Doppler ultrasound (CDU) evaluates the size, shape, echotexture, and blood flow of both testicles [5]. CDU of testicular torsion usually demonstrates a relative decrease or absence of blood flow within the affected testicle. CDU as a preoperative diagnostic tool for testicular torsion shows sensitivity and specificity ranging from 63 to 100% and from 80 to 100%, respectively, and a false-negative rate of 1–10% in children [6–10]. However, the accuracy of CDU in adult patients has not been clarified. Ultrasound can also evaluate other etiologies of acute scrotal pain in adult patients. The equipment used for US has evolved rapidly, and new technologies and methods have been developed, such as contrast-enhanced ultrasound and whirlpool sign [11]. The aim of this article was to report on the diagnostic accuracy of CDU with or without contrast enhancement in adult patients with testicular torsion. To better define the validity, role, and statistical significance of CDU in testicular torsion, a comprehensive literature review and meta-analysis was performed using a Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA)-format meta-analysis of the literature.

Materials and methods

Search strategy

The search strategy was developed using PubMed, Web of Science, Cochrane Library, Ichushi-Web, and Google Scholar without language limitations in July 2018. Searches were made filtering for the following keywords: 'acute scrotal pain', 'acute scrotum', 'ultrasound', 'Doppler', 'sensitivity', 'specificity', 'testicular torsion', and 'torsion of the appendix testis'. AND, OR, and NOT were applied to a database to create a subset of search results. An age restriction (≥ 19 years) was also applied to PubMed after using filter search results. Citations of studies obtained in the search were also comprehensively reviewed.

Study selection

Inclusion criteria

Studies investigating the diagnostic performance of Doppler ultrasound (DU) with or without color Doppler or grayscale US (B-mode ultrasound: US) for testicular torsion in adult patients were considered eligible for our study when they satisfied the following criteria: (1) the study population included patients ≥ 19 years who underwent DU or US because of suspected testicular torsion; (2) the outcomes of the study included the number of true-positive, false-positive, false-negative, and true-negative patients to calculate DU or US diagnostic performances for acute scrotal pain; and (3) final diagnoses were based on surgical findings and/or clinical follow-up.

Exclusion criteria

Studies meeting any of the following criteria were excluded:

(1) Studies only including pediatric patients (i.e., all patients were younger than 19 years); (2) studies for which the full text was not available in English or Japanese; (3) studies focusing on topics other than using ultrasound for diagnosis of acute scrotal pain; (4) studies that included only trauma patients; and (5) reviews, letters, or editorials.

Data extraction and quality assessment

The PRISMA guideline [12] and Cochrane Handbook for Systematic Reviews of Interventions were used for searching articles. We published the protocol for this meta-analysis in the PROSPERO database (identifier: CRD42018104983). The following data were extracted from eligible studies: (a) study characteristics [authors, year of publication, institution and country of the study, study period, number of patients, and study design (prospective vs. retrospective)]; (b) demographic characteristics [patient age and enrolled population]; and (c) US characteristics [machine manufacturer and model]. Eligible articles were fully screened by three reviewers (KO, MO, and MS). All disagreements were solved as consensus decisions following discussion. The methodological quality of the selected studies was assessed using Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) [13].

Data synthesis and statistical analysis

The primary endpoint of this study was the diagnostic performance of ultrasound including CDU for the adult population with acute scrotal pain, particularly testicular torsion. Sensitivity and specificity parameters were extracted and calculated from the selected studies. Because some zero parameters were obtained, 0.5 was added to each parameter to avoid algebraic errors. The numbers of each parameter in 2 × 2 tables were used to calculate positive and negative likelihood ratios with 95% confidence intervals (CIs).

Pooled estimates of sensitivity, specificity, and positive and negative likelihood ratios for the overall data set were calculated using a random-effects regression model in accordance with the methods of DerSimonian and Laird.

Heterogeneity was tested using the Cochrane Q statistic ($P < 0.1$), and influence was estimated using the I^2 statistic. The I^2 statistic describes the variation in effect size that is attributable to heterogeneity across studies, where 0% indicates large homogeneity and 100% indicates large heterogeneity. Publication bias was evaluated using the funnel plot. Sensitivity analysis was performed to detect the influence of a single study on the overall estimate by removing each of the studies in turn and then recalculating when necessary. Values of $P < 0.05$ were considered statistically significant. All statistical analyses were performed with Review Manager version 5.3 (The Cochrane Collaboration, Software Update, Oxford, UK) and R version 3.4.1 software.

Results

The electronic search yielded 290 articles, with the following breakdown: PubMed, 32 articles; Web of Science, 49 articles; Cochrane Library, 9 articles; Ichushi-Web, 3 articles; and Google Scholar, 192 articles. Articles were screened for both content and duplicates. Five other articles were identified from references provided in the selected studies. After the systematic literature search and study selection process, 26 studies were included (Fig. 1). These studies included 2116 patients with ages ranging from 1 day to 95 years, with sample sizes ranging from 7 to 236. Since the aim of this study was the diagnostic performance of ultrasound including CDU for the adult population with testicular torsion, pediatric patients younger than 19 years were excluded wherever possible, but some pediatric patients could not be excluded. Twenty-four studies included at least one patient younger than 19 years. Six studies were conducted in the United States [7, 14–18], five in India [19–23], three in Germany [24–26], two each in Australia [27, 28], Italy [29, 30], Israel [31, 32] and the United Kingdom [33, 34], and one each in China [35], Greece [36], Kuwait [37], and Taiwan [38] (Table 1). All six studies from the United States were conducted before 2001, whereas most studies from India were conducted in the 2010s. Eight studies were conducted under a prospective design and seven studies were conducted using a retrospective design. Study design was not documented in the other 11 studies (Table 1). The reference used in these studies for determining a diagnosis of testicular torsion was surgical exploration or follow-up for size of the testes.

Quality assessment

Ten studies were labeled as high risk in terms of the risk of bias for the patient selection domain, because the selection process was not documented (Table 2). Six studies were labeled as unclear, because the authors did not report whether patients were enrolled consecutively. The index test domain of three studies was labeled as high risk, because they did not use a prespecified threshold for CDU or Doppler ultrasound. All except three studies in the reference standard domain were labeled as high risk or unclear, because the surgeons were not blinded to the ultrasound results. In addition, clinical follow-up at outpatient or inpatient management was not blinded to the ultrasound results. For applicability concerns, the patient selection domain for all except two studies was labeled as high risk, because at least one patient younger than 19 years was included.

Meta-analysis

The overall diagnostic sensitivity was 0.86 (95% CI 0.79–0.91) and specificity was 0.95 (95% CI 0.92–0.97; Table 3). Subgroup analysis including the maximum number of patients (including all patients in the literature: 3291 patients in total) showed that pooled sensitivity and specificity were 0.93 (95% CI 0.90–0.95) and 0.97 (95% CI 0.96–0.98), respectively. Eight studies were conducted before 2000. Pooled sensitivity and specificity were 0.83 (95% CI 0.72–0.91) and 0.91 (95% CI 0.85–0.95), respectively. Ten studies were conducted from 2000 to 2009. Pooled sensitivity and specificity were 0.83 (95% CI 0.69–0.92) and 0.93 (95% CI 0.87–0.97), respectively. In addition, we calculated the sensitivity and specificity of studies conducted from 2000 to 2009, excluding Yuan et al. due to the unnaturally lower sensitivity and specificity; the resulting pooled sensitivity and specificity were 0.86 (95% CI 0.75–0.92) and 0.95 (95% CI 0.89-0.97), respectively. For the eight studies conducted after 2010, pooled sensitivity and specificity were 0.95 (95% CI 0.84–0.99) and 0.98 (95% CI 0.93–0.99), respectively. The pooled sensitivity and specificity of studies with prospective designs were 0.94 (95% CI 0.83–0.98) and 0.98 (95% CI 0.94–1.00), respectively. The pooled sensitivity and specificity of studies with retrospective designs were

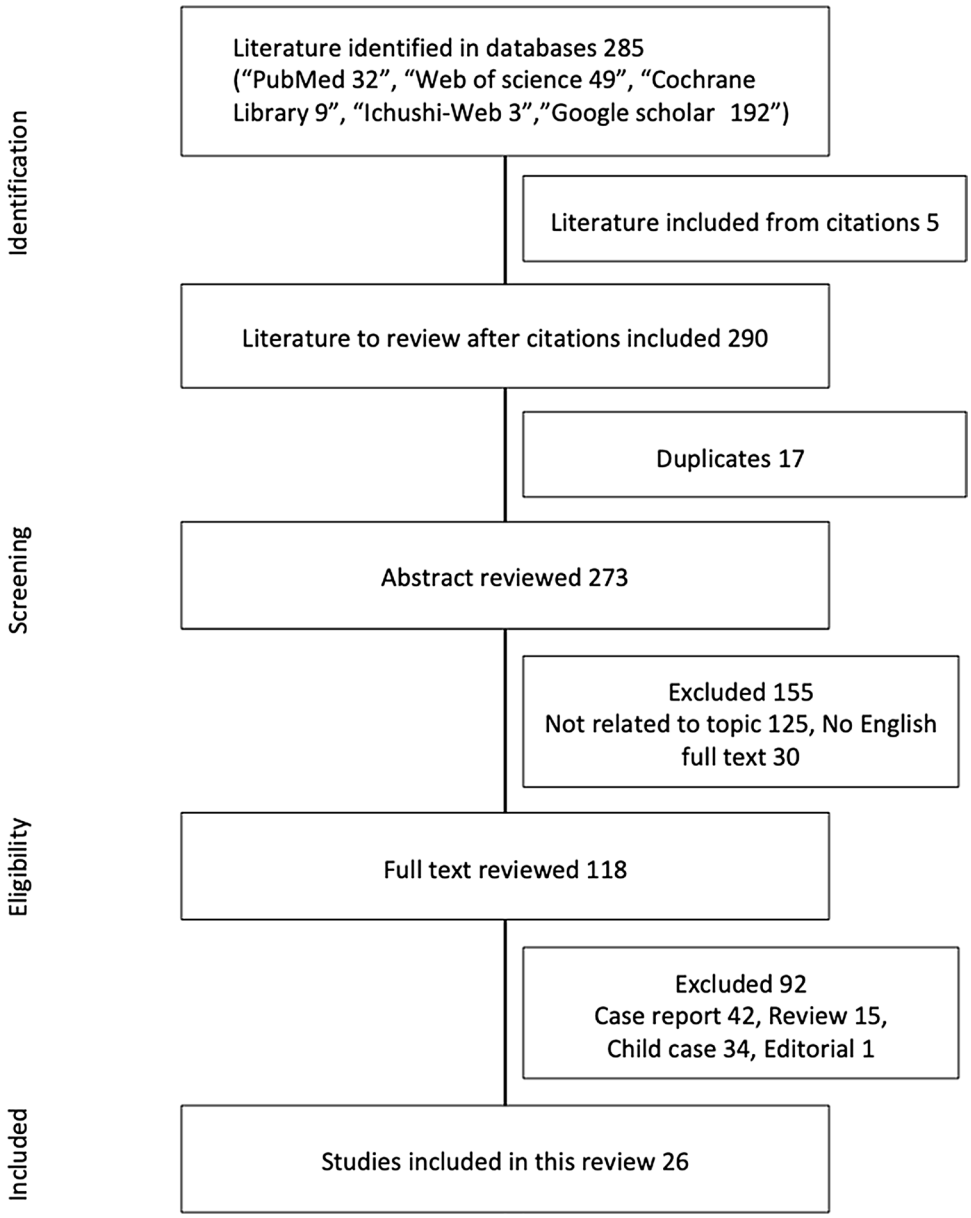

Fig. 1 Study flow diagram. Flow diagram of the study selection process and specific reasons for exclusion from the meta-analysis

0.85 (95% CI 0.76–0.91) and 0.97 (95% CI 0.94–0.98), respectively. The pooled sensitivity and specificity of the 11 studies for which details of the study design were not documented were 0.81 (95% CI 0.66–0.90) and 0.91 (95% CI 0.84–0.95), respectively. The present study found that the I2 statistic for the present meta-analysis was 0%, indicating a large degree of homogeneity across all studies. Figure 2 shows forest plots for each study. Summary receiver operator characteristic plots with 95% CIs of sensitivity against false-positive ultrasound imaging for testicular torsion are shown in Fig. 3.

Publication bias was analyzed by funnel plot and Deek's test, which provided evidence of publication bias for the outcome of diagnostic odds ratio (DOR) (*P* value for Deek's test = 0.03). The funnel plot is shown in Fig. 4.

Discussion

The present systematic review included 26 studies that investigated the value of ultrasound as an imaging modality for acute scrotal pain resulting from testicular torsion. The meta-analysis revealed that ultrasound was an effective diagnostic tool for testicular torsion, with an overall sensitivity and specificity of 0.86 and 0.95, respectively. Regarding applicability, at least one patient younger than 19 years was included in almost all studies, and high-risk concerns were present in patient selection.

Ultrasound systems have been developing rapidly, and recent high-resolution images can provide adequate information for blood flow assessment. Studies from the 2010s thus showed both high sensitivity and specificity of 0.95

Table 1 Characteristics of the included studies. Summary of literature included in the meta-analysis. UK, United Kingdom; USA, United States of America

Author (year)	Nation	Design	n	Age range	Study period	Machine
Bickerstaff et al. [33]	UK	Not mentioned	36	1–35	November 1985–April 1987	Sonicaid Vascular Flow Detector, Model BV102
Krieger et al. [14]	USA	Not mentioned	7	Age mean SD 29 ± 4	None	7-MHz linear array Acuson model 128 device (Acuson Mountain View, CA)
Middleton et al. [15]	USA	Prospective	28	1 day–41	May 1988–December 1989	QAD-1 unit (Quantum Medical Systems, Issaquah, WA) with a 7.5-MHz linear phased-array transducer
Fitzgerald et al. [17]	USA	Not mentioned	35	16–34	April 1988–August 1990	7.5-MHz linear transducer (Quantum Medical Systems, Issaquah, WA)
Dewire et al. [16]	USA	Not mentioned	20	15–32	September 1989–November 1990	Quantum QAD-1 scanner with a 6.0- and/or 7.5-MHz. transducer (Quantum Medical Systems, Issaquah, WA)
Wilbert et al. [24]	Germany	Prospective	40	12–46	November 1988–December 1991	QAD-1 unit with a 7.5-MHz. linear phased array transducer (Quantum-Philips, Hamburg, Germany)
al Mufti et al. (1995)	UK	Not mentioned	25	16–24	1 year	Hand-held Doppler ultrasound probe, with a transducer operating nominally at 8 MHz (BV102, Sonicaid Vascular Flow Detector)
Schwaibold et al. [25]	Germany	Not mentioned	30	None, 85% adult	March l988–April l991	QAD I scanner (Quantum/Philips) with a 7.5-MHz transducer
Dunne et al. [27]	Australia	Not mentioned	9	13–36	1990–1995	No detail
Baker et al. [7]	USA	Retrospective	103	2 days–23	September 1992–April 1997	Acuson XP-10 unit (Acuson, Mountain View, CA) using a 7-MHz linear array transducer
Yuan et al. [35]	China	Not mentioned	49	7–42	None	Aloka SSD-2000 ultrasonoscope and linear transducers with a frequency of 5 MHz
Blaivas et al. [18]	USA	Retrospective	36	10–62	July 1998–September 1999	7.5-MHz probe available on an ultrasound machine capable of color Doppler imaging
Andipa et al. [36]	Greece	Not mentioned	230	15–45	None	ATL 5000 HDI unit with a high-resolution linear transducer of 5–12 MHz (Philips: ATL HDI 5000)
Hod et al. [31]	Israel	Retrospective	27	1–49	January 1994–November 2001	7 ± 10-MHz linear transducer for both imaging and Doppler analysis
Abul et al. [37]	Kuwait	Retrospective	40	7–69	January 2002–December 2002	No detail
Vijayaraghavan et al. [19]	India	Prospective	221	3 months–57	April 2000–September 2005	Linear 5-12 MHz probe (HDI 3500 and HDI 5000; Philips Medical Systems, Bothell, WA)
Pepe et al. [29]	Italy	Not mentioned	149	2 months–86	July 2000–July 2005	GE Logiq 500 with multifrequency (7.5–10 MHz) linear probe Small Part
Liu et al. [38]	Taiwan	Retrospective	67	≤ 25 years	January 1993–October 2004	No detail

Table 1 (continued)

Author (year)	Nation	Design	n	Age range	Study period	Machine
Yagil et al. [32]	Israel	Retrospective	67	2 months–95	October 2004–October 2007	High-resolution linear array transducers (7–12 and 5–17 MHz) with HDI and iU22 ultrasound equipment (Philips Healthcare, Bothell, WA)
Jaison et al. [28]	Australia	Retrospective	173	33.8 ± 13.9	July 2003–December 2008	No detail
Valentino et al. [30]	Italy	Prospective	50	18–84 (50 patients)	March 2005–December 2009	HDI 5000 and IU22 Ultrasound machines (Philips, Amsterdam, the Netherlands). High-frequency 4- to 7-MHz and 5- to 12-MHz probes
Altinkilic et al. [26]	Germany	Prospective	236	0–53	1995–2012	7.5- to 10-MHz linear transducer (Combison® 420, Kretz Medical, Kraichtal, Germany, Pro Focus™, BK Medical, Quickborn, Germany or SA 8800 MT, Sonoace GmbH, Marl, Germany)
Prajapati et al. [21]	India	Prospective	108	1–80	None	LOGIQ 500 MD MR 3 WIPRO GE SONOGRAPHY MACHINE with linear array high-frequency (6-7-9 MHz) probe
Agrawal et al. (2014)	India	Prospective	50	None	January 2013–January 2014	(Philips HD7 XE) equipped with high-resolution and Color Doppler linear probe (7.5-12 MHz)
Shah et al. [22]	India	Not mentioned	200	None	20 months	No detail
Singh et al. [23]	India	Prospective	80	35.25 ± 12.93	None	Color Doppler ultrasonography using high-frequency linear transducer with frequency of 3–12 MHz

(95% CI: 0.84–0.99) and 0.98 (95% CI 0.93–0.99), respectively. Compared to studies before 2000, studies from 2000 to 2009 showed lower sensitivity and specificity. One study from Yuan et al. exaggerated the superiority of radionuclide scrotum scintigraphy over ultrasound for diagnosing testicular torsion. The sensitivity and specificity for diagnosing testicular torsion were 100% and 85.7% for radionuclide scrotum scintigraphy and 48.6% and 85.7% for ultrasound, respectively. These values seemed too low and different from those of other studies conducted in the same decade. When the study by Yuan et al. was excluded, the sensitivity and specificity of studies from 2000 to 2009 increased to 0.86 (95% CI 0.75–0.92) and 0.95 (95% CI 0.89–0.97), respectively. Thus, there seems to have been a tendency toward improvement in the diagnostic accuracy of ultrasound year after year.

New methods for detecting testicular torsion have been developed, such as contrast-enhanced ultrasound (CEUS) and whirlpool sign detection [19, 30]. CEUS was carried out after baseline CDU with injection of contrast media, thus representing a more time-consuming method than detecting the whirlpool sign. The whirlpool sign was described as a US image of a twisted cord superior to the testis, and this method was easier and less invasive than CEUS. Meta-analysis for the whirlpool sign showed pooled sensitivity of 0.92 (95% CI 0.70–0.98) and pooled specificity of 0.99 (95% CI 0.95–1.00), after removing those studies that only enrolled neonates [11].

A retrospective study showed that the sensitivity and specificity of dynamic contrast-enhanced subtraction magnetic resonance imaging (MRI) in the diagnosis of testicular torsion were 93% and 100%, respectively [39]. These values were similar to those in the studies from the 2010s (sensitivity and specificity of 0.95 and 0.98, respectively). This method using dynamic contrast-enhanced subtraction MRI was introduced in 2006, but it has not been established as a standard test for testicular torsion. It is perhaps because MRI is a more time-consuming and expensive method than CDU.

Table 2 Quality assessment of diagnostic accuracy studies-2 (QUADUS-2)

	Risk of bias				Concerns of applicability		
	Patient selection	Index test	Reference standard	Flow and timing	Patient selection	Index test	Reference standard
Bickerstaff et al. [33]	Low	Low	Low	Low	High	Low	Low
Krieger et al. [14]	Low	Low	Unclear	High	Low	Low	Low
Middleton et al. [15]	Unclear	Low	High	Unclear	High	Low	Low
Fitzgerald et al. [17]	Unclear	Low	High	Unclear	Unclear	Low	Low
Dewire et al. [16]	Low	Low	Unclear	Low	High	Low	Low
Wilbert et al. [24]	High	Low	Unclear	Unclear	High	Low	Low
al Mufti et al. (1995)	Low	Low	Unclear	Low	High	Low	Low
Schwaibold et al. [25]	High	Low	Unclear	Unclear	High	Low	Low
Dunne et al. [27]	High	High	High	High	High	Low	Low
Baker et al. [7]	High	Low	High	High	High	Low	Low
Yuan et al. [35]	High	Low	High	Unclear	High	Low	Low
Blaivas et al. [18]	High	Low	High	High	High	Low	Low
Andipa et al. [36]	High	Low	High	Unclear	High	Low	Low
Hod et al. [31]	High	Unclear	High	Unclear	High	Low	Low
Abul et al. [37]	Unclear	High	High	Unclear	High	Low	Low
Vijayaraghavan et al. [19]	Low	Low	Unclear	Unclear	High	Low	Low
Pepe et al. [29]	Unclear	Low	High	Low	High	Low	Low
Liu et al. [38]	Low	High	High	High	High	Low	Low
Yagil et al. [32]	Low	Low	Unclear	High	High	Low	Low
Jaison et al. [28]	Low	Unclear	Unclear	Unclear	Low	Low	Low
Valentino et al. [30]	Low	Low	Low	High	Unclear	Low	Low
Altinkilic et al. [26]	Low	Low	Low	Low	High	Low	Low
Prajapati et al. [21]	High	Low	Unclear	High	High	Low	Low
Agrawal et al. (2014)	Unclear	Low	Unclear	High	High	Low	Low
Shah et al. [22]	High	Unclear	Unclear	High	High	Low	Low
Singh et al. [23]	Unclear	Unclear	Unclear	Unclear	High	Low	Low

Quality assessment of the 26 studies included in the meta-analysis

Table 3 Pooled diagnostic accuracy for each group

All studies	Studies (TP, FP, FN, TN) (sample size)	Sensitivity (95% CI)	Specificity (95%CI)	Cochran's Q (P value)	I^2
	26 (425, 40, 79, 1572) ($n=2116$)	0.864 (0.794–0.913)	0.953 (0.922–0.972)	22.365 (0.615)	0%
1990s	8 (58, 7, 6, 150) ($n=221$)	0.832 (0.721–0.905)	0.914 (0.846–0.953)	4.705 (0.696)	0%
2000s	10 (198, 33, 39, 661) ($n=931$)	0.829 (0.685–0.915)	0.933 (0.867–0.967)	10.11 (0.342)	10.98%
2000s (excluded Yuan)	9 (181, 15, 37, 649) ($n=882$)	0.859 (0.754–0.924)	0.945 (0.889–0.974)	10.034 (0.263)	20.27%
2010s	8 (169, 0, 34, 761) ($n=964$)	0.949 (0.844–0.985)	0.978 (0.933–0.993)	0.479 (1.000)	0%
Prospective	8 (221, 2, 29, 561) ($n=813$)	0.94 (0.829–0.981)	0.982 (0.935–0.995)	4.621 (0.706)	0%
Retrospective	7 (89, 10, 8, 406) ($n=513$)	0.851 (0.760–0.911)	0.966 (0.940–0.981)	4.713 (0.581)	0%
Unspecified	11 (115, 28, 42, 605) ($n=790$)	0.806 (0.664–0.897)	0.911 (0.844–0.951)	8.196 (0.610)	0%

DerSimonian–Laird random-effects models used throughout

TP true positive, *FP* false positive, *FN* false negative, *TN* true negative

Epididymitis or EO and torsion of the appendix testis should be considered as differential diagnoses for testicular torsion. The former involves infection or inflammation of the epididymis. Epididymitis and EO are the most common causes of acute scrotum in adults in the outpatient setting [40]. The characteristic finding of epididymitis on CDU is

	TP	FP	FN	TN	Sensitivity (95%CI)	Specificity (95%CI)
Bickerstaff et al (1988)	12	0	3	21	0.78 0.54 - 0.92	0.89 0.69 - 0.96
Krieger et al (1990)	1	1	0	5	0.75 0.20 - 0.97	0.79 0.42 - 0.95
Middleton et al (1990)	7	0	0	21	0.94 0.60 - 0.99	0.98 0.82 - 1.00
Dewire et al (1992)	6	0	1	13	0.81 0.47 - 0.96	0.89 0.64 - 0.98
Fitzgerald et al (1992)	6	2	0	27	0.93 0.56 - 0.99	0.92 0.77 - 0.97
Wilbert et al (1993)	9	0	2	29	0.79 0.51 - 0.93	0.98 0.86 - 1.00
al Mufti et al (1995)	9	0	0	16	0.95 0.66 - 1.00	0.97 0.77 - 1.00
Schwaibold et al (1996)	8	3	1	18	0.66 0.42 - 0.84	0.79 0.56 - 0.92
Baker et al (2000)	16	1	2	84	0.87 0.66 - 0.96	0.98 0.93 - 1.00
Dunne et al (2000)	4	0	3	2	0.56 0.26 - 0.83	0.83 0.31 - 0.98
Blaivas et al (2001)	3	0	0	33	0.88 0.40 - 0.99	0.99 0.87 - 0.99
Yuan et al (2001)	17	2	18	12	0.49 0.33 - 0.64	0.83 0.58 - 0.95
Andipa et al (2004)	29	13	2	186	0.92 0.78 - 0.98	0.93 0.89 - 0.96
Hod et al (2004)	6	1	1	19	0.81 0.47 - 0.96	0.93 0.74 - 0.98
Abul et al (2005)	8	0	3	29	0.71 0.43 - 0.89	0.98 0.86 - 1.00
Pepe et al (2006)	21	20	0	108	0.98 0.82 - 1.00	0.89 0.82 - 0.93
Vijayaraghavan et al (2006)	65	0	0	156	0.99 0.93 - 1.00	1.00 0.97 - 1.00
Liu et al (2007)	29	2	4	32	0.87 0.72 - 0.95	0.92 0.77 - 0.98
Yagil et al (2010)	17	2	0	48	0.92 0.72 - 0.98	0.95 0.85 - 0.99
Jaison et al (2011)	10	2	0	161	0.96 0.68 - 1.00	0.99 0.95 - 1.00
Valentino et al (2011)	3	0	0	47	0.98 0.92 - 1.00	0.98 0.97 - 0.99
Altinkilic et al (2013)	119	29	0	88	1.00 0.96 - 1.00	0.75 0.67 - 0.82
Agrawal et al (2014)	8	0	0	42	0.94 0.63 - 0.99	0.99 0.90 - 1.00
Prajapati et al (2014)	4	0	0	104	0.90 0.46 - 0.99	1.00 0.96 - 1.00
Shah et al (2016)	2	1	0	197	0.83 0.31 - 0.98	1.00 0.98 - 1.00
Singh et al (2018)	6	0	0	74	0.93 0.56 - 0.99	0.99 0.94 - 1.00

Fig. 2 Forest plot. Forest plot of the probability of testicular torsion in patients with a positive ultrasonographic sign in the 26 published studies. *TP* true positive, *FP* false positivem, *FN* false negative, *TN* true negative

hyperemia within the epididymis, seen as increased flow compared with the unaffected side [40]. Scrotal wall thickening, hydrocele, or pyelocele can be seen, but are non-specific features of epididymitis or EO [41]. CDU was reported to have a sensitivity of almost 100% in detecting epididymitis [42]. The latter accounts for 20–40% of cases of acute scrotum in the pediatric population because of its pedunculated shape, but can occur later in life [43]. The appendix testis is a small vestigial structure on the anterosuperior aspect of the testis. Grayscale US can visualize an edematous appendix testis, and CDU may also visualize increased flow around it, which can allow differentiation from testicular torsion [43].

Our meta-analysis results were significantly higher than those reported in the literature on testicular torsion in pediatric patients and were presumably due to the characteristics of our target population, comprising mainly adult patients who were cooperative with the examination and in whom an adequate examination was possible to perform. CDU has been reported to fail to identify intratesticular flow in approximately 50% of pediatric patients [43]. If pediatric patients were excluded completely, the diagnostic performance would have been better than in this study. Color Doppler noise or motion artifacts can incorrectly be interpreted as blood flow within the testis, and not all sonographic units were sensitive enough to detect the low-volume, low-velocity flow in the testes, especially in infants in the 1990s. Several pediatric patients were excluded intentionally when descriptions about pediatric patients were included in 2×2 tables. This manipulation might have led to overestimation of the sensitivity and specificity, because false-positive and negative values were mainly excluded.

Several limitations need to be considered. First, only articles for which the full text was available in English were included, which may have influenced the results. Second, testicular torsion is relatively rare in adult populations, so studies that included at least one adult patient were used in the meta-analysis. This may also have influenced the true results for adult patients only, but subgroup analysis showed the same results, so we believe that our results would have closely approximated the true situation even

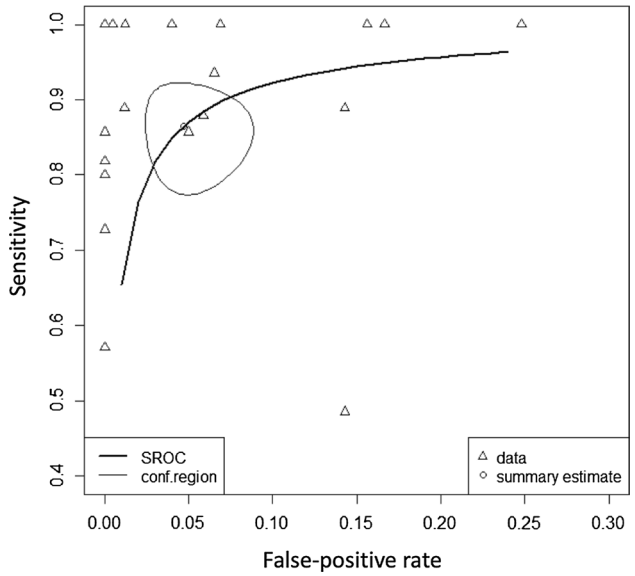

Fig. 3 Summary receiver operator characteristic plots with 95% CIs of sensitivity against false-positive ultrasound imaging for testicular torsion

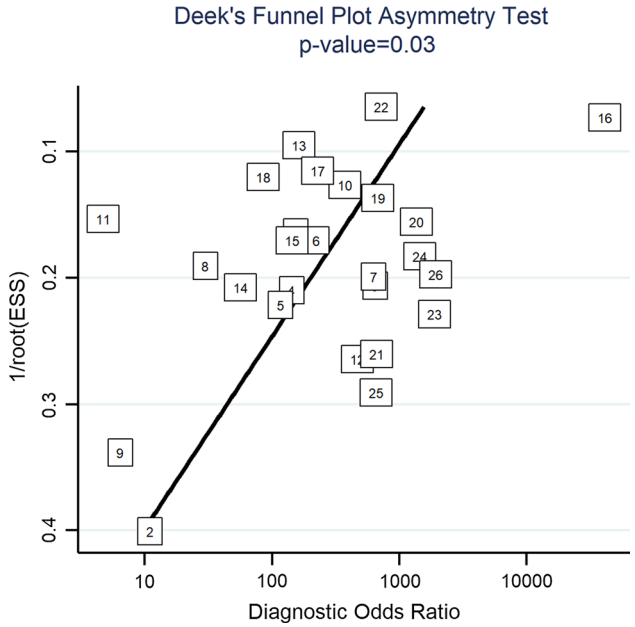

Fig. 4 Funnel plot for the assessment of publication bias. *ESS* effective sample size

with the inclusion of some pediatric patients. Third, studies were not conducted in the same setting, because ultrasound machines have changed and developed dramatically from the 1990s to 2018. Detection of blood flow in the scrotum was relatively difficult before the 2000s, especially in patients with agitation due to pain from Doppler ultrasound without color Doppler. However, detection has become much easier recently because of the progress in high-resolution ultrasound machines and the methods of detecting torsion such as CEUS or the whirlpool sign. Fourth, most studies showed high risk in at least one of the four domains about risk of bias or in patient selection about applicability concerns (Table 2: QUADUS-2). However, a prospective study design with selection of consecutive adult patients showed a slightly better, but largely similar result to a retrospective study design without selection of consecutive patients. Excluding the study by Yuan et al., the unclear study design showed results similar to those of other studies. We thus believe that the results of our meta-analysis were similar to the true diagnostic accuracy of ultrasound in purely adult patients with testicular torsion.

Conclusions

The present systematic review and meta-analysis indicate that ultrasound is an effective imaging modality for the diagnosis of testicular torsion in adult patients with acute scrotal pain. CDU should be performed for adult patients with acute scrotal pain. Further well-designed research is warranted to clarify the diagnostic accuracy of ultrasound in purely adult patients with testicular torsion.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest relevant to the content of this article.

Informed consent Given the anonymous nature of the data, informed consent was not required for this study.

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