The Utility of the Focused Assessment With Sonography in Trauma Examination in Pediatric Blunt Abdominal Trauma

A Systematic Review and Meta-Analysis

Tian Liang, MD,† Eric Roseman, MD,*† Melanie Gao, BA,*† and Richard Sinert, DO*†*

Objective: To evaluate the utility of the Point of Care Ultrasound (POCUS) Focused Assessment with Sonography for Trauma (FAST) examination for diagnosis of intra-abdominal injury (IAI) in children presenting with blunt abdominal trauma.

Methods: We searched medical literature from January 1966 to March 2018 in PubMed, EMBASE, and Web of Science. Prospective studies of POCUS FAST examinations in diagnosing IAI in pediatric trauma were included. Sensitivity, specificity, and likelihood ratios (LR) were calculated using a random-effects model (95% confidence interval). Study quality and bias risk were assessed, and test-treatment threshold estimates were performed.

Results: Eight prospective studies were included encompassing 2135 patients with a weighted prevalence of IAI of 13.5%. Studies had variable quality, with most at risk for partial and differential verification bias. The results from POCUS FAST examinations for IAI showed a pooled sensitivity of 35%, specificity of 96%, LR+ of 10.84, and LR− of 0.64. A positive POCUS FAST posttest probability for IAI (63%) exceeds the upper limit (57%) of our test-treatment threshold model for computed tomography of the abdomen with contrast. A negative POCUS FAST posttest probability for IAI (9%) does not cross the lower limit (0.23%) of our test-treatment threshold model.

Conclusions: In a hemodynamically stable child presenting with blunt abdominal trauma, a positive POCUS FAST examination result means that IAI is likely, but a negative examination result alone cannot preclude further diagnostic workup for IAI. The need for computed tomography scan may be obviated in a subset of low-risk pediatric blunt abdominal trauma patients presenting with a Glasgow Coma Scale of 14 to 15, a normal abdominal examination result, and a negative POCUS FAST result.

Key Words: trauma, ultrasound, hemorrhage

(*Pediatr Emer Care* 2019;00: 00–00)

Trauma is a leading cause of morbidity and mortality in children of all ages.[1] Hospitals in the United States care for more than 140,000 pediatric traumas yearly, with accidental injuries being the leading cause of death.[1,2] These injuries place a significant economic and public health burden on our society with costs exceeding tens of billions of dollars annually.[3]

Timely and accurate diagnosis of intra-abdominal injury (IAI) in children is challenging.[4] Detailed evaluations of an acutely injured child can be limited because of their inability to communicate verbally. Diagnostic peritoneal lavage, once the gold standard of diagnosing IAI, has fallen out of favor compared with noninvasive imaging.[5] Computed tomography (CT) has become the test of choice for diagnosing IAI in pediatric blunt abdominal trauma but also carries the small but increased risk of malignancy from radiation exposure.[4,6]

The Focused Assessment with Sonography for Trauma (FAST) has many advantages compared with diagnostic peritoneal lavage or CT, including ease of use, noninvasiveness, no exposure to ionizing radiation, and ability to repeat assessments. The FAST screening tool has been shown to be useful for detecting IAI in adult trauma.[7] However, its use in children is controversial, with some studies supporting its use and others questioning its utility.[8] Physician opinion on the routine use of FAST in pediatric trauma also varies between specialties, with most pediatric emergency medicine (PEM) physicians supporting its use compared with fewer than half of surveyed surgeons.[9] Both groups agree that FAST is useful in certain patients and believe that an ultrasound machine should be available in the trauma bay.[9] Further study is needed to determine the best use of FAST in pediatric trauma algorithms.

We conducted a systematic review and meta-analysis to evaluate the utility of Point of Care Ultrasound (POCUS) FAST in the diagnosis of IAI in pediatric blunt abdominal trauma patients. Past reviews of FAST in pediatric trauma concluded that its utility in routine use was questionable.[8] However, previous studies published on this topic were heterogeneous both in design and in training of the ultrasound operator (including radiologists and sonography technicians).[10–22] Specifically, we were interested in whether a negative POCUS FAST result performed at the bedside by PEM, emergency medicine (EM), or surgical physicians in pediatric blunt abdominal trauma patients could obviate the need for CTs, observation or more invasive testing.

METHODS

Study Design

We conducted a systematic review of studies that examined the utility of POCUS FAST by EM, PEM, or surgical physicians in pediatric blunt trauma patients. The systematic review was conducted using the Preferred Reporting Items for Systematic Review and Meta-analyses.[23]

Search Strategy

The design and manuscript structure of this systematic review conforms to the recommendations from the Meta-analysis of Observational Studies in Epidemiology statement.[24] In conjunction with a medical librarian, we independently searched the medical literature from January 1968 to March 2018 in PubMed, EMBASE, and Web of Science (WOS) for the search terms relating to the use of FAST in pediatric trauma. Abstracts from the Pediatric Academic Societies, American Academy of Pediatrics, Society of Academic Emergency Medicine, and American College of Emergency Physicians meetings from 2013 to 2018 were also searched.

From the *Department of Emergency Medicine, State University of New York/SUNY Downstate Medical Center; and †Department of Emergency Medicine, Kings County Hospital Center, Brooklyn, NY.
Disclosure: The authors declare no conflicts of interest.
Reprints: Tian Liang, MD, Department of Emergency Medicine, Kings County Hospital Center, 451 Clarkson Ave, Room CG27A, Brooklyn, NY 11203 (e-mail: tianzliang@gmail.com).

ISSN: 0749-5161

In PubMed, we searched under MeSH terms for hemorrhage, bleeding, sensitivity, specificity, ultrasound, and ultrasonography. In EMBASE, we searched for "focused assessment with sonography for trauma," bleeding, sensitivity, specificity, diagnostic value, and predictive value. In the WOS, we searched for terms related to "focused assessment with sonography for trauma" and bleeding. The searches were combined and limited by human subjects, pediatric patients, and English language titles.

Studies were included if they examined pediatric patients who underwent a FAST after blunt trauma, and if the FAST was completed and interpreted by PEM, EM, or surgical staff at the bedside. Studies were excluded if they did not provide sufficient data to construct a 2 × 2 table. Narrative review, case-control studies, retrospective studies, case reports, and studies with FAST examinations performed by radiology staff were excluded.

Types of Participants

We included studies that investigated the utility of FAST in pediatric patients presenting to the emergency department (ED) after blunt trauma. We excluded studies of patients who died in the ED, were hemodynamically unstable, or met the criteria for emergent surgical exploration (ie, peritoneal signs and central nervous system injury).

Type of Index Tests

We included studies that used POCUS FAST as index tests for pediatric trauma. Studies that used FAST were only included if performed and interpreted by PEM, EM, or surgical staff at the bedside. For FAST, any amount of free fluid in any of the 3 windows (hepatorenal, splenorenal, suprapubic) was considered positive.

Type of Reference Standard

We included studies that diagnosed the presence or absence of IAI as the reference standard by either CT scans, laparotomy, hospital observation, and/or outpatient follow-up to confirm the FAST results. We considered a CT scan as positive IAI for any evidence of free fluid. We defined a laparotomy as positive IAI with any degree of hemoperitoneum. Because we are writing from an EM perspective, we did not further differentiate our definition of a positive laparotomy into surgeries ultimately judged to be therapeutic (surgically repaired injury) or nontherapeutic.

Data Abstraction

Three authors independently selected articles from the combined PubMed/EMBASE/WOS search for full-text review. Using the previously mentioned inclusion and exclusion criteria, each reviewer independently selected potentially eligible studies. Differences were resolved by consensus before a final list of included studies was developed.

Quality Assessment

The methodological quality of the studies was assessed using the Quality Assessment Tool for Diagnostic Accuracy Studies (QUADAS-2) by 2 investigators (T.L., E.R.) who individually rated each study.[25] The last author (R.S.) resolved any discrepancies.

Four domains were assessed for biases: (1) patient selection; where the patients enrolled consecutively or randomly? Was a case-control design avoided? Were there inappropriate exclusions? Are there concerns that the included patients and setting do not match the review question? (2) Index test; was the index test interpreted without knowledge of the reference test? Were thresholds for vital signs predetermined for the study? Are there concerns that conduct or interpretation of the index test differs from the review question? (3) Reference standard; does the reference test correctly identify the target condition? Was the reference test interpreted without knowledge of index test results? Are there concerns that the target condition as defined by the reference test not match the question? (4) Flow and timing; could the order of how the index test and reference test were obtained and read introduced bias? Was the reference standard obtained on every patient in the study? Were all patients included in the analysis?

Studies would be considered low risk of bias if all 4 domains were rated no bias. All included studies used either CT or surgical exploratory laparotomy as the reference standard; however, if the reference standard was not clearly defined, that portion of QUADAS-2 was at high risk for bias. Similarly, if execution of the index test was not completely defined, that portion of QUADAS-2 would also be at high risk for bias. Each category is accompanied by a set of "yes" or "no" questions; answering "no" to any question places that portion of the study design at high risk for bias. An unweighted Cohen κ was calculated to measure agreement. Statistical agreement between these 2 reviewers was assessed via a κ analysis using SPSS. A meeting was held between the 2 QUADAS-2 raters and the last author (R.S.) who adjudicated any differences in QUADAS-2 rating.

Data Analysis

We calculated the operating characteristics of the FAST examination as sensitivities, specificities, and likelihood ratios (LRs) based on the construction of 2 × 2 tables for each included study. To compute meta-analysis summary estimates when more than one study assessed the same index test, we combined test characteristic data using a random-effects model with MetaDiSc software.[26] Interstudy heterogeneity was assessed for pooled estimates of the FAST operating characteristics using the DerSimonian-Laird random effect model.

Test-Treatment Threshold Estimates

We used the Pauker-Kassirer method to evaluate the testing and treatment thresholds for CT scans and determined whether POCUS FAST could have sufficient discriminatory power to eliminate the need for CT scan in pediatric blunt trauma ED patients and facilitate patient disposition.[27]

The accuracy and risks associated with CT diagnostic imaging as well as the risk and benefits of treatment were used to estimate the thresholds for testing and treatment for CT scans. Using the operating characteristics of POCUS FAST, we were subsequently able to estimate the posttest probability of a positive FAST by applying Bayes theorem. We compared posttest probabilities of a positive FAST to the testing and treatment thresholds of CT to investigate if the presence or absence of a positive FAST can rule in or rule out IAI without the use of radiology department resources.

RESULTS

We searched the medical literature from January 1966 through March 2018. The PubMed, EMBASE, and WOS searches identified 752 citations that involved POCUS and pediatric trauma (Fig. 1). Upon review of bibliographies, 11 additional citations were added for consideration. After removal of 22 duplicates, we assessed the 741 remaining citations for inclusion. We removed 698 articles based on title or abstract, leaving 43 for full-text evaluation. We further excluded studies with mixed pediatric/adult populations (5), studies with no patient-level data (5), retrospective studies (13), and studies with gross selection bias (POCUS was completed by someone other than an PEM, EM, or surgical physician) (12).

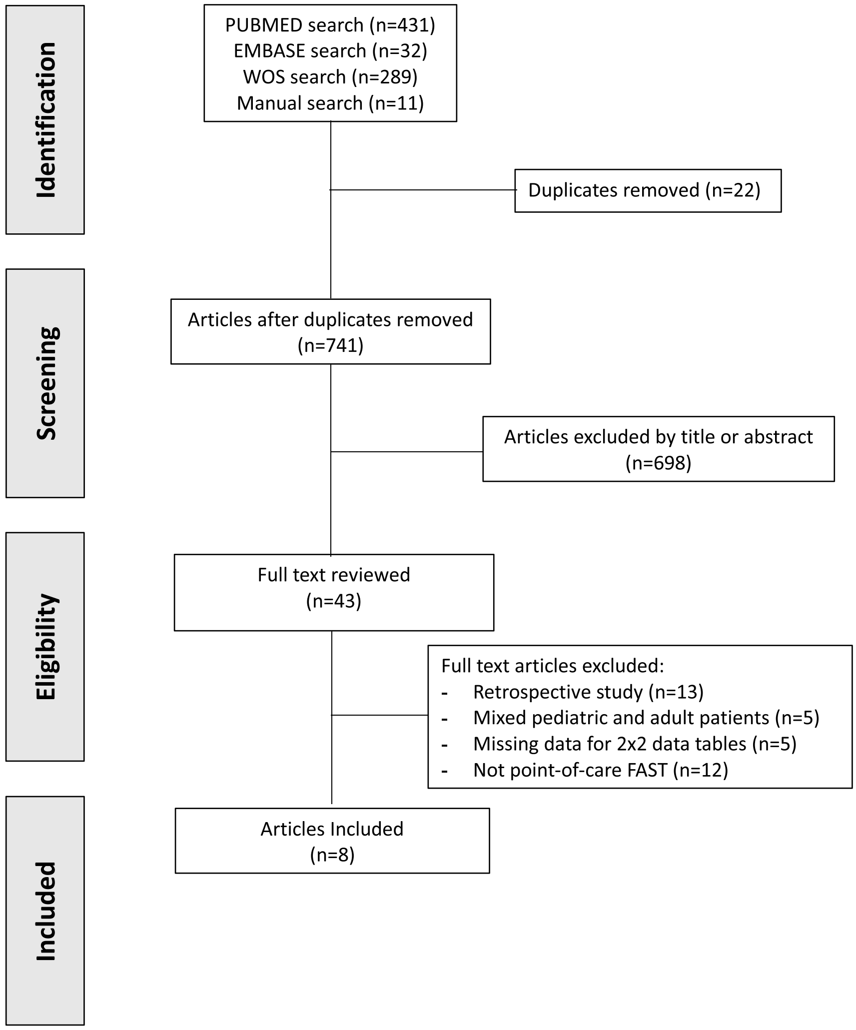

FIGURE 1. Study selection process.

We identified 8 prospective, pediatric-only studies for inclusion in our systematic review/meta-analysis.[9,28–34] Study selection process is detailed in Figure 1.

The combined population from 8 studies was 2135, of which 289 were diagnosed with IAI. The individual prevalence of IAI ranged from 5.2% to 29.7%.[9,28] The weighted prevalence based on the entire 2135 patients assessed in this systematic review/meta-analysis was 13.5%.

In Table 1, we identify the primary descriptions for the 8 studies evaluated in this systematic review/meta-analysis.[9,28–34] Age inclusion criteria varied between an upper limit of 13 years by Tummers et al[32] to 18 years by Corbett et al,[29] Scaife et al,[9] and Holmes et al.[34] The mechanism of injuries used for inclusion was defined by 4 studies as all patients who required trauma activation, but the exact policies governing this level of alert were not stated.[9,29,31,33] Thourani et al[28] used "suspected of abdominal injury," and Suthers et al[30] included subjects with both blunt and penetrating injuries. Holmes et al[34] was the most specific in including Glasgow Coma Scale (GCS), motor vehicle collision, and other injury presentations as their subject entry criteria.

Exclusion criteria were not specified in Thourani et al,[28] Suthers et al,[30] and Fox et al.[31] Penetrating trauma was excluded by Scaife et al,[9] Calder et al,[33] and Holmes et al.[34] Transfers from other institutions were excluded by Scaife et al[9] and Holmes et al.[34] Holmes et al[34] and Tummers et al[32] were the only studies that specifically excluded hypotensive patients, but we expect most of our studies also operationalized if not explicitly state that hypotensive patients were evaluated outside their study protocols.

Sample size ranged from 47 to 816 patients.[29,33] Mean ages ranged from 6.9 to 9.8 years.[28,30] Most subjects were male ranging from 62% to 67%.[28,30,34]

Operators and interpreters of FAST examinations were surgical residents/attendings in 5 of our reviewed studies.[9,28,30,32,33] Emergency medicine attendings or residents performed POCUS in 2 studies,[29,34] with 1 study used a mixture of EM residents/attendings and surgeons.[31] One study also included medical students who completed a training course in POCUS FAST.[32]

Training for FAST examinations was not specified by Calder et al.[33] Studies by Holmes et al[34] and Fox et al[31] met or exceeded the American College of Emergency Physicians guideline for ultrasound competency. Corbett et al[29] based their 8-hour course on the Society for Academic Emergency Medicine ultrasound guidelines. Scaife et al,[9] Thourani et al,[28] and Suthers et al[30] developed their own course based on 30, 50, and 50 FAST examinations,

TABLE 1. Descriptions of Reviewed Studies

Study	Patient Characteristics	Point-of-Care US	Gold Standard	IAI Prevalence (95% CI), %
Thourani et al[28]	Inclusion criteria: • Age <15 y • Abdominal injury Exclusion criteria • Not specified Sample size • 192 FAST examinations Mean age • 6.9 y. (range, 3 mo–14 y) Sex • 62% (M)	Operator • Surgery residents • Trauma fellows • Surgery attending Interpreter • Surgery attending	Observation (n = 132) CT scan (n = 56) OR (n = 4)	5.21 (2.74–9.44)
Corbett et al[29]	Inclusion criteria • Age <18 y • Trauma activations or consults Exclusion criteria • Minor trauma Sample size • 47 FAST examinations Mean age • 9 y (range, 5–13 y) Sex • Not specified	Operator • EM residents (71%) • EM attendings (29%) Interpreter • All scans by both ED and radiology attendings (blinded)	Observation (n = 0) CT scan (n = 42) OR (n = 5)	25.5 (15.1–39.6)
Suthers et al[30]	Inclusion criteria • Age <17 y • Blunt and penetrating Exclusion criteria • Not specified Sample size • 118 FAST examinations Mean age • 9.8 y (±5 y) Sex • 67% (M)	Operator • Surgery attendings • Surgery residents Interpreter • Operator	CT scan (n = 118)	22.9 (16.2–31.3)
Fox et al[31]	Inclusion criteria • Age <17 y • Trauma activations or consults Exclusion criteria • Not specified Sample size • 357 FAST examinations Mean age • 0–2 y (9.5%), 2–6 y (24.6%), 7–12 y (22.1%), 13–17 y (43.7%) Sex • 64% (M)	Operator • EM residents (62%) • EM attendings (21%) • US fellows (8%) • Surgeons (8%) Interpreter • Operator	Observation (n = 0) CT scan (n = 357) OR (n = 0)	26.1 (21.8–30.9)
Scaife et al[9]	Inclusion criteria • Age <18 y • Trauma activations or consults Exclusion criteria • Transfers • Penetrating trauma Sample size • 74 FAST examinations Mean age • 7 y (IQR, 2–12 y) Sex • Not specified	Operator • Surgery attendings Interpreter • Operator	Observation (n = 0) CT scan (n = 74) OR (n = 0)	29.7 (20.5–41.0)

Continued next page

TABLE 1. *(Continued)*

Study	Patient Characteristics	Point-of-Care US	Gold Standard	IAI Prevalence (95% CI), %
Tummers et al[32]	Inclusion criteria • MVC without seat belt (>35 km/h) • MVC with seat belt (45 km/h) • Vehicle displacement of >7 m • Ejection from car • Fall from height (>3 m) • Pedestrian struck • Age <13 y Exclusion criteria • Hemodynamic instability Sample size • 75 FAST examinations Mean age • 5.4 y (range, 3 mo–13 y) Sex • 64% (M)	Operator • Surgeon or medical student trained in FAST Interpreter • Operator	Observation (n = 67) CT scan (n = 8) OR (n = 1)	13.3 (7.2–23.0)
Calder et al[33]	Inclusion criteria • Age <16 y • Trauma activations or consults Exclusion criteria • Penetrating/burn/hanging/fall/Isolated head/extremity • >6 h from injury Sample size • 816 FAST examinations Mean age • Average 7.8 ± 4.6 y Sex • Not specified	Operator • Surgery resident Interpreter • Operator	Observation (n = 476) CT scan (n = 340)	11.2 (9.2–13.5)
Holmes et al[34]	Inclusion criteria • Age <18 y • GCS < 15 • MVC (>60 mph), ejection or rollover • Pedestrian or bicyclist vs automobile • Extremity paralysis • Multiple long bone fractures Exclusion criteria • Transfers • GCS < 9 • Hypotension • Penetrating trauma • >24 h from presentation Sample size • 456 FAST examinations Mean age • 9.7 (±5.3 y) Sex • 62% (M)	Operator • ED attendings Interpreter • Operator read	Observation (n = 249) CT scan (n = 241) OR (n = 7) Telephone follow-up (n = 126) EMR (n = 88)	5.3 (3.5–7.7)

EMR indicates electronic medical record (some patients were followed up with record of the electronic record after discharge; IQR, interquartile range; MVC, motor vehicle collision; OR, odds ratio (laparostomy/laparotomy); US, ultrasound.

respectively, followed by competency examinations. Interobserver reliability of FAST examinations was only measured by Corbett et al[29] with a $\kappa = 0.56$.

The primary outcome for our reviews was the presence or absence of IAI. We allowed studies in our review to use either, CT scans, laparotomy/laparoscopy (operating room [OR]), in-hospital observation, or outpatient follow-up as our gold standard for IAI. We did not further differentiate therapeutic from nontherapeutic laparotomy. Two studies exclusively used CT as the gold standard.[9,30] Six studies used a combination of CT scans, inpatient observation, or OR.[28,29,31,32–34] Holmes et al[34] also included telephone and electronic medical records follow-ups to CT, observation, and OR.

We calculated operating statistics for FAST including sensitivity, specificity, positive LR (LR+), and negative LR (LR−) in all 8 studies by organizing 2 × 2 tables from available patient-level data and compared our results with those published (Table 2). Holmes et al[34] did not publish operating characteristics but provided them directly to be included in our meta-analysis. We adjusted data where necessary to affect the most conservative approach to FAST in pediatric blunt trauma. Scaife et al[9] removed "inconclusive" FAST for non-IAI, which we added back as false

TABLE 2. Operating Characteristics of FAST Examination

Studies	Sample Size	Sensitivity (95% CI)	Specificity (95% CI)	LR+ (95% CI)	LR− (95% CI)
Thourani et al[28]	192	80% (44%–97%)	100% (98%–100%)	282.82 (17.4–4588.6)	0.23 (0.08–0.68)
Corbett et al[29]	47	75% (43%–95%)	97% (85–99%)	26.25 (3.7–108.2)	0.26 (0.10–0.69)
Suthers et al[30]	118	70% (50%–86%)	100% (96%–100%)	128.14 (7.9–2055.4)	0.31 (0.17–0.54)
Fox et al[31]	357	20% (13%–30%)	98% (95%–99%)	8.99 (3.7–21.8)	0.81 (0.73–0.90)
Scaife et al[9]	74	36% (17%–59%)	77% (63%–87%)	1.58 (0.80–3.3)	0.83 (0.58–1.17)
Tummers et al[32]	75	50% (19%–81%)	100% (94%–100%)	66.00 (3.9–1111.5)	0.50 (0.28–0.91)
Calder et al[33]	816	29% (20%–39%)	96% (95%–98%)	7.67 (4.7–12.5)	0.74 (0.65–0.85)
Holmes et al[34]	456	25% (10%–47%)	93% (91%–95%)	3.72 (1.7–8.1)	0.80 (0.64–1.01)
Heterogeneity (I^2)		84%	89%	81%	79%
Pooled values	2135	35% (29%–40%)	96% (95%–97%)	10.84 (4.36–26.92)	0.64 (0.51–0.80)

negatives. With Holmes et al,[34] we added "indeterminate" FAST for IAI as false negatives. Similarly, we added "indeterminate" FAST for non-IAI as false positive. Calder et al[33] included hypotensive patients, which we removed altogether. The remaining 5 studies reported operating statistics that matched our own calculations.[28–32] Sensitivities for FAST examinations varied widely among the 8 included studies ranging from 20% to 80%.[28,31] The 3 oldest studies[28–30] reported higher sensitivities (range, 70% to 80%) compared with the 5 more recent studies (range, 20% to 50%).[9,31–34]

Pooled operating characteristics across the 8 studies are outlined in Table 2. Overall sensitivity of our analysis is 35% (95% confidence interval [CI], 29%–40%). Five of the 8 studies fell within this CI.[9,31–34] The 3 of the earliest published studies all had higher sensitivities that fell outside our pooled CI.[28–30] The pooled specificity of our analysis is 96% (95% CI, 95% to 97%), with one study falling above the CI[28] and 1 falling below.[9]

We have one outlier in our LR calculations, which is the LR+ for Scaife et al.[9] This study also found a POCUS FAST specificity falling below the pooled CI[9] (Table 2). Three studies also had LR+ higher than 50.[28,30,32] All had a POCUS FAST specificity of 1.00, which subsequently lead to very high positive LR+ in these calculations. All of the negative LR− calculations for the studies fell within our pooled LR− of 0.64 (95% CI, 0.51–0.80). Interstudy heterogeneity (I^2) was high and ranged between 79% and 84% across operating characteristics.(Table 2)

QUADAS-2 analysis was completed by 2 reviewers (E.R., T.L.) who demonstrated strong interrater reliability (κ = 0.69). All authors agreed 100% on the final QUADAS-2 scoring as demonstrated in Table 3.

Patient Selection

None of our studies were a retrospective study design, and all avoided a case-control methodology. However, patient selection was a source of bias in many of our studies. None of these authors explicitly acknowledged convenience sampling or discussed unavoidable exclusions. The study by Corbett et al[29] was the only to acquiesce to this sampling bias directly by citing the lack of trained sonographers as an unavoidable exclusion. Thourani et al,[28] Scaife et al,[9] Fox et al,[31] and Calder et al[33] all enrolled patients based on trauma activations, consults, or admissions and thus missed low-risk nonactivations treated primarily by ED physicians.

Exclusion criteria were not specified by Thourani et al,[28] Suthers et al,[30] and Fox et al.[31] The other 5 studies excluded studying subjects at very high risk for IAI, which we deemed inappropriate for FAST examinations before operative intervention.[9,29,32–34] Scaife et al[9] excluded those children with open abdominal wounds and transfers from nontrauma centers. Tummers et al[32] excluded "hemodynamically unstable" patients defined as "lack of adequate tissue perfusion, resulting in the need for transfusion of >20 mL/kg of fluid." Holmes et al[34] excluded patients with "seat belt sign," transfers, prehospital or ED age-adjusted hypotension, and patients with GCS <9. Calder et al[33] included hypotensive patients, which

TABLE 3. Quality Assessment With QUADAS-2 Instrument

Study	Thourani et al[28]	Corbett et al[29]	Suthers et al[30]	Fox et al[31]	Scaife et al[9]	Tummers et al[32]	Holmes et al[34]	Calder et al[33]
Risk of bias								
Patient selection	Low	Low	Low	Unclear	Low	Low	Low	Low
Index test	Low	Low	Low	Low	Low	Low	Low	Unclear
Reference standard	Low	Low	Low	Low	Low	Unclear	Low	Unclear
Flow and timing	High	High	Low	High	Low	Low	High	High
Applicability concerns								
Patient selection	Low	Low	Low	Low	Low	Low	Low	Low
Index test	Low	Low	Low	Low	Low	Low	Low	Unclear
Reference standard	Low	Low	Low	Low	Low	Low	Low	Low

QUADAS-2 assessment of included studies.

we subsequently removed from provided patient-level data to be included in this review.

Patients with high-risk mechanisms or unstable vital signs have a higher pretest probability for positive FAST. Their inclusion in studies evaluating FAST results in a type of spectrum bias, which falsely elevate sensitivities making FAST seem more valuable as a rule out tool for IAI.[35] The studies in this review all avoided inclusion of very high-risk patients, which minimizes any potential spectrum bias. It allows us to generalize operating characteristics found here across all low-risk populations, which we believe is the most appropriate setting for the FAST examination in pediatric blunt trauma.

Index Test

Each study in this review had the index test (FAST) performed as part of the initial patient assessment. The results from the FAST examinations were considered positive if any amount of free fluid was detected in hepatorenal, splenorenal, suprapubic windows. Two studies found a small percentage of index tests to be "indeterminate" or "inconclusive."[9,34] These authors excluded such results from the statistical analysis, which opens them to a similar type of spectrum bias discussed earlier.[35] Exclusion of FAST examinations for patients with IAI inaccurately raises sensitivity, whereas exclusion of FAST for non-IAI patients raises specificity. As discussed earlier, we addressed this spectrum bias by results by counting inconclusive FAST for non-IAI as false negatives and inconclusive FAST for IAI as false positive. In doing so, we knowingly skewed sensitivity and specificity down, which we believe reflects a more conservative and cautious approach for evaluating FAST in pediatric blunt trauma.

Reference Standard

This review included studies with 3 different reference standards: CT, laparoscopy, and observation. The inclusion of multiple reference tests introduces an imperfect gold standard bias. As described by Kohn et al,[35] an imperfect gold standard bias occurs when there are multiple gold standards that do not equally categorize a patient as disease positive or negative. With respect to this meta-analysis, laparotomy seems to be the clear gold standard regarding diagnosis of IAI. Computed tomography is likely a close second "silver standard," as it is excellent at diagnosing free air, solid organ injury, and free fluid. However, CT scan can still miss hollow viscus injuries at time zero that would otherwise be diagnosed by laparotomy. Observation is likely a "bronze standard," as it will routinely miss patients with IAI who had a negative FAST result at time zero, which ultimately resolved during the course of observation. Similarly, if the observation period is inadequate or patients are lost to follow-up, it will miss patients with negative FAST results that subsequently developed IAI during the course of observation. The FAST results in either of these scenarios would be counted as true negative instead of false negatives, which inaccurately raises both sensitivity and specificity. Most patients in these combined studies underwent CT imaging as their reference standard. Observation was used by Thourani et al,[28] Corbett et al,[29] Tummers et al,[32] Calder et al,[33] and Holmes et al,[34] and all of which are subject to imperfect gold standard bias.

Flow and Timing

The most obvious source of bias in this review is related to flow and timing. The very nature of FAST is such that it can be performed quickly as part of a primary survey, well in advance of any other diagnostic tests. Furthermore, the results are interpreted in real time, which then serve to guide the subsequent course of care. This opens every study in this review to both partial and differential verification bias. Partial verification applies to studies with a single gold standard for which patients with a positive index are more likely to get the gold standard and only patients who got the gold standard were included in the analysis. Scaife et al[9] and Suthers et al[30] both suffer from partial verification bias, given that they only included patients who received both FAST and CT. These studies both likely excluded patients with a negative FAST result who never got a follow-up CT, which has the potential to inflate sensitivity.

Differential verification bias applies to studies with multiple gold standards for which the results of the index test influence the type of gold standard subsequently used. Patients with a positive index are more likely to receive an immediate, invasive reference test (ie, CT or Laparotomy), whereas patients with a negative index are more likely evaluated with noninvasive follow-up (ie, observation). Thourani et al,[28] Tummers et al,[32] Calder et al,[33] and Holmes et al[34] all used observation for patients with negative FAST examination results, which has the potential to inflate sensitivity in cases where IAI was missed at time zero and then resolved spontaneously or developed after the observation period. Thourani et al[28] and Tummers et al,[32] for example, only observed patients during their hospital stay. Holmes et al[34] contacted patients 1 week after discharge but were unable to follow up with 178 (41%) of 425 patients. Calder et al[33] endorsed "follow-up" 30 days after discharge and suggested "no documented missed injuries" but failed to specify the type of follow-up or whether any patients were unreachable.

Test-Treatment Threshold Estimates

The test-treatment threshold model we developed was designed to aid physicians to rule in or rule out IAI. We built this model to investigate if the pediatric FAST examination had sufficient discriminatory power given the pretest probability of IAI to obviate a CT scan of the abdomen. In Figure 2, we created a test-treatment threshold model using an abdominal CT scan to diagnose IAI.

For an abdominal CT scan result, a set of test and treatment thresholds were defined across a range of 0% to 100%. Based on the work of Pauker and Kassirer,[27] this model used the unique operating characteristics of an abdominal CT scan while controlling for the risks of treatment for patients without IAI (Rrx), the risk of the diagnostic test, and the benefit of treatment (Brx) of a patient with IAI.

We used the data from Ellison et al[36] to estimate the operating characteristics of abdominal CT scans in diagnosing IAI. Ellison et al reviewed the abdominal CT scans of 5276 pediatric blunt torso trauma patients, of which 4897 had documented use or nonuse of oral contrast. In this study, the prevalence of IAI was 14%, very similar to our studies' weighted prevalence of 13.5%. In our test-treatment threshold model, we chose 2 CT scan models, one with oral contrast (sensitivity 97.7%/specificity 84.7%) and without oral contrast (sensitivity 98%/specificity 81%).

We judged the risk of the diagnostic test of the CT scan as 0.00023. This risk is based on the lifetime risk of radiation-induced cancer after a single abdominal CT scan in a 5-year-old as reported by Wan et al[37] (20/100,000 in male patients and 26/100,000 in female patients).

We defined Rrx as the risk of developing complications after nontherapeutic laparotomy. We chose the risk of specifically nontherapeutic laparotomy to be the most conservative estimate of risk from a surgical exploration, which did not result in the repair of a significant injury. In a nontherapeutic laparotomy, the patient receives all the risk of the procedure but none of the potential benefits. Tharakan et al[38] reviewed 16,321 pediatric trauma

$T_{\text{testing threshold}}$ =[(Ppos/nd) x (Rrx) + Rt] ÷ [(Ppos/nd x Rrx) + (Ppos/d x Brx)]
$T_{\text{treatment threshold}}$ =[(Pneg/nd) x (Rrx) - Rt] ÷ [(Pneg/nd x Rrx) + (Pneg/d x Brx)]

Sensitivity: CT scan with Oral Contrast = 97.7% CT scan without Oral Contrast = 98%
Specificity: CT scan with Oral Contrast = 84.7% CT scan without Oral Contrast = 81%

Ppos/nd = probability of a positive result in patients without disease = 1-specificity
Pneg/nd = probability of a negative result in patients without disease = specificity
Rrx = risk of treatment in patients without disease = 0.012 (risk of non-therapeutic laparotomy)
Rt = risk of diagnostic test = 0.00026
Ppos/d = probability of a positive result in patients with disease = sensitivity
Pneg/d = probability of a negative result in patients with disease = 1 – sensitivity
Brx = benefit of treatment in patients with disease = 0.9

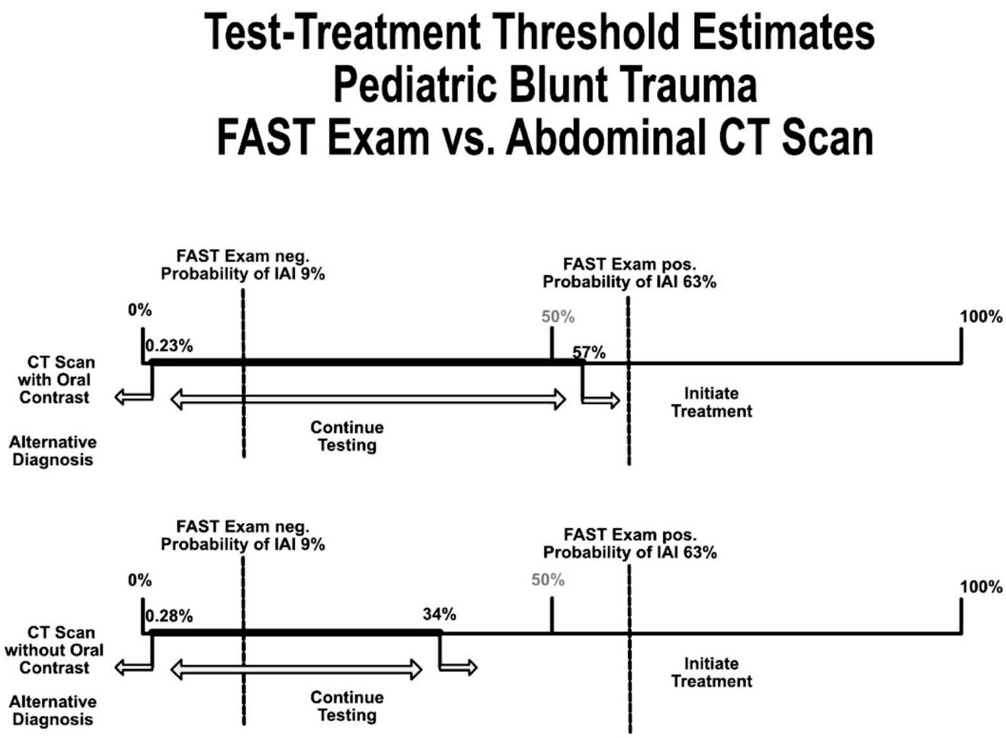

FIGURE 2. Test-treatment threshold model.

admissions over a 13-year period at a level 1 pediatric trauma center. Of the 119 patients (0.7%) who required surgical exploration, 14 patients (11.8%) had nontherapeutic laparotomies. Complications from nontherapeutic laparotomies after trauma were estimated to be 10% due to the procedure by Schnuriger et al.[39] Because the probability of a nontherapeutic laparotomy was 11.8% with a complication rate of 10%, we estimated Rrx to be 1.2%.

Finally, the Brx of patients with IAI has never been or ever will be tested by a randomized, double-blinded placebo-controlled methodology; it would be unethical to study the spontaneous recovery rate of IAI without surgery. Without evidence-based studies, we used a conservative estimate of the benefit from treating IAI (Brx) = 0.90.

The test thresholds are depicted as the leftmost open arrow for each diagnostic modality with oral contrast (0.23%) and without oral contrast (0.28%). If the posttest probability of the index test we choose from our systematic review (dashed vertical line) falls left of the test threshold, further testing for IAI is not warranted, and an alternative diagnosis other than IAI should be considered. The treatment thresholds are represented by the rightmost open arrow for each diagnostic modality with oral contrast (57%) and without oral contrast (34%). When the posttest probability of our index test is to the right of the treatment threshold, further testing is unnecessary, and treatment should be initiated based only on the results of our index test. If the posttest probability of our index test falls between the test and treatment thresholds, then our analysis recommends continued testing with that diagnostic modality for IAI. The horizontal dashed lines represent the ranges of posttest probabilities of a positive or negative pediatric FAST examination result consistent with IAI.

We used our pooled positive and negative LRs for POCUS FAST in our test-treatment models (Fig. 2). Applying Bayes Theorem, using the weighted prevalence of IAI (13.5%) across our studies as the pretest probability of IAI and the range of LR+ (10.84) and LR− values (0.64), we can calculate a range of posttest probabilities. If the POCUS FAST examination result is positive, then the posttest probability of IAI would be 63%. Back-calculating to our posttest probability greater than our treatment threshold of 57% would require an LR of >8.0, which was found in 5 of 8 of our reviewed studies.[28–31] For a negative FAST examination result, the posttest probability would be 9%, higher than the test-treatment threshold of 0.23%. None of our studies had sufficiently low LR− to obviate testing with an abdominal CT scan, continued observation, or laparotomy/laparoscopy.

DISCUSSION

Our systematic review examined the utility of the POCUS FAST examination in pediatric blunt trauma for the diagnosis of IAI and found that a negative FAST result alone cannot obviate the need for further testing to rule out IAI. Eight studies of moderate quality met our inclusion/exclusion criteria for our review.[9,28–34] All studies were prospective in design with FAST examinations performed at the bedside by emergency and/or surgical physicians.

Compared with a previous systematic review on pediatric FAST by Holmes et al,[8] we used more rigorous inclusion/exclusion criteria, including only prospective studies, and only FASTs performed point of care by emergency or surgical physicians. Holmes et al included 25 studies, and more than half were retrospective in design (14/25) and had FAST performed by radiologists or sonographers (18/25).[8] A majority (5/8) of the studies included in our analysis were done after the publication of Holmes et al.[9,31–34] The remaining 3 studies[28–30] are included in both reviews. One study by Soundappan et al[40] included by Holmes et al was a prospective study of FAST performed by a surgeon. However, the FAST was interpreted by a pediatric radiologist and thus excluded from our systematic review.

Our results also found that FAST had better specificity compared with sensitivity, which is consistent with the results in the systematic review by Holmes et al.[8] Our pooled sensitivity of 35%, however, was much lower than that of Holmes et al, 66%, for identifying any IAI with FAST. When Holmes et al[8] only included prospective studies, the sensitivity decreased to 55%, but still higher than our finding of 35%. This prospective analysis included studies with radiologists performing FAST examinations, who typically have more training in ultrasonography compared with emergency or surgical physicians, and may explain the lower sensitivity appreciated in this review.

Our analysis excluded unstable patients including patients with hypotension and hemorrhage, which also likely contributed to the differences in our sensitivity analysis. Including unstable patients would likely increase the number of true-positive results of the FAST and thus improve sensitivity.

Holmes et al found a pooled specificity of 93% in identifying any IAI with FAST and 97% when only including prospective studies.[8] This is comparable to our pooled specificity of 96%. He found LR+ values of 9.8 and 19.3 in all studies and prospective studies, respectively, compared with our pooled LR+ of 10.8. His LR− values of 0.37 and 0.46 are lower than our LR− of 0.64.[8]

The FAST tool is well studied in the adult population and is an integral part in many adult trauma protocols.[41] Published sensitivity values of FAST in detecting IAI range from 22% to 98%, and a negative FAST result can obviate the need for CT in some adult patients.[42,43] A high false-negative rate of FAST in blunt abdominal trauma can be partially attributed to a significant portion of blunt IAI in both adults and children that do not show hemoperitoneum.[44,45] Up to 37% of blunt IAI in children do not show peritoneal fluid.[44] This highlights the need for additional data points in addition to the FAST in determining workup and disposition.

In children suspected of having IAI after blunt abdominal trauma (pretest probability of 13.5%) and a positive POCUS FAST result, our test-treatment threshold model (Fig. 2) estimates a posttest probability of IAI of 63%. Therefore, a positive POCUS FAST result indicates that an IAI is likely and the patient should undergo further trauma management, which includes extended observation, repeat FAST, CT scans, and/or exploratory laparotomy/laparoscopy as clinically indicated. A negative POCUS FAST result decreases the posttest probability to 9%, which is higher than the posttest probability of 0.23% to 0.28% needed to obviate the need for further testing to rule out IAI. Accurately diagnosing IAI in an emergency setting requires multiple data points including history, physical examination, laboratory tests, and/or imaging. Our analysis shows that POCUS FAST alone cannot be used alone in ruling out IAI in pediatric blunt abdominal trauma.

Clinical decision rules such as the Pediatric Emergency Care Applied Research Network Pediatric Head Injury/Trauma or National Emergency X-Radiography Utilization Study criteria for cervical spine imaging were designed to reduce unnecessary testing and radiation exposure for patients during their medical care.[46,47] These rules use multiple criteria to identify low-risk patients that may be observed or discharged without further imaging.

Holmes et al[48] developed a clinical decision rule with 7 criteria (physical evidence of abdominal wall trauma, GCS, abdominal tenderness, physical evidence of thoracic trauma, abdominal pain, abnormal breath sounds on auscultation, and vomiting) to identify low-risk patients in pediatric blunt abdominal trauma. This study found that children with blunt torso trauma without evidence of abdominal wall trauma or seatbelt sign, GCS of 14 to 15, and no abdominal tenderness on examination had a 0.3% pretest probability of an IAI requiring intervention (defined by death caused by IAI, therapeutic laparotomy, angiographic embolization, blood transfusion for intra-abdominal hemorrhage, or administration of intravenous fluids for 2 or more nights).[48] Applying our POCUS FAST LR− of 0.64 to this pretest probability (0.3%) in low-risk pediatric blunt abdominal trauma yields a posttest probability of 0.2%, which is below the lower limit in our test-treatment threshold model (Fig. 2) for both CT scan with intravenous contrast only (0.28%) and intravenous/oral contrast (0.23%) in diagnosing IAI. In other words; a pediatric blunt abdominal trauma patient presenting without physical evidence of trauma, a normal GCS, no abdominal tenderness, and a negative POCUS FAST result may not need further workup for IAI because the risk of harm from testing in this patient outweighs the probability of identifying a condition requiring intervention.

Limitations

We excluded all studies in languages other than English, which can decrease the generalizability of the findings. Our search criteria were imperfect and did not identify one of the studies included in our analysis.[32]

CONCLUSIONS

In hemodynamically stable pediatric patients presenting to the ED with blunt abdominal trauma, a negative POCUS FAST examination result alone cannot preclude further workup for IAI. A positive POCUS FAST result shows that IAI is likely and may obviate the need for a CT scan to proceed to the OR directly. A negative POCUS FAST result in a child presenting with blunt abdominal trauma with a normal GCS and normal abdominal examination result may obviate the need for further testing to identify clinically important IAI.

Areas for Future Research

Although our conclusions show that a negative POCUS FAST result alone cannot obviate the need for further workup for IAI in pediatric blunt abdominal trauma, there is potential for POCUS FAST to be used in addition to other clinical and laboratory findings together to identify low-risk patients that can be safely observed or discharged without additional testing. Creation of a clinical decision tool that incorporates POCUS FAST in the evaluation of pediatric blunt trauma is an area for further investigation.

One advantage of FAST as an imaging modality is its ease of use and repeatability. The studies in this review all performed POCUS FAST at the initial evaluation of the patient. There is evidence that serial FAST examinations raise the sensitivity in detecting IAI.[49,50] In addition, a significant number of solid organ injuries are missed by FAST because they often present without concomitant hemoperitoneum.[44] Contrast-enhanced ultrasound technology can help improve detection of these injuries that traditional ultrasound may miss.[51] Further investigation into these methods and technologies can give more clarity into the best role of FAST in trauma algorithms and protocols.

ACKNOWLEDGMENT

The authors thank Christopher Stewart, senior assistant librarian at SUNY Downstate Medical Center, for his help in formulating the literature searches, and Dr. James F. Holmes MD, MPH, for his help in providing operating characteristics of POCUS FAST in his pediatric trauma research.

REFERENCES

1. Murphy SL, Xu JQ, Kochanek KD, et al *Deaths: Final Data for 2015. National Vital Statistics Reports. Vol. 66, No. 6*. Hyattsville, MD: National Center for Health Statistics:2017.
2. Committee on Trauma, American College of Surgeons. *NTDB Annual Pediatric Report*. Chicago, IL; 2016. Available at: https://www.facs.org/~/media/files/quality%20programs/trauma/ntdb/ntdb%20pediatric%20annual%20report%202016.ashx. Accessed September 15, 2018.
3. Miller TR, Romano EO, Spicer RS. The cost of childhood unintentional injuries and the value of prevention. *Future Child*. 2000;10:137–163.
4. Holmes JF, Sokolove PE, Brant WE, et al. Identification of children with intra-abdominal injuries after blunt trauma. *Ann Emerg Med*. 2002;39:500–509.
5. Whitehouse JS, Weigelt JA. Diagnostic peritoneal lavage: a review of indications, technique, and interpretation. *Scand J Trauma Resusc Emerg Med*. 2009;17:13.
6. Brenner DJ. Estimating cancer risks from pediatric CT: going from the qualitative to the quantitative. *Pediatr Radiol*. 2002;32:228–221; discussion 242–4.
7. Bode PJ, Edwards MJ, Kruit MC, et al. Sonography in a clinical algorithm for early evaluation of 1671 patients with blunt abdominal trauma. *AJR Am J Roentgenol*. 1999;172:905–911.
8. Holmes JF, Gladman A, Chang CH. Performance of abdominal ultrasonography in pediatric blunt trauma patients: a meta-analysis. *J Pediatr Surg*. 2007;42:1588–1594.
9. Scaife ER, Rollins MD, Barnhart DC, et al. The role of focused abdominal sonography for trauma (FAST) in pediatric trauma evaluation. *J Pediatr Surg*. 2013;48:1377–1383.
10. Akgür FM, Tanyel FC, Akhan O, et al. The place of ultrasonographic examination in the initial evaluation of children sustaining blunt abdominal trauma. *J Pediatr Surg*. 1993;28:78–81.
11. Ben-Ishay O, Daoud M, Peled Z, et al. Focused abdominal sonography for trauma in the clinical evaluation of children with blunt abdominal trauma. *World J Emerg Surg*. 2015;10:6.
12. Glaser K, Tschmelitsch J, Klingler P, et al. Ultrasonography in the management of blunt abdominal and thoracic trauma. *Arch Surg*. 1994;129:743–747.
13. Patel JC, Tepas JJ 3rd. The efficacy of focused abdominal sonography for trauma (FAST) as a screening tool in the assessment of injured children. *J Pediatr Surg*. 1999;34:44–47; discussion 52-4.
14. Price RN, Tayal VS. The accuracy of trauma ultrasound in a pediatric population with stratification by age and trauma code status. *Ann Emerg Med*. 2007;50:S2–S2.
15. Retzlaff T, Hirsch W, Till H, et al. Is sonography reliable for the diagnosis of pediatric blunt abdominal trauma? *J Pediatr Surg*. 2010;45:912–915.
16. Richardson MC, Hollman AS, Davis CF. Comparison of computed tomography and ultrasonographic imaging in the assessment of blunt abdominal trauma in children. *Br J Surg*. 1997;84:1144–1146.
17. Roche BG, Bugmann P, Le coultre C. Blunt injuries to liver, spleen, kidney and pancreas in pediatric patients. *Eur J Pediatr Surg*. 1992;2:154–156.
18. Rossi D, de Ville de Goyet J, Clément de Cléty S, et al. Management of intra-abdominal organ injury following blunt abdominal trauma in children. *Intensive Care Med*. 1993;19:415–419.
19. Sirlin CB, Brown MA, Andrade-Barreto OA, et al. Blunt abdominal trauma: clinical value of negative screening US scans. *Radiology*. 2004;230:661–668.
20. Sola JE, Cheung MC, Yang R, et al. Pediatric FAST and elevated liver transaminases: an effective screening tool in blunt abdominal trauma. *J Surg Res*. 2009;157:103–107.
21. Soudack M, Epelman M, Maor R, et al. Experience with focused abdominal sonography for trauma (FAST) in 313 pediatric patients. *J Clin Ultrasound*. 2004;32:53–61.
22. Zhou J, Huang J, Wu H, et al. Screening ultrasonography of 2,204 patients with blunt abdominal trauma in the Wenchuan earthquake. *J Trauma Acute Care Surg*. 2012;73:890–894.
23. Shamseer L, Moher D, Clarke M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. *BMJ*. 2015;347:g7647.
24. Stroup DF, Berlin JA, Morton SC, et al. Meta-analysis of observational studies in epidemiology: a proposal for reporting. Meta-analysis of observational studies in epidemiology (MOOSE) group. *JAMA*. 2000;283:2008–2012.
25. Whiting PF, Rutjes AW, Westwood ME, et al. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. *Ann Intern Med*. 2011;155:529–536.

26. Zamora J, Abraira V, Muriel A, et al. Meta-DiSc: a software for meta-analysis of test accuracy data. *BMC Med Res Methodol*. 2006;6:31.
27. Pauker SG, Kassirer JP. The threshold approach to clinical decision making. *N Engl J Med*. 1980;302:1109–1117.
28. Thourani VH, Pettitt BJ, Schmidt JA, et al. Validation of surgeon-performed emergency abdominal ultrasonography in pediatric trauma patients. *J Pediatr Surg*. 1998;33:322–328.
29. Corbett SW, Andrews HG, Baker EM, et al. ED evaluation of the pediatric trauma patient by ultrasonography. *Am J Emerg Med*. 2000;18:244–249.
30. Suthers SE, Albrecht R, Foley D, et al. Surgeon-directed ultrasound for trauma is a predictor of intra-abdominal injury in children. *Am Surg*. 2004; 70:164–167; discussion 167–8.
31. Fox JC, Boysen M, Gharahbaghian L, et al. Test characteristics of focused assessment of sonography for trauma for clinically significant abdominal free fluid in pediatric blunt abdominal trauma. *Acad Emerg Med*. 2011;18: 476–482.
32. Tummers W, van Schuppen J, Langeveld H, et al. Role of focused assessment with sonography for trauma as a screening tool for blunt abdominal trauma in young children after high energy trauma. *S Afr J Surg*. 2016;54:28–34.
33. Calder BW, Vogel AM, Zhang JW, et al. Focused assessment with sonography for trauma in children after blunt abdominal trauma: a multi-institutional analysis. *J Trauma Acute Care Surg*. 2017;83:218–224.
34. Holmes JF, Kelley KM, Wootton-Gorges SL, et al. Effect of abdominal ultrasound on clinical care, outcomes, and resource use among children with blunt torso trauma: a randomized clinical trial. *JAMA*. 2017;317: 2290–2296.
35. Kohn MA, Carpenter CR, Newman TB. Understanding the direction of bias in studies of diagnostic test accuracy. *Acad Emerg Med*. 2013;20: 1194–1206.
36. Ellison AM, Quayle KS, Bonsu B, et al. Use of oral contrast for abdominal computed tomography in children with blunt torso trauma. *Ann Emerg Med*. 2015;66:107–14.e4.
37. Wan MJ, Krahn M, Ungar WJ, et al. Acute appendicitis in young children: cost-effectiveness of US versus CT in diagnosis—a Markov decision analytic model. *Radiology*. 2009;250:378–386.
38. Tharakan SJ, Kim AG, Collins JL, et al. Laparoscopy in pediatric abdominal trauma: a 13-year experience. *Eur J Pediatr Surg*. 2016;26:443–448.
39. Schnuriger B, Lam L, Inaba K, et al. Negative laparotomy in trauma: are we getting better? *Am Surg*. 2012;78:1219–1223.
40. Soundappan SV, Holland AJ, Cass DT, et al. Diagnostic accuracy of surgeon-performed focused abdominal sonography (FAST) in blunt paediatric trauma. *Injury*. 2005;36:970–975.
41. Richards JR, McGahan JP. Focused assessment with sonography in trauma (FAST) in 2017: what radiologists can learn. *Radiology*. 2017;283:30–48.
42. Carter JW, Falco MH, Chopko MS, et al. Do we really rely on fast for decision-making in the management of blunt abdominal trauma? *Injury*. 2015;46:817–821.
43. Pearl WS, Todd KH. Ultrasonography for the initial evaluation of blunt abdominal trauma: a review of prospective trials. *Ann Emerg Med*. 1996; 27:353–361.
44. Taylor GA, Sivit CJ. Posttraumatic peritoneal fluid: is it a reliable indicator of intraabdominal injury in children? *J Pediatr Surg*. 1995;30:1644–1648.
45. Chiu WC, Cushing BM, Rodriguez A, et al. Abdominal injuries without hemoperitoneum: a potential limitation of focused abdominal sonography for trauma (FAST). *J Trauma*. 1997;42:617–623; discussion 623–5.
46. Kuppermann N, Holmes JF, Dayan PS, et al. Identification of children at very low risk of clinically-important brain injuries after head trauma: a prospective cohort study. *Lancet*. 2009;374:1160–1170.
47. Tran J, Jeanmonod D, Agresti D, et al. Prospective validation of modified NEXUS cervical spine injury criteria in low-risk elderly fall patients. *West J Emerg Med*. 2016;17:252–257.
48. Holmes JF, Lillis K, Monroe D, et al. Identifying children at very low risk of clinically important blunt abdominal injuries. *Ann Emerg Med*. 2013;62: 107–116.e2.
49. Blackbourne LH, Soffer D, McKenney M, et al. Secondary ultrasound examination increases the sensitivity of the FAST exam in blunt trauma. *J Trauma*. 2004;57:934–938.
50. Mohammadi A, Ghasemi-Rad M. Evaluation of gastrointestinal injury in blunt abdominal trauma "FAST is not reliable": the role of repeated ultrasonography. *World J Emerg Surg*. 2012;7:2.
51. Menichini G, Sessa B, Trinci M, et al. Accuracy of contrast-enhanced ultrasound (CEUS) in the identification and characterization of traumatic solid organ lesions in children: a retrospective comparison with baseline US and CE-MDCT. *Radiol Med*. 2015;120:989–1001.