

Accuracy of Point-of-Care Ultrasound for Diagnosis of Skull Fractures in Children

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KEY WORDS

ultrasound, skull fracture, head trauma, pediatrics, emergency medicine

ABBREVIATIONS

CI—confidence interval
CT—computed tomography
ED—emergency department
PEM—pediatric emergency medicine

Dr Rabiner conceptualized and designed the study, collected data, performed statistical analyses, drafted the manuscript, and approved the final manuscript as submitted; Dr Friedman conceptualized and designed the study, collected data, performed initial statistical analyses, drafted the initial manuscript, and approved the final manuscript as submitted; Drs Avner and Khine co-supervised the overall conduct of the study at 1 of the 2 sites, critically reviewed the manuscript, and approved the final manuscript as submitted; and Dr Tsung conceptualized and designed the study, supervised the overall conduct of the study at 1 of the 2 sites, assisted with data and statistical analysis, critically reviewed the manuscript, and approved the final manuscript as submitted.

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WHAT'S KNOWN ON THIS SUBJECT: Head injuries and concern for skull fracture are common in pediatrics. Point-of-care ultrasound is an imaging tool that can be used to diagnose fractures. However, there are scant data regarding the accuracy of point-of-care ultrasound in skull fracture diagnosis.



WHAT THIS STUDY ADDS: Clinicians with focused point-of-care ultrasound training are able to diagnose skull fractures in children with high specificity. Ultrasound may be valuable to diagnose skull fractures in children at the point of care.

abstract

OBJECTIVE: To determine the test performance characteristics for point-of-care ultrasound performed by clinicians compared with computed tomography (CT) diagnosis of skull fractures.

METHODS: We conducted a prospective study in a convenience sample of patients ≤ 21 years of age who presented to the emergency department with head injuries or suspected skull fractures that required CT scan evaluation. After a 1-hour, focused ultrasound training session, clinicians performed ultrasound examinations to evaluate patients for skull fractures. CT scan interpretations by attending radiologists were the reference standard for this study. Point-of-care ultrasound scans were reviewed by an experienced sonologist to evaluate interobserver agreement.

RESULTS: Point-of-care ultrasound was performed by 17 clinicians in 69 subjects with suspected skull fractures. The patients' mean age was 6.4 years (SD: 6.2 years), and 65% of patients were male. The prevalence of fracture was 12% ($n = 8$). Point-of-care ultrasound for skull fracture had a sensitivity of 88% (95% confidence interval [CI]: 53%–98%), a specificity of 97% (95% CI: 89%–99%), a positive likelihood ratio of 27 (95% CI: 7–107), and a negative likelihood ratio of 0.13 (95% CI: 0.02–0.81). The only false-negative ultrasound scan was due to a skull fracture not directly under a scalp hematoma, but rather adjacent to it. The κ for interobserver agreement was 0.86 (95% CI: 0.67–1.0).

CONCLUSIONS: Clinicians with focused ultrasound training were able to diagnose skull fractures in children with high specificity. *Pediatrics* 2013;131:e1757–e1764

Head trauma is one of the most common childhood injuries, accounting for >600 000 emergency department (ED) visits, 60 000 hospitalizations, and 6000 deaths in children annually in the United States.¹ It is estimated that 16% of children with nontrivial head injuries may have skull fractures, and the presence of a skull fracture is associated with a fourfold increased risk of an underlying intracranial injury.² The gold standard diagnostic test to evaluate for skull fracture and intracranial hemorrhage is head computed tomography (CT), which is highly sensitive for identification of children with intracranial injuries requiring acute intervention.³ However, CT imaging exposes developing brains to ionizing radiation^{4–7} and may require sedation in young children. Clinicians caring for children need to decide, on the basis of the risks and benefits, whether to perform a head CT in a child presenting with a closed head injury.

Point-of-care ultrasound is an imaging modality used by a variety of medical specialties,^{8–10} and it is widely accepted as a diagnostic tool for use in the ED.¹¹ Multiple studies show that ultrasound for fracture diagnosis has good accuracy when used by clinicians^{12–15} as well as when used by radiologists.^{16,17} In addition, ultrasound is well tolerated by children, even in areas of injury.^{12,15} Emerging data suggest that ultrasound diagnosis of skull fractures in children is promising,^{13,15,17–20} and additional investigation of its utility is warranted. Our principal objective was to determine the test performance characteristics for point-of-care ultrasound performed by clinicians compared with CT scan for the diagnosis of skull fractures in children.

METHODS

Study Design and Setting

This was a prospective observational study conducted from September 2010 to March 2012 in 2 urban, level II trauma

center pediatric EDs with a combined annual census of 100 000 patients. A convenience sample of patients ≤ 21 years of age with head injuries requiring CT scan for suspected fracture and/or intracranial injury, who presented when a trained study physician was available, was eligible for inclusion in this study. Written informed consent was obtained from the patient or parent/guardian, and written assent was obtained from patients ≥ 7 years of age. This study was approved by the hospitals' institutional review boards, and it adhered to the STARD (Standards for Reporting of Diagnostic Accuracy) criteria for research involving diagnostic accuracy.²¹ The methods were similar to those that have been published elsewhere.^{15,22}

Selection of Participants

Inclusion criteria included patient age of ≤ 21 years with a head trauma and/or suspected skull fracture requiring radiographic evaluation with a head CT scan as recommended by the treating pediatric emergency medicine (PEM) physician. Patients were excluded if they presented with completed radiologic studies, a confirmed skull fracture, an open fracture, or if urgent intervention was required.

Ultrasound Technique

Before the start of the study, all enrolling PEM attending and fellow physicians attended a 30-minute didactic session to learn how to use ultrasound to evaluate the skull for fracture and to standardize the method in which

bedside ultrasound was performed by participating physicians, followed by a 30-minute hands-on practical session. A reference manual complete with instructions and images was available throughout the study. All study sonologists except for one were novices to musculoskeletal ultrasound at the start of the study. We defined an experienced sonologist as having performed ≥ 25 musculoskeletal ultrasound examinations, which is the minimum recommended number of scans for ultrasound credentialing per American College of Emergency Physicians Emergency Ultrasound Guidelines.¹¹

SonoSite ultrasound systems (SonoSite Inc, Bothell, WA) with high-frequency linear transducer probes (10–5 MHz) were used to perform focused ultrasound examinations to evaluate for skull fracture. Ultrasound gel was layered onto the ultrasound probe, and then the probe was lightly applied to the scalp to avoid pressure on the injured skull. The transducer was placed over the area of soft tissue swelling, hematoma, point of impact, or point of maximal tenderness (Fig 1). Scans were performed in 2 perpendicular planes, and still pictures and video clips were recorded in each orientation. Skull suture lines were differentiated from skull fractures by following suspected sutures to a fontanelle. If a suspected fracture crossed a suture line or fontanelle, the contralateral area on the skull was imaged for comparison.

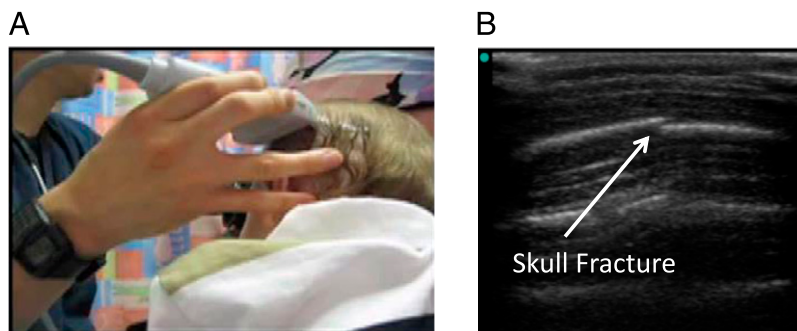


FIGURE 1

A, Linear transducer probe placement for skull ultrasound. B, Corresponding ultrasound image with skull fracture.

The sagittal, coronal, and metopic sutures can be traced to the anterior fontanelle, and the lambdoid sutures can be traced to the posterior fontanelle. The squamous sutures, however, may be difficult to follow to an open fontanelle, but sonologists were encouraged to scan the contralateral area of the skull for comparison. A diagram of suture anatomy was included in the study reference manual.

Enrollment Protocol

Before performing the point-of-care ultrasound, enrolling PEM physicians filled out data collection forms to record clinical characteristics, including scalp hematoma and location, loss of consciousness, vomiting, altered mental status or a Glasgow coma scale score <15, and/or palpable skull fracture. The PEM physician also determined and recorded his or her impression of the clinical likelihood of skull fracture before the ultrasound ($\leq 1\%$, 2%–25%, 26%–50%, 51%–75%, 76%–98%, or $\geq 99\%$).

A positive skull ultrasound was defined as the enrolling PEM physician's determination of a cortical disruption or irregularity visualized on the point-of-care ultrasound (Fig 1B). The enrolling sonologist recorded the point-of-care ultrasound findings (positive or negative for skull fracture) on the data collection sheet immediately after the procedure and before reviewing any radiographic imaging studies. All test performance characteristics were analyzed on the basis of the enrolling PEM physician's determination of the presence or absence of skull fracture.

A PEM physician with expertise in ultrasonography (J.W.T.), who has >10 years of point-of-care ultrasound clinical and teaching experience, reviewed all recorded ultrasound scans to provide a measure of agreement and to classify diagnostic errors made by enrolling PEM physicians. The expert

PEM sonologist was blinded to the patient's clinical findings, the enrolling sonologist's ultrasound interpretation, and radiographic imaging. The time to perform the point-of-care ultrasound was determined from the time stamps on the first and last images recorded for each patient.

After completion of the point-of-care ultrasound, all patients received a head CT as per the discretion of the treating PEM attending physician. The gold standard for skull fracture was defined as "fracture" or "cortical irregularity" as documented in the attending radiologist's report of the head CT. The radiologists were blinded to the point-of-care ultrasound examination results. Patients without definite fracture on CT scan in the ED received a structured telephone follow-up at least 1 week after the initial ED visit to ascertain outcomes.

Our primary outcome was to determine the test performance characteristics of point-of-care ultrasound for skull fracture performed and interpreted by trained PEM physicians compared with the diagnosis of fracture on CT scan with clinical follow-up. Our secondary objectives were to compare interobserver agreement between enrolling PEM physicians and an expert PEM sonologist and to compare skull fracture with clinical assessment, findings, and follow-up. Last, we combined our data with published studies that used similar methodology and performed a pooled-analysis for accuracy of point-of-care ultrasound for diagnosis of skull fracture in children.

Statistical Analysis

Data were analyzed by using SPSS Statistics (IBM, Armonk, NY) and are described by using sensitivity, specificity, positive and negative predictive values, positive and negative likelihood ratios, and 95% confidence intervals (CIs). Descriptive statistical analyses

were used for categorical data. κ Values were calculated as a measure of interobserver agreement.

By using the method of Arkin and Wachtel,²³ a sample size of 60 patients would be needed to obtain a 95% CI (SD: 5%) with an estimated 96% specificity for ultrasound diagnosis of skull fractures based on the study by Weinberg et al.¹⁵

RESULTS

Sixty-nine patients with a mean age of 6.4 years (SD: 6.2 years; range: 7 days to 21 years) were enrolled. Patient demographic and clinical information is presented in Tables 1 and 2. The study flowchart is presented in Fig 2.

Skull fracture was present on CT scan in 8 (12%) patients. The test performance characteristics for point-of-care ultrasound diagnosis of skull fractures compared with CT imaging with 95% CIs and κ values for interobserver agreement between enrolling physicians and an experienced PEM sonologist are presented in Table 3. The diagnostic test results for each point-of-care ultrasound performed compared with the reference standard imaging test and the interobserver agreement between enrolling PEM physicians and the expert PEM sonologist for each point-of-care ultrasound are shown in Fig 3.

TABLE 1 Patient Demographic Characteristics

| | <i>n</i> (%) |
|----------------------------------|--------------|
| Male | 45 (65) |
| Scalp hematoma | 43 (62) |
| Frontal | 9 (13) |
| Temporal | 8 (12) |
| Temporal and parietal | 2 (3) |
| Parietal | 11 (16) |
| Parietal and occipital | 1 (1) |
| Occipital | 11 (16) |
| Location not noted | 1 (1) |
| Loss of consciousness | 9 (13) |
| Vomiting | 22 (32) |
| GCS <15 or altered mental status | 8 (12) |
| Palpable fracture | 4 (6) |

N = 69. GCS, Glasgow coma scale.

TABLE 2 Pretest Clinical Assessment of Skull Fracture

| Pretest Clinical Assessment of Skull Fracture | Frequency, <i>n</i> (%) | Skull Fracture Rate by Pretest Clinical Assessment, <i>n</i> (%) |
|---|-------------------------|--|
| <1% | 13 (19) | 0/13 (0) |
| 2%–25% | 39 (57) | 2/39 (5) |
| 26%–50% | 9 (13) | 3/9 (33) |
| 51%–75% | 2 (3) | 0/2 (0) |
| 76%–98% | 2 (3) | 1/2 (50) |
| ≥99% | 2 (3) | 1/2 (50) |
| Missing data | 2 (3) | 1/2 (50) |

Seventeen PEM physicians performed a mean of 4.1 ultrasound scans (SD: 4.0; range: 1–13 scans) and a median of 2 scans each (interquartile range: 1–7). It took PEM physicians a median of 68 seconds (interquartile range: 39–148 seconds) to obtain the skull ultrasound images necessary to make a diagnosis. One PEM physician, who enrolled 12 patients, had previous experience in skull ultrasound before the start of the study, and this PEM physician did not enroll any patients with skull fracture according to ultrasound or CT scan.

Of the 4 (6%) patients who had reported palpable skull fractures on physical examination before ultrasound or radiographic imaging, 2 patients had parietal skull fractures, 1 patient had negative ultrasound and CT imaging studies, and 1 patient had an ultrasound positive for fracture as determined by the enrolling and expert PEM physician and a CT scan that was negative for fracture.

The anatomic locations of the skull fractures were as follows: 5 parietal (7%), 1 frontal (1%), 1 temporal/parietal (1%), and 1 parietal/occipital (1%). Four (6%) patients had intracranial hemorrhage on CT: 2 (3%) with epidural hematoma, both of whom had associated skull fractures; 1 (1%) with a subdural hematoma; and 1 (1%) with subarachnoid hemorrhage not associated with skull fractures. On telephone follow-up, there was no change in clinical status among patients who had negative imaging studies at the initial ED visit. Seven patients (10%) did not have telephone follow-up after the

initial ED visit. However, all 7 of these patients had a negative ultrasound and head CT for fracture at the initial ED visit; these patients were included in the analysis categorized as “fracture absent.”

By using point-of-care ultrasound, fracture was diagnosed by the enrolling sonologist in 9 patients (13%). Overall, there were 3 (4%) discordant results between point-of-care ultrasound and radiographic imaging, with 1 false-negative result and 2 false-positive results. The false-negative case was a 7-month-old male who presented with a temporal scalp hematoma after head trauma. The clinical likelihood of skull fracture before the ultrasound was 26% to 50%. Point-of-care ultrasound was performed over the scalp hematoma, and no skull fracture was visualized by the enrolling PEM physician or the expert PEM sonologist. On CT scan, the patient was found to have a parietal nondepressed skull fracture adjacent to but not directly underneath the scalp hematoma (Fig 4). This patient was admitted for observation and did not require any additional intervention.

The first false-positive case was due to an error by the PEM physician early in the study. The PEM physician interpreted the ultrasound as positive and the expert PEM sonologist interpreted the ultrasound as negative for fracture (Fig 5A); the CT scan was also negative for fracture. The second false-positive case was a minimally displaced skull fracture in the temporal fossa that was visualized on ultrasound. This skull fracture was confirmed on clip review by the expert PEM sonologist but not visualized by CT scan (Fig 5B).

Combining our data with the results of other published studies^{15,18,19} for a total of 185 patients, the pooled fracture rate was 27%. Skull ultrasound for fractures had a combined sensitivity of 94% and a specificity of 96% (Table 4).

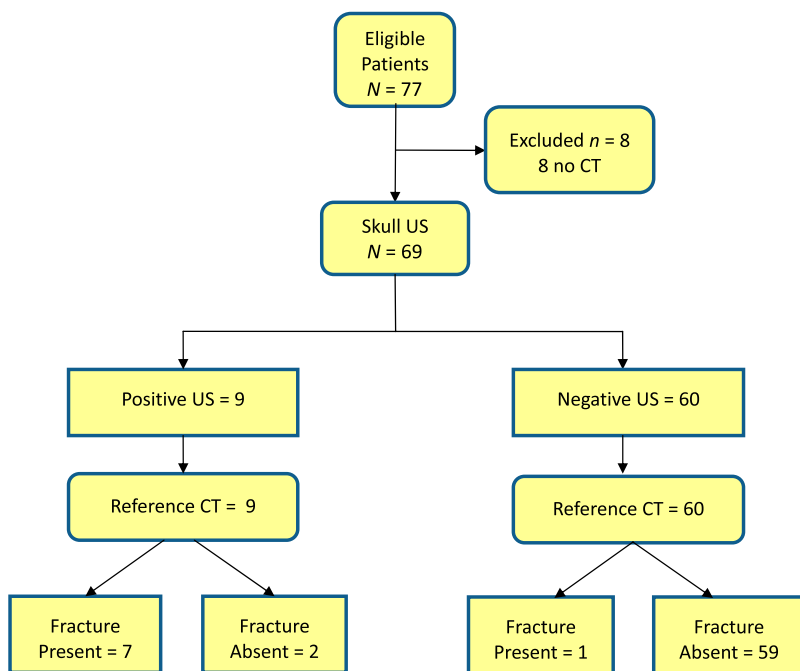


FIGURE 2 STARD (Standards for Reporting of Diagnostic Accuracy) flowchart.

TABLE 3 Test Performance Characteristics for Point-of-Care Ultrasound Diagnosis of Skull Fractures

| | N | Fractures, n (%) | Sensitivity, % | Specificity, % | PPV | NPV | LR+ | LR- | κ |
|--------------------|----|------------------|----------------|----------------|------------------|-----------------|------------------|------------------|-----------------|
| Overall | 69 | 8 (12) | 88 (53–98) | 97 (89–99) | 0.78 (0.45–0.94) | 0.98 (0.91–1.0) | 26.7 (6.7–106.9) | 0.13 (0.02–0.81) | 0.86 (0.67–1.0) |
| Novice sonologists | 57 | 8 (14) | 88 (53–98) | 96 (86–99) | 0.78 (0.45–0.94) | 0.98 (0.89–1.0) | 21.4 (5.4–85.4) | 0.13 (0.02–0.82) | 0.85 (0.66–1.0) |

Data are test performance characteristics (95% CI). LR+, likelihood ratio of a positive test; LR-, likelihood ratio of a negative test; NPV, negative predictive value; PPV, positive predictive value.

DISCUSSION

We have demonstrated in the largest cohort of patients to date that with a 1-hour, focused musculoskeletal ultrasound training session, novice sonologists are able to quickly and accurately diagnose skull fractures with high specificity. Previous data on ultrasound by radiologists for skull fracture diagnosis revealed high accuracy.^{17,20} In addition, studies of ultrasound by clinicians with focused training have

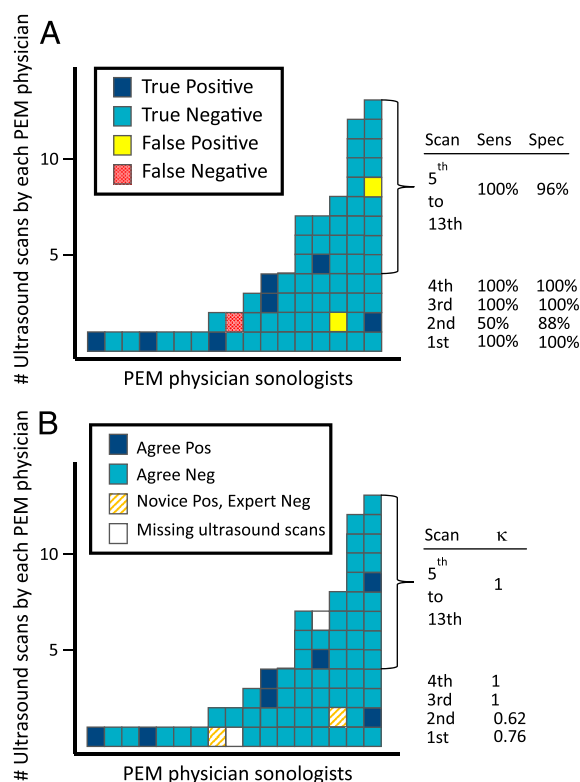
also revealed rapid and accurate diagnosis of skull fractures with point-of-care ultrasound.^{15,18,19} In our study, as with most ultrasound applications, the specificity was higher than the sensitivity (Table 3).

Clinical assessment may not be completely reliable for predicting skull fractures and intracranial injuries in children.²⁴ In our data, 2 of 39 (5%) patients assessed to have a 2% to 25% likelihood of fracture and 3 of 9 (33%)

assessed to have a 26% to 50% likelihood of fracture after obtaining the history and physical examination had confirmed skull fractures (Table 2). In addition, of the 4 patients in our study who had reported palpable skull fractures on physical examination, only 2 (50%) had confirmed skull fracture by CT scan.

In current practice, head CT serves as the gold standard diagnostic test to evaluate for skull fractures and intracranial bleeding after head trauma. However, there are several advantages of using point-of-care ultrasound in the detection of skull fractures. First, ultrasound can be performed rapidly, which can allow earlier detection of skull fracture as a marker for suspected intracranial injury and neurosurgical consultation. Second, point-of-care ultrasound has the potential to reduce CT use and ionizing radiation exposure in children. The estimated lifetime risk of cancer from a head CT is substantially higher for children than for adults because of a longer latency period and the greater sensitivity of developing organs to radiation.^{4–7} However, intracranial injury may occur without skull fracture, and clinicians must use clinical judgment or decision rules^{25–28} for obtaining CT scan regardless of the presence or absence of skull fracture. In addition, ultrasound can also be performed in young children without the need for sedation.

Point-of-care ultrasound for skull fractures may be especially useful in places without access to CT scan. It has been estimated by the World Health Organization that up to two-thirds of the world's population does not have access to diagnostic imaging technology,²⁹ and portable ultrasound may be

**FIGURE 3**

A, Diagnostic results for each point-of-care ultrasound performed by a PEM physician compared with the reference standard of head CT with clinical follow-up. B, Agreement between enrolling PEM physicians and an experienced PEM sonologist for each point-of-care ultrasound performed. Each block represents a unique patient enrolled by a PEM physician sonographer (x-axis) with the number of ultrasound scans performed by each PEM physician (y-axis), and each block is color-coded to show the test result compared with the reference standard (A) or the agreement with the expert sonologist (B). The blocks are arranged vertically in chronological order, with the first ultrasound scan at the bottom. The sensitivity and specificity (A) and κ values for interobserver agreement (B) for point-of-care skull ultrasound are given for the first, second, third, fourth, and fifth to thirteenth ultrasound scans performed by physicians. Neg, negative; Pos, positive; Sens, sensitivity; Spec, specificity.

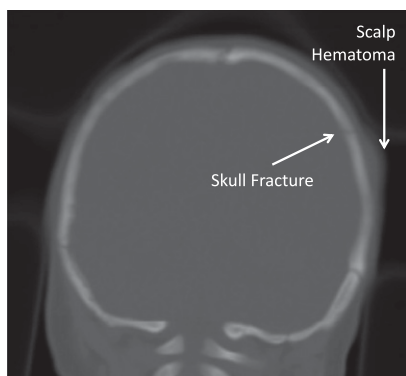


FIGURE 4
Coronal CT scan of a skull fracture adjacent to scalp hematoma missed on point-of-care ultrasound.

implemented in these resource-scarce locations.³⁰ In addition, ultrasound may be useful for triage in mass casualty disasters³¹ or in austere environments.³² Last, ultrasound may be used in pediatricians' offices or in urgent care centers for patients with suspected isolated skull fracture without ready access to CT scan. Ultrasound may diagnose minimally or nondisplaced skull fractures that can be missed on CT scan. Recent research has revealed that ultrasound has superior sensitivity to radiography in certain types of fractures,³³ and it has been shown to detect nondisplaced fractures as small as 1 mm.³⁴ Our study included a case of a 16-year-old male who presented with a boggy frontal scalp hematoma after an assault. Skull ultrasound performed by a novice sonologist was interpreted as positive for fracture and confirmed on expert review (Fig 5B). The CT was

read as negative for skull fracture, and the patient was discharged from the ED. On telephone follow-up, the patient was asymptomatic.

Knowledge of suture anatomy is essential in performing ultrasound examinations of infant skulls.^{18,19} A suture appears symmetric and regular and leads to a fontanelle, whereas a fracture is jagged and may be displaced. All enrolling sonologists in our study were taught to differentiate sutures from skull fractures by following sutures to a fontanelle. If a suspected fracture crossed a suture or fontanelle, the contralateral area of the skull was imaged for comparison. No errors in our study were due to sutures.

There have been several recent studies published on ultrasound for diagnosis of skull fractures in children that involved small sample sizes of children.^{15,18,19} Our study adds the largest cohort to the current literature. In addition, pooling our data with these similar studies to form a cohort of 185 patients reveals ultrasound to be highly sensitive and specific for diagnosing skull fractures in children (Table 4). The study by Weinberg et al¹⁵ looked at fracture detection for all bones and included a small subset of patients with suspected skull fracture. In the study by Riera and Chen,¹⁹ few enrolling sonologists with no formalized skull ultrasound training performed skull ultrasound. Parri et al¹⁸ reported a very high prevalence of skull

fracture because they enrolled patients with localizing evidence of trauma. However, all of these studies used clinician sonologists who performed blinded point-of-care ultrasound imaging and compared skull ultrasound with CT as the reference standard.

Skull ultrasound may be particularly useful in well-appearing patients with suspected isolated skull fracture on the basis of history and physical examination and low risk for clinically important traumatic brain injury. The question remains whether the absence of skull fracture on ultrasound in selected patients with head injury in the presence of single isolated risk factors for intracranial bleeding can obviate the need for CT scan. Two children in our study, one with isolated scalp hematoma and another with isolated loss of consciousness, had no skull fracture detected on ultrasound or CT scan but were subsequently found to have intracranial hemorrhage. Thus, caution is warranted in using ultrasound to rule out intracranial injury, and additional research is needed to fully answer this question.

Our study has several limitations. Our study population consisted of a convenience sample of patients enrolled when a trained physician was available, but the prevalence of skull fractures of 12% in our study is similar to other studies.^{15,19,24} Ultrasound is an operator-dependent modality, but because a novice group of sonologists was trained to perform skull ultrasound with such high specificity, we believe that our results may be generalizable to other clinicians with focused training. Last, there was a limitation in our ultrasound scanning technique. Our only false-negative result was due to a skull fracture that was adjacent to but not directly beneath the scalp hematoma, and therefore this fracture was missed on ultrasound but confirmed on CT scan (Fig 4). We now recommend scanning the areas around the scalp hematoma

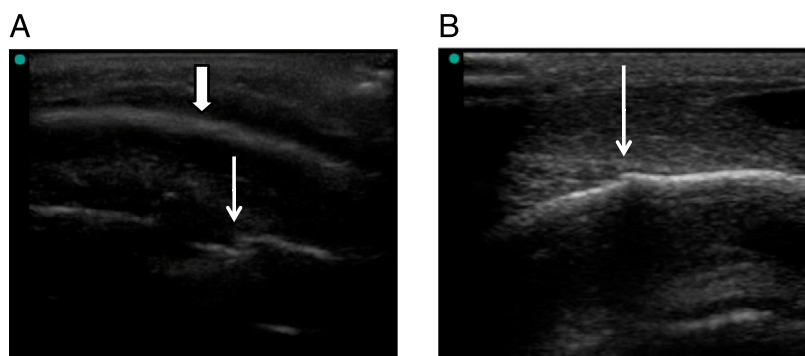


FIGURE 5
A, Negative skull ultrasound (thick arrow) incorrectly interpreted as a fracture (thin arrow) by the PEM physician. B, Skull fracture (arrow) visualized on point-of-care ultrasound and not detected by head CT.

TABLE 4 Pooled-Data Analysis of Point-of-Care Ultrasound for Skull Fracture Diagnosis

| Study (Reference) | N | Fractures, n (%) | Sensitivity, % | Specificity, % | LR+ | LR- |
|---------------------|-----|------------------|----------------|----------------|-------------------------|------------------|
| Weinberg et al (15) | 21 | 2 (10) | 100 (20–100) | 100 (79–100) | Infinity (2.1–infinity) | 0 (0–2.15) |
| Riera and Chen (19) | 40 | 5 (13) | 60 (17–93) | 94 (79–99) | 10.5 (2.3–48.2) | 0.42 (0.15–1.25) |
| Parri et al (18) | 55 | 35 (64) | 100 (88–100) | 95 (75–100) | 13.8 (3.0–64.6) | 0.02 (0–0.24) |
| Rabiner et al | 69 | 8 (12) | 88 (53–98) | 97 (89–99) | 26.7 (6.7–106.9) | 0.13 (0.02–0.81) |
| Total pooled data | 185 | 50 (27) | 94 (84–98) | 96 (92–98) | 25.4 (10.7–60.2) | 0.06 (0.02–0.19) |

Data are test performance characteristics (95% CI). LR+, likelihood ratio of a positive test; LR-, likelihood ratio of a negative test.

if a skull fracture is not visualized directly beneath it, similar to the method proposed by Riera and Chen.¹⁹

CONCLUSIONS

Clinicians with focused, point-of-care ultrasound training were able to diagnose skull fractures in children with head trauma with high specificity and high negative predictive value. In addition, almost perfect agreement was observed

between novice and experienced sonologists. Pooled analysis of published studies for skull fracture reveals high specificities with variable sensitivities. Future research is needed to determine if ultrasound can reduce the use of CT scans in children with head injuries.

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