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Original Contribution

Comparison of pediatric post-reduction fluoroscopic- and ultrasound forearm fracture images☆

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ABSTRACT

Objective: Emergency department (ED) reduction of pediatric fractures occurs most commonly in the forearm and can be challenging if fluoroscopy is not available. We sought to assess the ability of point of-care ultrasonography (POCUS) to predict adequacy of reduction by fluoroscopy.

Methods: We prospectively enrolled ED patients 0–17 years of age with radial and/or ulnar fractures requiring reduction under fluoroscopic guidance. Post-reduction POCUS (probe dorsal, volar, and coronal) and fluoroscopic (AP and lateral) fracture images were recorded. Fracture angles were compared between blinded POCUS and fluoroscopic measurements and between POCUS measurements by a blinded emergency physician and a blinded radiologist, reporting mean differences and 95% confidence intervals. We calculated sensitivity, specificity, and likelihood ratios of POCUS in the prediction of fluoroscopically detected post-reduction malalignment, as interpreted by a blinded pediatric orthopaedist.

Results: The 58 patients were 7.9 $\pm$ 3.5 years of age and had 21 radial (36%), 1 ulnar (2%), and 36 radioulnar (62%) fractures. Fluoroscopy and POCUS angles were within a mean of 0.1°–3.2°, depending on the site and surface measured. Radiologist- and emergency physician-interpreted POCUS measurements were within a mean of 1° in all dimensions. POCUS identified inadequate reductions with 100% sensitivity and 92–93% specificity.

Conclusions: Blinded emergency medicine and radiology interpretations of post-reduction POCUS fracture images agree closely. Post-reduction POCUS measurements are comparable to those obtained by fluoroscopy and accurately predict adequacy of reduction. POCUS can be used to guide pediatric fracture reduction when bedside fluoroscopy is not available in the ED.

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1. Introduction

The forearm accounts for 30–50% of pediatric fractures [1,2]. Closed reductions of both-bone pediatric forearm fractures can be both time consuming and associated with greater fracture instability [3]. Fluoroscopy can reliably predict the adequacy of post-reduction forearm fracture position on formal radiography [4,5]. Reductions performed without fluoroscopic guidance incur an increased risk for repeated sedation and imaging [5]. Minimizing avoidable radiation exposure remains an important priority in caring for a child in the emergency setting [6]. In settings where fluoroscopy is not readily available, point of care (POC) ultrasonography (US) is a radiation free alternative for guiding pediatric forearm reductions [7]. POCUS has been shown to perform comparably to fluoroscopy in the subjective post-reduction review of single-bone pediatric forearm fracture reductions [8].

US and standard radiography yield comparable angular measurements for both pediatric single-bone and both-bone forearm fractures [9]. US-guided pediatric forearm fracture reductions have been reported with 90–92% rate of agreement in predicting successful alignment when compared against radiologist interpretation of post reduction radiographs [10,11]. Utilizing previously published rules for acceptable post-reduction radiographic angles, a 94% rate of successful POCUS guided single and both-bone forearm fracture reductions has been reported in a resource limited setting [2,7]. However, prior research comparing POCUS and fluoroscopic images included only subjective assessment of single-bone forearm fracture reductions [8]. Therefore,

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we sought to demonstrate the ability of POCUS to determine residual post-reduction angulation and adequacy of alignment among fluoroscopically guided pediatric forearm fracture reductions. We aimed to compare adequacy of alignment by both subjective and rules-based comparison of post-reduction POCUS and fluoroscopic images in the pediatric emergency setting [7].

2. Methods

2.1. Study design

We conducted this prospective observational study in the emergency department (ED) of a free-standing urban children's hospital. We used a pragmatic sampling approach, scheduling enrollment and screening all patients presenting with fractures between 10 am and 10 pm on 37 dates between March 7 and July 2, 2015 inclusive when the enrolling investigator (JA) was free from clinical duties. The Institutional Review Board of the University of California San Diego reviewed and approved this study.

2.2. Study setting and population

Our subjects were children 0–17 years of age with isolated forearm fractures involving radius, ulna, or both, determined by the orthopaedic consultant, based upon institutional clinical practice and attending orthopaedic surgeon's discretion, to require reduction with fluoroscopic guidance in the ED. We excluded patients with fractures in the proximal third of the radius or ulna, fractures other than the radius or ulna, comminuted or intra-articular fractures, or fractures requiring operative intervention, including open fractures or those with vascular compromise.

2.3. Study protocol

One month prior to initiation of enrollment, an US fellowship-trained emergency medicine attending physician (NH) provided physician-investigators responsible for acquiring, interpreting or analyzing imaging data a 30-minute lecture on POCUS of the radius and ulna, and a one-hour practical session using human volunteers. On pre-determined study days, pediatric emergency medicine attending physicians or fellows identified eligible patients after orthopaedic consultation determined need for closed reduction. A single investigator and sole study sonographer (JA) presented the study and obtained informed consent from parents, written assent from children 7–12 years of age, and written consent from adolescents aged 13–17 years of age. This investigator (JA) was a pediatric emergency medicine fellow with POCUS experience during an emergency medicine residency, but <15 POCUS studies for fracture detection and no prior formal training in POCUS for fracture care. With the exception of study POCUS imaging, patients underwent routine care provided by non-investigator clinicians according to institutional practice. Emergency physicians provided sedation or analgesia, and orthopaedic consultants performed reduction at their discretion. The orthopaedic consultant used fluoroscopy (OrthoScan FD Pulse Mini C-arm, OrthoScan Inc., Scottsdale AZ, USA) or Digital Radiography (Optima XR240amx, GE Healthcare, Chicago, Illinois, USA) according to existing local practice to guide and document reduction (Fig. 1). Only reductions guided by fluoroscopy at the site of a discrete cortical defect identifiable by POCUS were included in the data analysis. Radioulnar fractures in which one bone a non-angulated or torus fracture, an ulnar styloid fracture, or a plastic deformity without cortical breach underwent analysis as single-bone radial fractures.

After the orthopaedic consultant determined that fluoroscopically-guided fracture reductions were adequate, the study sonographer obtained, without rendering interpretations, 3 static ultrasound images of each fracture site using a 15–6 MHz linear array US probe (Sonosite Edge II, Fuji Film, Tokyo, Japan) positioned longitudinally over the dorsal and volar surfaces and the radial or ulnar border (Fig. 2) [9,12]. Immediately following POCUS image acquisition, the final post-reduction fluoroscopic images were obtained in AP and lateral projections with care to avoid changes in fracture position. The orthopaedic consultant applied a cast without reviewing post-reduction sonography. A radiology administrator, who was not a member of the research team and who was unaware of the study objectives, stored de-identified POCUS and final fluoroscopic image sets in the hospital's picture archiving and communication system (PACS, Merge Healthcare; Hartland, WI, USA). Radioulnar image sets are defined as six views obtained by POCUS or two views obtained by fluoroscopy. We recorded for each subject: age, sex, and weight; fracture site and morphology; duration of fluoroscopy; and sedation and analgesia administered. For patients with radioulnar fractures, we recorded whether 1 or both bones underwent reduction.

A pediatric radiologist (JN) and a US fellowship-trained emergency physician (NH), blinded to clinical decisions and pre- and post-reduction plain radiography, used the PACS angle measurement tool to measure fracture angles from the post-reduction US (NH, JN) and fluoroscopic (JN) images, presented as separate image sets. The arms of US angles were lines placed tangentially over the cortices proximal and distal to the fracture. The reviewers differentiated periosteum from cortex by its contour, more superficial position, lesser echogenicity, narrower and more delicate appearance, and the presence of subperiosteal fluid. For fluoroscopic angles, the arms were lines bisecting the medullary canals. For physeal and other distal fractures, the distal arm of the fluoroscopic angle was a line perpendicular to the physis. Both reviewers recorded measurements separately for each of the three US positions (dorsal, volar and lateral) on each individual bone. A blinded pediatric orthopaedist (AP), whose clinical practice

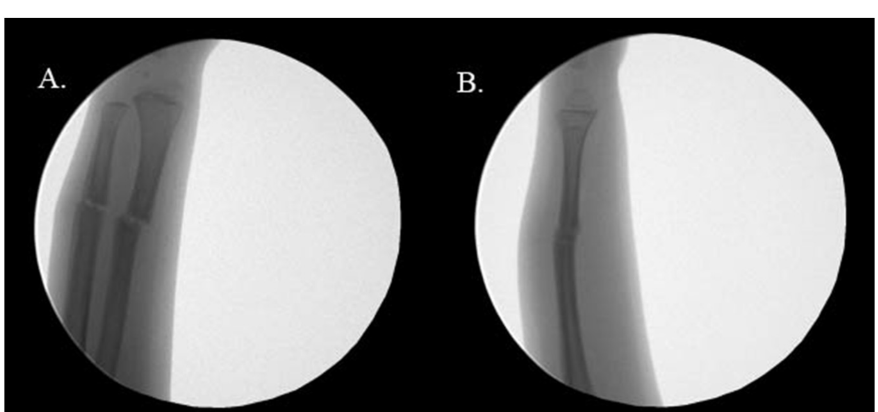

Fig. 1. Post reduction fluoroscopic images of 4-year-old subject with radioulnar fracture in anteroposterior (A) and lateral (B) projections.

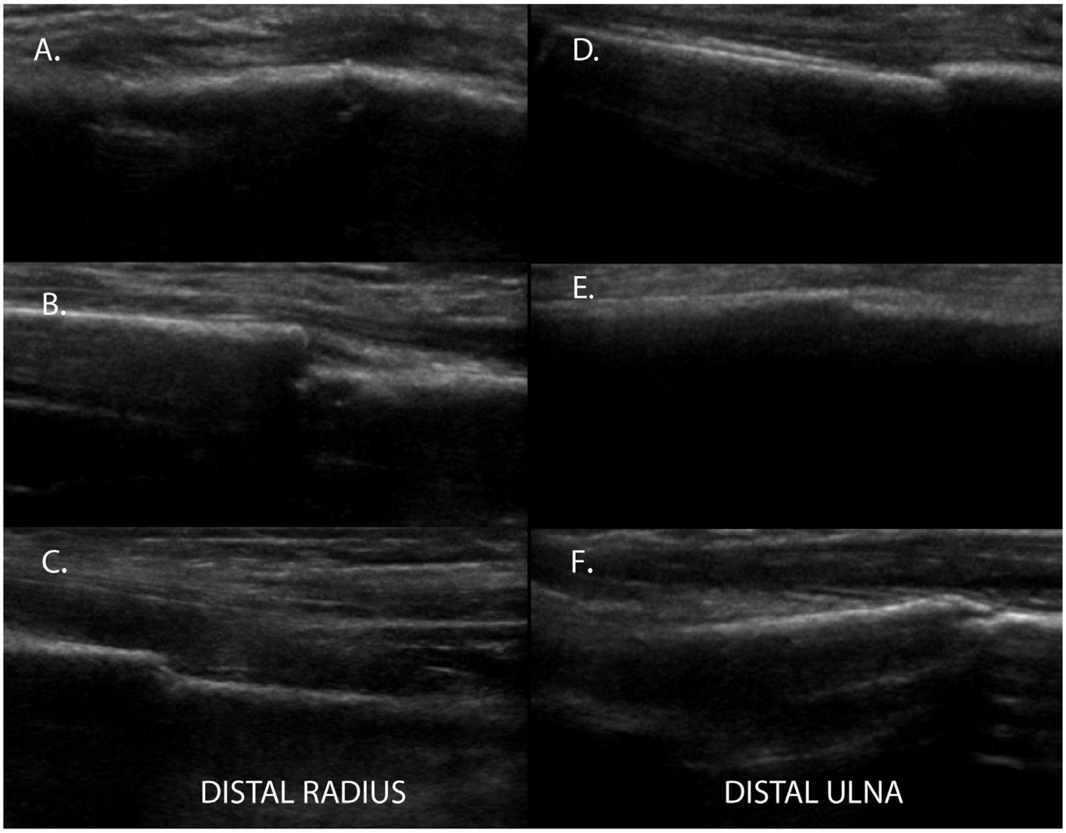

Fig. 2. Post reduction POCUS images of 4-year-old subject with radioulnar fracture depicting radius with probe on dorsal (A), coronal (B), volar (C) surfaces and ulna with probe on dorsal (D), coronal (E), volar (F) surfaces.

utilized bedside sonography but whose only formal POCUS education came from the pre-enrollment training, reviewed study US and fluoroscopic images presented as separate image sets. He then rendered 2 separate determinations of adequacy of alignment based on 1) local orthopaedic practice and 2) age-related tolerances for residual deformity (rules-based criteria). Using the latter criteria, the acceptable residual fracture angle for patients <9 years old was ≤15° for all fractures. Acceptable angles for patients ≥9 years old were ≤10° and ≤15° for fractures proximal and distal to the midpoint of the forearm, respectively. Complete displacement was accepted for patients <9 years of age and bayonet apposition for patients ≥9 years of age [2]. All reviewers were blinded to each other's recorded measurements. Two investigators not involved in determining the primary angular or secondary reduction outcomes (KH, JK) compiled and analyzed the angular measurements and determinations of adequacy of reduction.

2.4. Data analysis

Our primary outcome was the difference in post-reduction fracture angles between US, as measured by the blinded study radiologist, and the reference standard fluoroscopy. Our secondary outcomes were 1) the differences between radiologist and emergency physician in ultrasound angular measurements and 2) the ability of US to predict adequacy of reduction as determined by a pediatric orthopaedic surgeon (AP). Based on reported differences in fracture angles measured by US and plain radiography (1.6° $\pm$ 4.8°), we calculated a sample size of 58 fractures to demonstrate non-inferiority with α 0.05 and β 0.20 [9]. We, therefore, recruited 60 subjects in order to provide at least this number of radial fractures and an unknown number of additional ulnar fractures. This sample would also provide reasonable precision for the prediction of adequacy of reduction (lower limit 95% CI of 0.05 if sensitivity were 1.0) [13,14]. We reported demographic and clinical characteristics as counts and percentages or means with 95% confidence intervals. We calculated predictive indices (sensitivity, specificity) with 95% confidence intervals for the ability of US to detect inadequate reduction as determined by fluoroscopy. We conducted additional analyses of fracture characteristics, agreement and interrater reliability, and results for subsets of single- and both-bone fractures (Appendix 1, Supplementary Tables A–C). All analyses were performed using STATA version 14.2 (College Station, TX).

3. Results

3.1. Study participants

Of the 158 children with forearm fractures who presented to the ED during study shifts, we excluded 95. Two of 63 eligible subjects were missed, 1 declined enrollment, and 2 met exclusion criteria after enrollment, leaving 58 patients who comprised the study population (Fig. 3). Mean age was 7.9 $\pm$ 3.5 years of age, and reductions imaged by study protocol included 21 radial (36%), 1 ulnar (2%) and 36 radioulnar (62%) fractures (Table 1). Six orthopaedic residents and 2 advanced practice providers performed reductions. The median (interquartile range [IQR]) fluoroscopy duration was 18.5 s (14, 24 s) and did not differ between single- and both-both fracture reductions.

3.2. Comparison of POCUS and fluoroscopic angular measurements

POCUS angles measured by probes placed on dorsal and volar surfaces differed from the corresponding lateral fluoroscopic angles by an

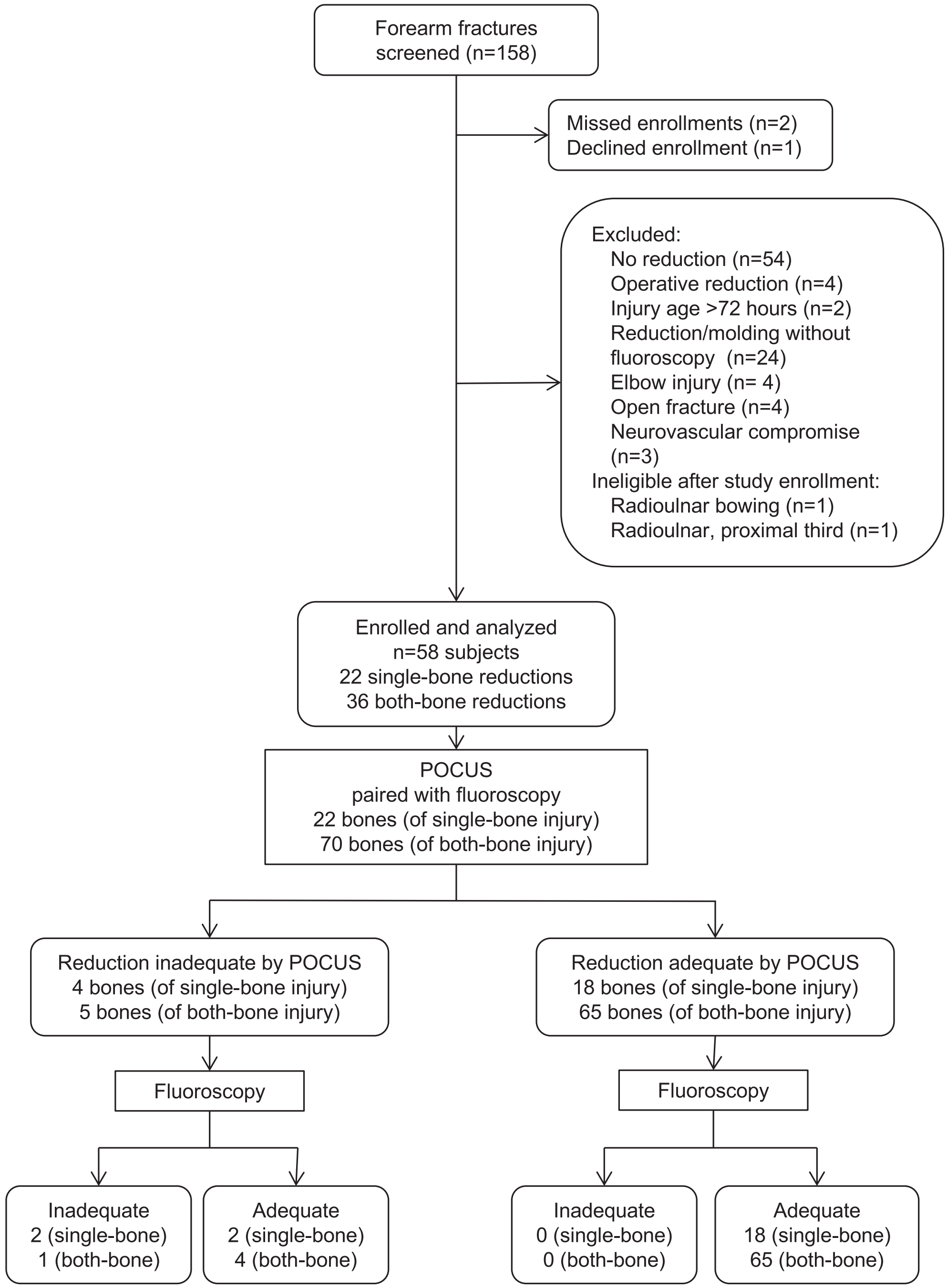

Fig. 3. Diagram of study enrollment and analysis of prediction by POCUS adequacy of post-reduction alignment (subjective criteria).

average of 3.2° and 1.4°, respectively. Angles measured by probes placed on radial and ulnar borders differed from AP fluoroscopic angles by an average of 0.1° (Table 2). Post-reduction angles measured by blinded radiologist and emergency physician from POCUS images were within a mean of 1° in all dimensions (Table 3).

3.3. Point of care ultrasound diagnostic performance

For all fractures combined, the orthopaedist's POCUS determination of reduction adequacy agreed with fluoroscopy in 86 of 92 cases (93%) by subjective criteria and 85 of 92 (92%) cases by rules-based criteria, yielding a sensitivity of 100% and specificity of 92% to 93% in the prediction of inadequate reduction (Table 4). The corresponding positive and negative LRs were 12.7–14.8 and zero, respectively.

4. Discussion

In one of the first pediatric studies comparing post-reduction POCUS and fluoroscopy imaging in a study population with single- and both-bone forearm fractures, mean post-reduction POCUS and fluoroscopic angles varied by up to 3.2° depending on sonographic plane and fluoroscopic projection. Mean sonographic measurements by radiologist and emergency physician were within 1° in all planes. Post-reduction POCUS identified all reductions deemed inadequately aligned by fluoroscopy (sensitivity 100%) and correctly identified the majority of adequately aligned reductions (specificity 92–93%). Predictive performance of POCUS was excellent whether determined by subjective and rules-based criteria or analyzed by subsets of single- and both-bone reductions.

The overall difference in post-reduction angles measured by POCUS and fluoroscopy in our study was greater than those previously

Table 1
Subject, fracture, and reduction characteristics.

Age, y, mean ± SD	7.9 ± 3.5
Sex, male, *n* (%)	39 (67)
Arm injured, left, *n* (%)	37 (64)
Bone(s) fractured, *n* (%)	
Radius	10 (17)
Radius/ulna[a]	48 (83)
Bone(s) reduced with study imaging, *n* (%)	
Radius alone	21 (36)
Radius/ulna	36 (62)
Ulna alone	1 (2)
Reduction guidance, (%)	
Fluoroscopy	53 (91)
Digital radiography	5 (9)
Fracture translation, radial, *n* (%)	
0%	21 (37)
1–49%	12 (21)
50–99%	13 (23)
100%	11 (19)
Fracture translation, ulnar, *n* (%)	
0%	19 (51)
1–49%	6 (16)
50–99%	9 (24)
100%	3 (8)
Fracture translation, single bone reductions, *n* (%)	
0%	6 (27)
1–49%	9 (41)
50–99%	6 (27)
100%	1 (5)
Maximal fracture translation, 2-bone reductions, *n* (%)	
0%	10 (28)
1–49%	3 (8)
50–99%	12 (33)
100%	11 (31)
Maximal fracture translation, per subject, *n* (%)	
0%	16 (28)
1–49%	12 (21)
50–99%	18 (31)
100%	12 (21)
Fracture location, radial, *n* (%)	
Physeal	11 (19)
Metaphysis	13 (23)
Metadiaphyseal junction	14 (25)
Diaphysis	19 (33)
Fracture location, ulnar, *n* (%)	
Physeal	3 (8)
Metaphysis	5 (14)
Metadiaphyseal junction	9 (24)
Diaphysis	20 (54)
Sedative/analgesic	
Ketamine	56 (97)
Hematoma block[b]	2 (3)

Percentages may not add to 100% because of rounding.
[a] Components of radioulnar injuries excluded from analysis of post-reduction POCUS imaging: ulnar non-angulated or torus fractures (5); ulnar styloid fractures (5); ulnar plastic deformity (1); radial plastic deformity (1).
[b] Performed with adjunctive fentanyl (1), midazolam (1).

Table 2
Comparison of post-reduction fracture angles measured from US and fluoroscopy images.

	Mean difference	95% CI
Fluoroscopy, lateral vs. US, dorsal		
Radius (n = 50)	−4.26	−6.61, −1.92
Ulna (n = 27)	−1.11	−5.07, 2.84
Pooled (n = 77)	−3.16	−5.19, −1.22
Fluoroscopy, lateral vs. US, volar		
Radius (n = 45)	−1.51	−3.51, 0.49
Ulna (n = 24)	−1.29	−3.67, 1.09
Pooled (n = 69)	−1.43	−2.94, 0.73
Fluoroscopy, AP vs. US, coronal		
Radius (n = 45)	0.84	−1.10, 2.70
Ulna (n = 24)	−1.88	−5.68, 1.93
Pooled (n = 69)	−0.10	−1.86, 1.66

Table 3
Comparison of post-reduction fracture angles measured from US images by radiologist and US-trained emergency physician.

	Mean difference	95% CI
Dorsal		
Radius (n = 43)	−0.58	−2.33, 1.16
Ulna (n = 26)	−0.12	−1.36, 1.13
Pooled (n = 69)	−0.41	−1.57, 0.76
Volar		
Radius (n = 45)	0.44	−0.34, 1.23
Ulna (n = 22)	0	−1.25, 1.25
Pooled (n = 67)	0.30	−0.35, 0.95
Coronal		
Radius (n = 43)	−0.19	−1.14, 0.77
Ulna (n = 21)	0.76	−0.55, 2.07
Pooled (n = 64)	0.13	−0.63, 0.88

reported (<2°) between radiologist-interpreted US and plain radiography [9,20]. In contrast to prior studies including only a minority of combined radioulnar or exclusively isolated distal radial fractures, our study included a larger subset (62%) of potentially unstable radioulnar fractures [8-10,20]. In addition, angular differences between modalities are far less than the published tolerances for residual deformity used in this and other studies [2,7]. While measured angles may be slightly larger than in prior research, our findings have potential for greater applicability [9,20]. Our findings apply to a greater range of pediatric forearm fractures including radioulnar fractures, which may be more unstable in the intervals from reduction to immobilization and from initial immobilization to outpatient follow-up.

POCUS determinations by subjective and rules-based criteria agreed in 91 of 92 bones (99%) and resulted in excellent diagnostic performance. Prior studies on POCUS in pediatric forearm reduction have used different measures to determine adequacy of reduction. In a pediatric ED setting, POCUS-guided reduction produced adequate first-attempt alignment in 92% of forearm fractures based on parameters of age-based published angle tolerances on post reduction radiographs [15].Two prior studies have cited published objective criteria for determining adequacy of reduction [7,15]. In a separate study of a convenience sample of pediatric forearm fractures non-blinded emergency medicine interpretations of post reduction POCUS and radiographic images agreed on adequacy of reduction in 38 of 42 (90%) [11]. Post reduction POCUS following reduction of pediatric single-bone forearm fractures predicted 89% of blinded pediatric orthopaedic interpretation of adequate post-reduction fluoroscopy [8]. Comparable to its use in disaster relief, POCUS-guided pediatric forearm reduction in a resource-

Table 4
Performance of orthopaedist-interpreted POCUS in prediction of post-reduction malalignment by subjective and rules-based criteria.

Assessment	Sensitivity	Specificity	LR+	LR−
Radius, subjective	3/3	47/53	8.8	0.0
	1.0 (0.44–1.0)	0.89 (0.77–0.95)	(4.2, 18.8)	(–)
Radius, rules-based[a]	3/3	46/53[b]	7.6	0.0
	1.0 (0.44–1.0)	0.87 (0.75–0.94)	(3.8, 15.1)	(–)
Ulna, subjective	0/0	36/36	–	–
	–	1.0 (0.90–1.0)		
Ulna, rules-based[a]	0/0	36/36	–	–
	–	1.0 (0.90–1.0)		
Pooled, subjective	3/3	83/89	14.8	0.0
	1.0 (0.44–1.0)	0.93 (0.86–0.97)	(6.9, 32.1)	(–)
Pooled, rules-based[a]	3/3	82/89[b]	12.7	0.0
	1.0 (0.44–1.0)	0.92 (0.85–0.96)	(6.2, 25.9)	(–)

LR+, likelihood ratio of positive test; LR−, likelihood ratio of negative test.
[a] Rules-based criteria for acceptable residual fracture angles: for patients <9 years old, ≤15° for all fractures; for patients ≥9 years old, ≤10° for proximal fractures and ≤ 15° for distal fractures.
[b] Subjective and rules-based determinations differed by a single radial fracture whose dorsal POCUS angle was 14° by non-orthopaedic readers (1 of 92 eligible bones, 1%). Difference in specificities: 1° (95% CI: −7° to 9°).

limited environment resulted in successful alignment in 94% of cases unblinded review of post-reduction radiographs by the orthopaedic surgeon responsible for initial reduction and subsequent operative care [7,16]. In adult and combined adult and pediatric populations, POCUS-guided reductions resulted in rates of satisfactory reduction and need for operative repair comparable to fluoroscopic and blind reductions [17-19].

The average age of 7.9 years makes our population one of the youngest studied in the role of ultrasound in pediatric fracture care [9,21]. Previous studies utilizing POCUS in pediatric forearm fracture reduction have averaged between 9 and 12 years of age [8,10,15]. This study is unique in that over half of the study group was <9 years of age, an age group in which higher post reduction residual fracture angles are tolerated [2]. The greatest practical benefit of ultrasound may exist in the younger cohort of children in whom the ultrasound probe covers a greater portion of the bone length. For example, a 3.8 cm linear US probe allows visualization of approximately one-third of the 13 cm radius of the average 4-year-old boy but only 15% of the 25 cm radius of the average18-year-old male [22-23].

Prior pediatric studies used 2 US views per fracture during forearm fracture reductions [8,10,15]. Adult studies have used 1, 2, or 3 views per fracture during forearm fracture reductions [17-19]. We obtained 3 post-reduction US views per fracture because of the previously reported increased sensitivity and specificity (both 98%) compared with 2 views (sensitivity 96%, specificity 90%) in the detection of pediatric forearm fractures, particularly because of better identification of overlapping or volar displacement of fragments [21]. While the radiation dose from fluoroscopy is low compared to other modalities such as CT, reduction of radiation exposure is a benefit of POCUS in fracture care. Previously reported median fluoroscopy-related radiation exposure time was 6.7 s [8]. Replacement of fluoroscopy with POCUS in our population would have eliminated a median of 19 s of fluoroscopy exposure. The total fluoroscopy exposure time in our study was higher in comparison to single bone forearm fracture reductions, but not unexpected as reduction of both bone fractures is more time consuming and complicated [3].

We acknowledge several limitations of our study. Because criteria for adequate reductions vary with age, we relied on a blinded pediatric orthopaedic surgeon's subjective assessment as well as rules based objective criteria from a single publication as our reference standards [2]. Image acquisition by a single investigator decreased variability in technique and demonstrated the feasibility of POCUS for fracture reduction by relative novices without formal training. However, a single sonographer may have systematically introduced technical variations affecting the blinded interpretations and limits our ability to generalize to other providers with different levels of experience. In addition, the ED investigator obtained static images with knowledge of the location and morphology of the fracture. The US operator likely adjusts in real-time for the visual difference between US angles at cortex and fluoroscopic angles along medullary midlines. However, reviewers were blinded to fracture location and real-time imaging, viewing only static images of a short segment of cortex led to a subset of images that could not be confidently interpreted. Reasons the reviewers cited for inability to interpret images were: unclear fracture site, static nature of the image, length of fracture not captured on image frame, and difficulty measuring angle near the metaphysis. Future studies may include a visual marker at the fracture site of a static image or record dynamic video clips of the site. Furthermore, despite the marked initial displacement, our orthopaedists' use of real-time fluoroscopic guidance may have resulted in an over-representation of well-reduced fractures, and we cannot generalize our findings to populations with higher prevalence or severity of post-reduction malalignment. However, we expect that POCUS would more easily identify less well-aligned fractures. In addition, the only data available to inform our sample size calculation compared ultrasonography and plain radiography for initial diagnosis rather than reduction, excluded an unknown number of subjects with minimal angulation, and did not state methods of measurement [9]. The potentially greater instability of radioulnar fractures may have allowed undetected changes in post-reduction position during the brief interval between ultrasound and fluoroscopy. Most fractures were in the distal forearm, where the flaring of metaphysis exaggerates the angle detected by ultrasound compared to fluoroscopy, which allows measurement along the midline of the medullary canal. Finally, in the absence of repeated measurements, we were unable to determine the reproducibility of our blinded reviewers' measurements.

5. Conclusions

POCUS determination of post-reduction fracture alignment is comparable to that obtained by fluoroscopy and should be used to guide pediatric fracture reduction when bedside fluoroscopy is not available in the ED or in resource-limited medical environments. If the sensitivity demonstrated in our study can be reproduced, POCUS might suffice to determine adequacy of reduction before casting, reserving fluoroscopy for fractures with inadequate reduction on POCUS. Future research employing a randomized comparison of US against blind or fluoroscopy-guided reduction would better demonstrate the chronologic, radiologic, anatomic, and age-related outcomes of US in guiding fracture reduction in children.

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Conflicts of interest

None.

Disclaimers

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Appendix 1. Fracture characteristics, alignment prediction, agreement and interrater reliability for subsets of single- and both-bone fractures

Following analysis of data for our primary and secondary objectives, we conducted additional analyses in order to provide information on the performance of POCUS and on the agreement between investigators providing interpretations.

Characteristics of fractures interpretable and uninterpretable by POCUS

During data analysis, blinded investigators found a subset of post-reduction POCUS images difficult to interpret. We sought to identify differences in fractures interpretable and uninterpretable on POCUS by comparing their fluoroscopic characteristics. Defining sagittal plane POCUS studies as interpretable if both blinded readers provided measurements from dorsal and volar surfaces images, we compared their lateral fluoroscopic angular measurements against those without both dorsal and volar angles interpreted by both readers. Similarly, we compared AP fluoroscopic angular measurements between POCUS studies that had coronal angles (from radial or ulnar surfaces) interpretable by both readers with studies without coronal angles interpreted by both readers. The fluoroscopic post-reduction angulation did not differ between interpreted and uninterpreted POCUS images (Supplemental Table A).

Agreement between readers and interrater reliability of POCUS and fluoroscopy

In addition to mean angular differences presented in the main results, we calculated other measures of agreement between readers for both study imaging modalities. For agreement on POCUS interpretation, we used the angular measurements by the blinded radiology (JN) and POCUS-trained emergency medicine (NH) readers. For agreement on fluoroscopic measurements, an investigator blinded to clinical details (JK) measured fracture angles from de-identified fluoroscopic images in AP and lateral projections using the same instrument and rules as for measurements as detailed in our Methods section. We analyzed POCUS angles from all 3 probe surfaces and fluoroscopic angles from both projections and calculated the following measures for each bone alone and for both bones combined: correlation coefficient with p-value, proportion of measurements agreeing within 1° with 95% confidence interval, and proportion of measurements agreeing within 3° with 95% confidence interval. For images in the sagittal plane (POCUS with dorsal and volar probe placement and fluoroscopy in lateral projection), we used our rules-based criteria [2] to categorize angular data as representing adequate or inadequate post-reduction alignment and calculated the corresponding kappa statistic. We omitted coronal plane POCUS and AP fluoroscopic images from calculations of kappa statistic because published criteria describe angles that most clinicians would not find acceptable for radial and ulnar deviation. We also calculated differences in fluoroscopic angular measurements between the blinded radiology and emergency medicine reader.

Correlation coefficients for POCUS measurements ranged from 0.77 to 0.93, and for fluoroscopy ranged from 0.71 to 0.90, all p values <0.0001 (Supplementary Table B). Agreement for POCUS angular measurements were within 1° in 47% to 69% and increased to 70% to 82% for agreement within 3°. Fluoroscopy agreed within 1° for 38%–58% of fractures and within 3° for 87–9%. Kappa statistics for POCUS were 0.65–0.88 and for fluoroscopy were 0.79 for all comparisons, but the 95% confidence intervals were wide except when fractures of both bones were pooled. Mean differences between the 2 readers for 94 fluoroscopic angular measurements were 0.9° (0.4°, 1.4°) for pooled lateral and 0.4° (−0.1°, 0.9°) for pooled AP projections.

Ability of POCUS to predict fracture alignment in subsets with single- or both-bone reductions

POCUS performed well with sensitivity of 100% and specificity of 92–93% when radial and ulnar fractures were analyzed together (Supplementary Table C). In order to demonstrate whether POCUS performed differently based on fracture complexity, we analyzed diagnostic performance of POCUS by subjective and rules-based criteria in subsets undergoing single- and both-bone reductions. Although the 95% CIs widened with the smaller numbers analyzed, the point estimates for sensitivity, specificity, and positive likelihood ratio differed little from the previously calculated diagnostic indices.

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