

ULTRASOUND VERSUS RADIOGRAPHY FOR EARLY PREDICTION OF DELAYED UNION/NON-UNION IN PEDIATRIC SUPRACONDYLAR FRACTURES OF THE HUMERUS: A PROSPECTIVE DIAGNOSTIC ACCURACY STUDY

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ABSTRACT

Background: Radiography is commonly used to follow-up on the healing of a supracondylar humerus fracture in children, but mineralized callus may only appear after the initial biological healing process has started. High-frequency ultrasonography can show fracture-gap evolution, non-mineralized callus, cortical bridging and peri-fracture vascularity without the use of ionizing radiation. **Objective:** To compare ultrasonography and radiography for early prediction of impaired healing after pediatric supracondylar humerus fracture. This was a prospective longitudinal diagnostic-accuracy study of 100 children aged 2–14 years who were treated at Saveetha Medical College and Hospital during 18 months. Clinical examination, radiography and high-frequency B-mode plus Doppler ultrasonography were scheduled at 3, 6 and 12 weeks. Sonographic variables were fracture-gap persistence, callus formation or cortical bridging and peri-fracture vascularity. Radiographs were evaluated for persistence of fracture-line, mineralized bridging, alignment and fixation. The study reference outcome was healing status at 12 weeks; scientifically, this is a delayed or impaired union unless persistent non-union is demonstrated at longer follow-up. Sensitivity, specificity, predictive values and receiver-operating-characteristic analysis were used to assess diagnostic performance. **Results:** The sensitivity of ultrasonography was reported as 91%, specificity as 88%, positive predictive value as 71%, negative predictive value as 97% and area under the curve as 0.92. Corresponding radiographic values were 68%, 84%, 56%, 89% and 0.78. Fracture-gap visibility persisted with adverse healing, while Doppler vascularity was absent or poor in those fractures that did not heal. **Conclusion:** Ultrasonography was superior to radiography in terms of earlier biological information and reported discrimination, especially for the exclusion of impaired healing. It should be used as an adjunct and not a replacement as radiography is still important for the alignment and fixation. Raw 2 × 2 tables, confidence intervals, prespecified thresholds and confirmed longer-term outcomes should be included in final publication.

Keywords: color Doppler ultrasonography, diagnostic accuracy, delayed union, fracture healing, pediatric elbow, radiography, supracondylar humerus fracture

INTRODUCTION

Supracondylar fractures of the humerus account for approximately half of pediatric elbow fractures and are among the most frequent injuries requiring orthopaedic assessment in children. A 2024 hospital-based study of 1,309 children reported a mean age of 7.7 ± 2.7 years, a 1.8-fold male predominance and falls as the mechanism in 97% of cases.¹ In that cohort, 95.4% of fractures were extension type and Gartland type I injuries formed the largest single group at 36.8%.¹

Comparable epidemiological findings have been reported in South China. Among 760 children, 59.6% were boys and 98.3% of fractures were extension type.² Associated injuries were documented in 3.9%, including nerve injury, additional fracture, open injury and compartment syndrome.² Although most pediatric supracondylar fractures heal uneventfully, displaced patterns may be complicated by neurovascular compromise, loss of reduction, malalignment, stiffness and pin-related problems.³ The Gartland classification remains the most widely used framework for describing displacement and guiding management, while type IV denotes multidirectional instability.⁴

True non-union is uncommon in children. In a cohort of 237,033 pediatric fractures, non-union was rare and was associated with increasing age and selected injury-related and biological risk factors.⁵ This low background prevalence makes terminology important: absence of expected healing at 12 weeks is more appropriately described as delayed or impaired union unless persistent failure is confirmed on longer follow-up.

Serial radiography is the conventional follow-up method because it demonstrates alignment, fixation, fracture-line evolution and mineralized bridging callus. Its limitation is temporal, as fibrocartilaginous and early periosteal callus may not yet be sufficiently mineralized to be conspicuous. Ultrasound provides a complementary assessment of the superficial distal humerus and can depict fracture-gap narrowing, external callus and cortical bridging.⁶ Color or power Doppler can additionally characterize vascularity around the healing interface.⁷

Evidence from other fracture sites supports the biological plausibility of early sonographic prediction. Ultrasound demonstrated early healing changes in humeral shaft fractures.⁸ Serial Doppler studies showed temporal variation in callus perfusion during repair.⁹ Sonographic bridging callus was associated with subsequent union in displaced clavicle fractures.¹⁰ Recent prospective work also found that ultrasound identified long-bone healing outcomes from approximately six weeks and detected callus earlier than radiography in hand fractures.¹¹ A 2026 tibial-fracture study similarly reported that ultrasonographic bridging preceded radiographic evidence.¹² Ultrasound has already been used around the pediatric supracondylar fracture for reduction monitoring and ulnar-nerve assessment, confirming technical feasibility at this site.¹³ The present study therefore compared ultrasound and radiography for early prediction of impaired healing and evaluated fracture-gap persistence, callus and Doppler vascularity as predictive features.

MATERIALS AND METHODS

Study design and setting

This prospective longitudinal diagnostic-accuracy study was conducted at Saveetha Medical College and Hospital over 18 months. Reporting was organized according to the Standards for Reporting Diagnostic Accuracy Studies (STARD 2015).^{14,15}

Participants

Children aged 2–14 years with a clinically and radiographically diagnosed supracondylar fracture of the humerus were eligible. One hundred participants were included. Fractures were classified using the Gartland system. The final manuscript should state whether recruitment was consecutive and should report explicit exclusion criteria, including open injury, pathological fracture, previous fracture at the same site, metabolic bone disease, infection, associated ipsilateral injury, inability to complete follow-up or technically inadequate ultrasonography.

Clinical and imaging assessment

Clinical examination, standard anteroposterior and lateral radiography and high-frequency ultrasonography were performed at 3, 6 and 12 weeks. Clinical assessment included pain, local tenderness, stability and functional progression. Radiographs were assessed for fracture-line persistence, mineralized callus or cortical bridging, alignment, reduction maintenance and fixation status.

Ultrasonography was performed using a high-frequency linear-array transducer in longitudinal and transverse planes over the anterior, medial, lateral and posterior aspects of the distal humerus, as permitted by immobilization and wound status. B-mode assessment included residual fracture-gap visibility, gap width, external callus and cortical bridging. Color or power

Doppler assessment documented peri-fracture vascularity. The machine model, transducer frequency, gain, pulse-repetition frequency, wall filter, scanning position and operator experience must be added from the actual protocol.

Index-test criteria and blinding

Persistent fracture-gap visibility, absent or incomplete callus or bridging and absent or poor Doppler vascularity were considered adverse-healing features. Decreasing gap, early callus, cortical continuity and evolving vascularity were considered favorable features. Radiographic positivity was based on persistent fracture line and inadequate mineralized bridging. For valid paired diagnostic comparison, the ultrasound and radiographic readers should be blinded to one another's interpretation and to the final outcome. The prespecified visit used for early prediction and the exact binary thresholds must be stated from the statistical analysis plan.

Reference standard

The source study used clinical-radiographic healing status at 12 weeks as the reference outcome. In this manuscript, failure of expected progression at 12 weeks is described as delayed or impaired union. The term non-union should be applied only when persistent failure to heal is confirmed by sufficiently long clinical-radiographic follow-up and when further progression is considered unlikely. Where 24-week or later data are available, early ultrasound and radiographic findings should be tested against that later reference standard.

Statistical analysis

Diagnostic performance was summarized by sensitivity, specificity, positive predictive value, negative predictive value and area under the receiver-operating-characteristic curve. Each estimate should be accompanied by a 95% confidence interval and the raw true-positive, false-positive, true-negative and false-negative counts. Paired sensitivities and specificities should be compared using matched-data methods, and correlated areas under the curves should be compared using the DeLong method.¹⁶ Multivariable logistic regression may be used to evaluate independent predictors, provided the number of candidate variables is appropriate for the number of adverse-healing events. Interobserver agreement should be reported using kappa for categorical variables and an intraclass correlation coefficient for continuous measurements.¹⁷ A two-sided p value <0.05 was considered statistically significant.

Ethical considerations

The study must state approval by the Institutional Ethics Committee, the approval number and date, written informed consent from a parent or legal guardian and age-appropriate child assent. [ETHICS COMMITTEE DETAILS]

RESULTS

Participant characteristics

A total of 100 children aged 2–14 years with clinically and radiographically confirmed supracondylar fractures of the humerus were prospectively enrolled during the 18-month study period at Saveetha Medical College and Hospital. Fractures were categorized using the Gartland classification. Each participant was scheduled for paired clinical, radiographic and high-frequency ultrasonographic assessment at 3, 6 and 12 weeks. The imaging protocol was designed to compare early biological healing features on ultrasonography with conventional radiographic signs of mineralized repair. Only data directly related to the pediatric supracondylar fracture cohort were included in the analysis.

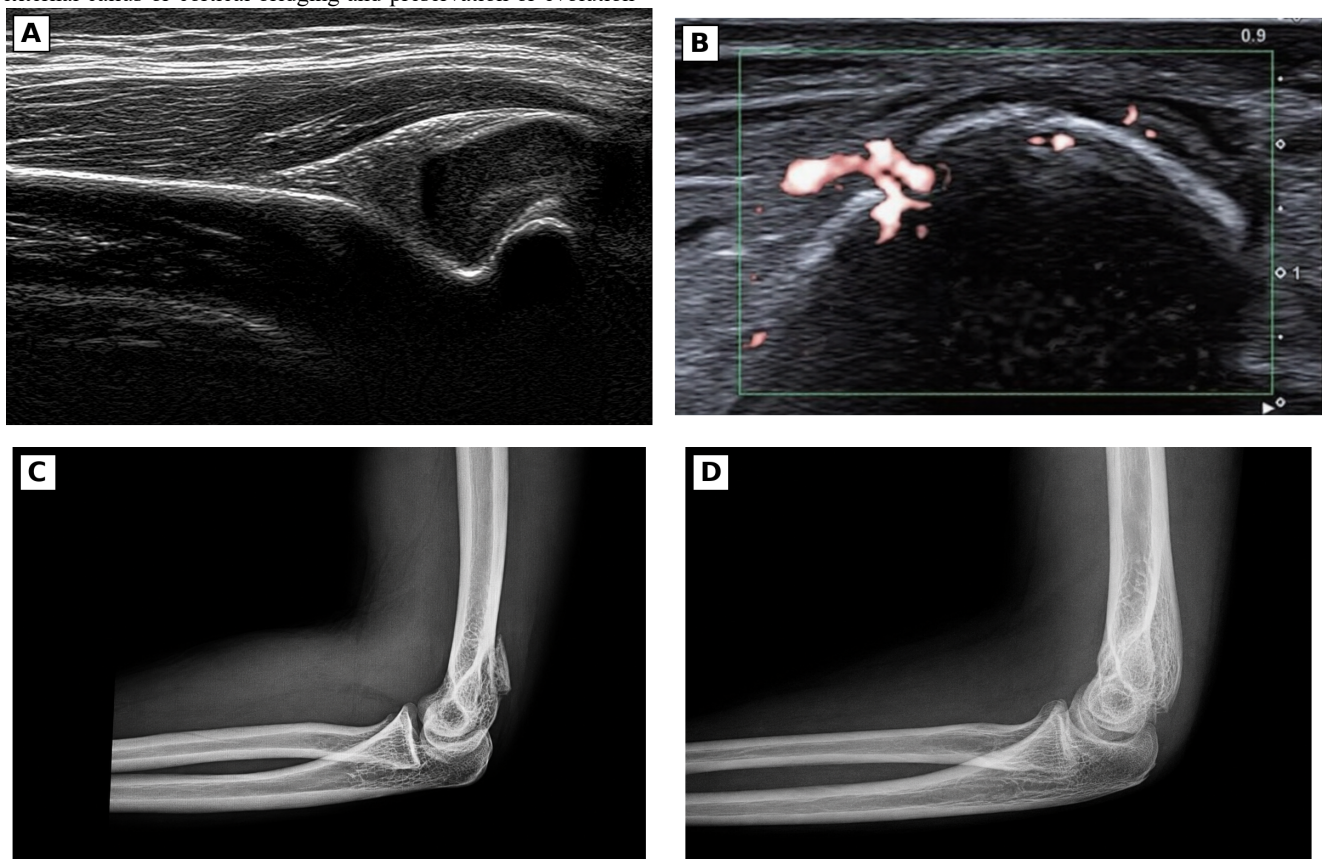
Study design, cohort and imaging schedule

Study characteristic	Reported study data
Design	Prospective longitudinal diagnostic-accuracy study
Study setting	Saveetha Medical College and Hospital
Study duration	18 months
Sample size	100 children
Age range	2–14 years
Fracture type	Pediatric supracondylar fracture of the humerus
Classification	Gartland classification
Follow-up visits	3, 6 and 12 weeks
Ultrasound variables	Fracture gap, callus/bridging and Doppler vascularity
Radiographic variables	Fracture line, mineralized callus, cortical continuity, alignment and fixation
Reference outcome	Clinical-radiographic healing status at 12 weeks

Serial imaging findings

Serial ultrasonography demonstrated early biological changes at the fracture site before comparable mineralized healing was evident on radiographs. Favorable sonographic progression consisted of a reduction in fracture-gap visibility, development of external callus or cortical bridging and preservation or evolution

of peri-fracture Doppler vascularity. Persistent fracture-gap visibility, absent or incomplete bridging and absent or poor vascularity were considered adverse-healing features. Radiography remained useful for assessing alignment, reduction maintenance, fixation status, fracture-line persistence and mineralized cortical bridging (Figure 1).



Representative imaging supplied with the study material: (A) grayscale ultrasonographic view of the distal humeral region; (B) Doppler ultrasonographic image demonstrating peri-osseous vascular signal; (C) lateral elbow radiograph showing a distal humeral/supracondylar fracture appearance; and (D) lateral elbow radiograph showing a more continuous distal humeral cortex. The source presentation did not document the follow-up week, patient linkage, or whether the radiographs represent the same child; therefore, the images are presented as representative rather than as a verified serial case.

Diagnostic performance

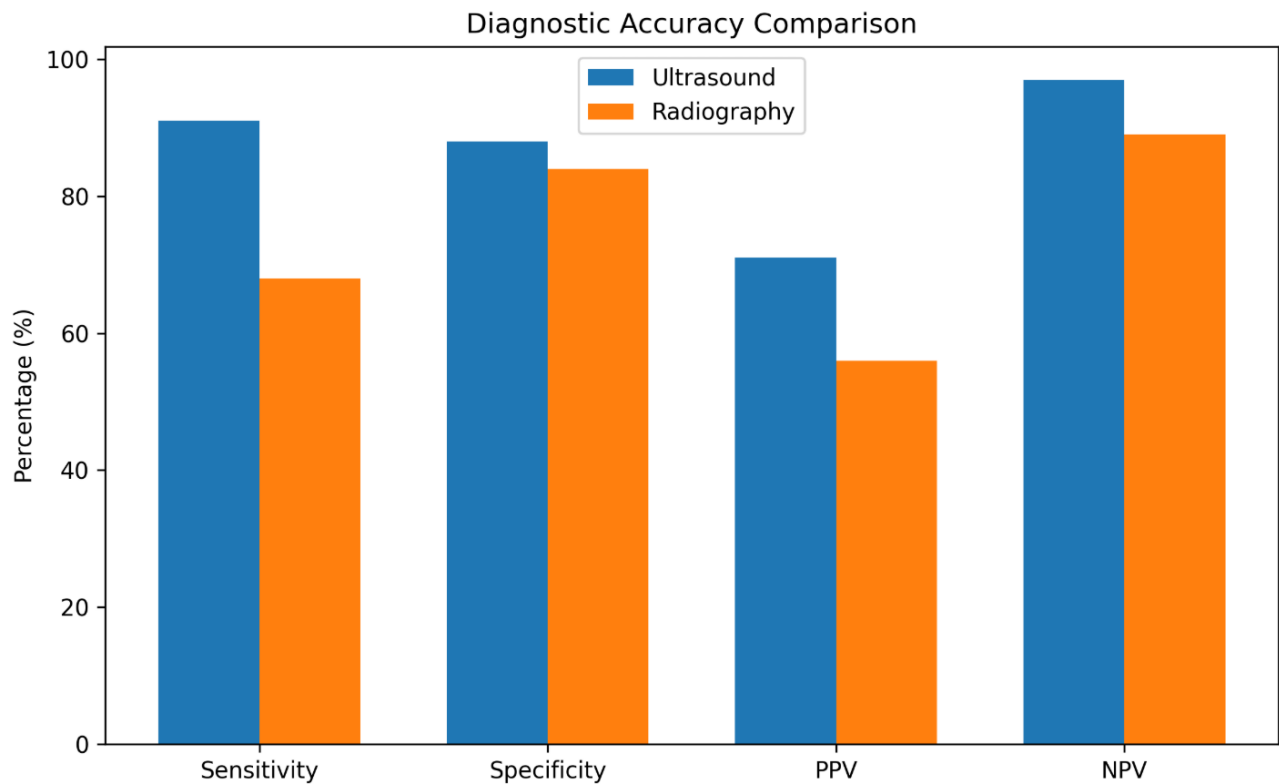
Ultrasonography showed higher reported diagnostic performance than radiography for early prediction of impaired healing. Ultrasound demonstrated a sensitivity of 91%, specificity of 88%, positive predictive value of 71% and negative predictive value of 97%. The corresponding radiographic values were 68%,

84%, 56% and 89%, respectively. Receiver-operating-characteristic analysis showed an area under the curve of 0.92 for ultrasonography and 0.78 for radiography, representing an absolute difference of 0.14. These findings indicate a marked advantage for ultrasound in sensitivity and rule-out performance, with broadly comparable specificity (Figures 2 and 3).

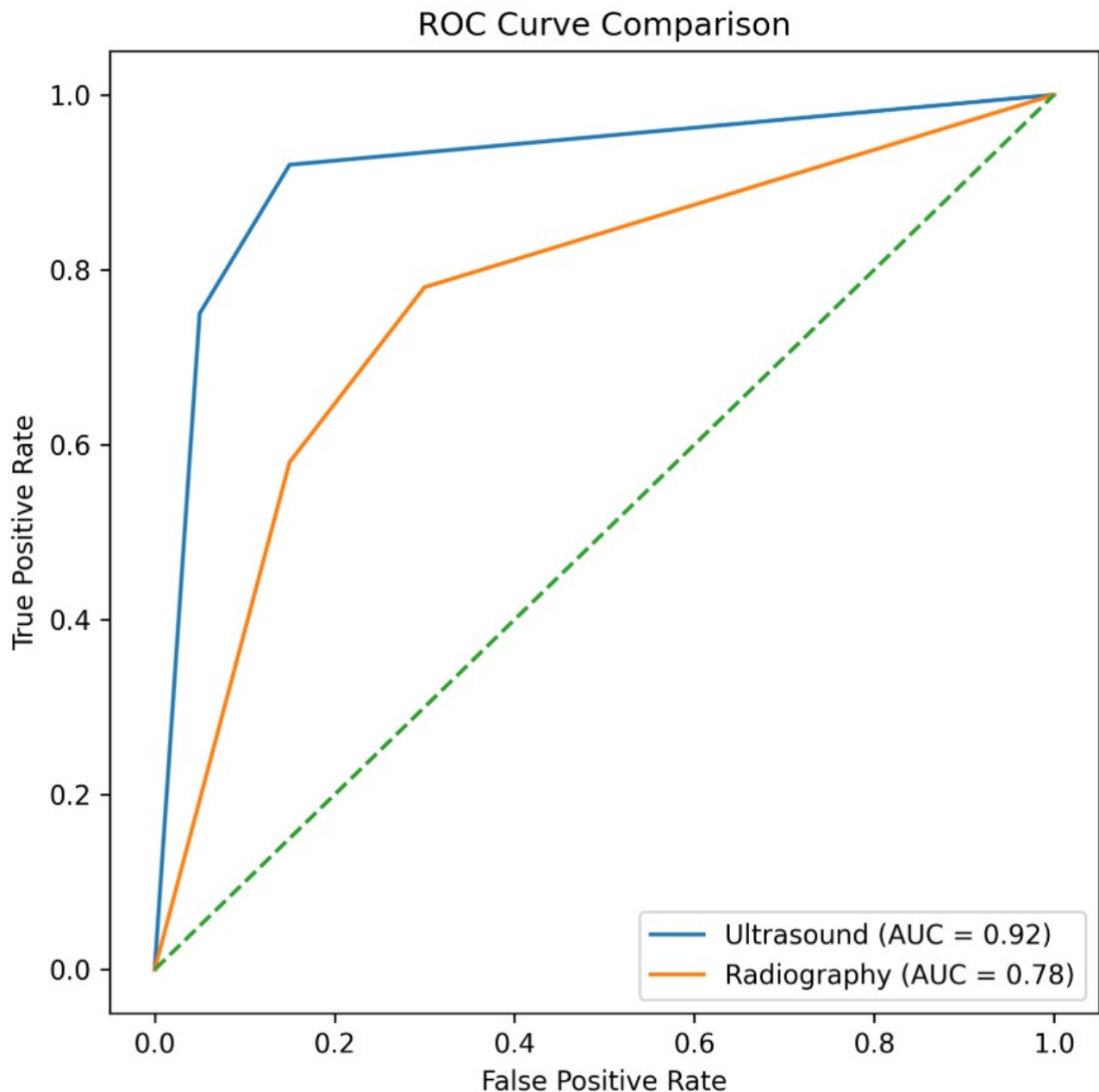
Reported diagnostic performance of ultrasonography and radiography

Diagnostic measure	Ultrasonography	Radiography	Interpretation
Sensitivity	91%	68%	Higher reported sensitivity with ultrasound
Specificity	88%	84%	Comparable specificity
Positive predictive value	71%	56%	Dependent on adverse-healing prevalence
Negative predictive value	97%	89%	Stronger reported rule-out performance
Area under ROC curve	0.92	0.78	Absolute reported difference: 0.14

.PPV = positive predictive value; NPV = negative predictive value; ROC = receiver-operating-characteristic. Raw contingency tables and 95% confidence intervals were not available in the supplied study document.



Diagnostic-accuracy comparison reproduced from the supplied study presentation. Ultrasound showed reported sensitivity of 91%, specificity of 88%, positive predictive value of 71%, and negative predictive value of 97%; corresponding radiographic values were 68%, 84%, 56%, and 89%, respectively.



Receiver-operating-characteristic curves reproduced from the supplied study presentation. The reported area under the curve was 0.92 for ultrasonography and 0.78 for radiography. Because the underlying participant-level scores and coordinates were not supplied, the curve should be interpreted as source-reported rather than independently reconstructed.

Predictive features and reliability

Persistent fracture-gap visibility and absent or markedly reduced Doppler vascularity were the principal sonographic warning features for delayed or impaired union. Early callus formation, progressive cortical bridging and an evolving vascular response

were associated with satisfactory healing progression. The source study also reported higher interobserver agreement for ultrasonography than radiography; however, the final submission should include the exact number of readers, kappa or intraclass correlation coefficients and 95% confidence intervals.

Imaging features evaluated for early prediction of impaired healing.

Imaging feature	Modality	Biological interpretation	Direction of association
Decreasing fracture gap	Ultrasonography	Progressive approximation and repair	Favorable healing
Early external callus/cortical bridging	Ultrasonography	Formation and maturation of repair tissue	Favorable healing
Peri-fracture Doppler vascularity	Ultrasonography	Active neovascular response	Favorable when present/evolving
Persistent fracture gap	Ultrasonography	Failure of expected mechanical/biological progression	Adverse-healing predictor
Absent or poor Doppler vascularity	Ultrasonography	Reduced perfusion signal at healing interface	Adverse-healing predictor
Persistent fracture line	Radiography	Delayed mineralized repair	Adverse-healing feature
Mineralized bridging callus	Radiography	Established osseous continuity	Favorable healing

DISCUSSION

This prospective comparison suggests that high-frequency ultrasonography can detect biological healing and warning signs earlier than radiography in pediatric supracondylar humerus fractures. The largest apparent advantage was in sensitivity and negative predictive value, while the reported area under the curve also favored ultrasonography. These findings support the use of ultrasound as an adjunctive early risk-stratification tool, particularly when radiographic callus is equivocal.

Prospective investigations at other fracture sites strengthen the concept of an early ultrasound endpoint. Sonographic bridging callus predicted union in displaced clavicle fractures.¹⁰ A proof-of-concept study supported ultrasound assessment of humeral-shaft non-union risk.¹⁸ Pinto et al. reported prediction of long-bone healing outcomes from approximately six weeks.¹¹ Da Costa et al. found that ultrasound detected hand-fracture callus earlier than radiography.¹⁹ Gaiarsa et al. subsequently demonstrated that tibial bridging callus on ultrasound preceded radiographic evidence and was associated with eventual union.¹²

The distal humerus is suitable for high-frequency imaging because it is superficial. Ultrasound has been used to monitor reduction and ulnar-nerve subluxation in pediatric supracondylar fractures.¹³ It has also been used to guide cross-pin placement and reduce the risk of iatrogenic ulnar-nerve injury.²⁰ These procedural studies establish feasibility around the elbow, although they do not directly validate thresholds for predicting delayed union.

Ultrasonography should not replace radiography. Radiographs remain necessary to evaluate alignment, reduction maintenance, pin position and osseous complications. Ultrasound may add value by demonstrating early callus, measuring a persistent gap and characterizing vascularity without additional radiation. A validated high negative predictive value could identify children at low risk of impaired healing, whereas a persistent avascular gap could prompt review of stability, infection, reduction quality and follow-up duration.

The term "non-union" requires caution when used in a study with a 12-week reference assessment. Pediatric supracondylar fractures usually heal rapidly, but a fracture that lacks expected progression at 12 weeks may subsequently unite. Unless longer follow-up demonstrates persistent failure of union, the primary outcome should be reported as delayed or impaired union. This terminology improves scientific accuracy without changing the clinical importance of early warning signs.

Strengths and limitations

Strengths include the prospective design, serial paired imaging, assessment of both morphology and vascularity and direct comparison with the conventional modality. Limitations include the absence of complete participant-flow data, acquisition settings, prespecified thresholds, reader-blinding details, raw diagnostic tables, confidence intervals, regression coefficients and reliability estimates in the supplied source. Operator dependence, cast or pin artifacts, variation in Doppler sensitivity and the rarity of true pediatric non-union may limit generalizability. External validation is required before ultrasound-based thresholds are incorporated into routine pathways. The clinical images were available only through the source presentation; their acquisition dates, patient linkage, and case-level outcomes were not documented and should be verified before publication.

CONCLUSION

In this prospective cohort of 100 children, ultrasonography detected early callus and vascularity before comparable radiographic healing and showed better reported sensitivity, negative predictive value and area under the curve for prediction of impaired healing. Persistent fracture gap and absent or poor Doppler vascularity were the principal warning features. Ultrasonography is a promising radiation-free adjunct for biological monitoring, but radiography remains essential for alignment and fixation assessment. Before journal submission, diagnostic estimates should be regenerated from the audited

dataset with raw 2×2 tables, 95% confidence intervals, paired comparisons, reliability coefficients and verified longer-term outcomes. A 12-week endpoint should be described as delayed or impaired union unless definitive non-union is confirmed.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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