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Elbow injury in pediatric patients

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Elbow injury in pediatric patients

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Editorial: Elbow injury in pediatric patients

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Editorial on the Research Topic
Elbow injury in pediatric patients

Fractures of the distal humerus in children and adolescents present a diagnostic and therapeutic challenge to the orthopedic surgeon. "Pity the young surgeon whose first case is a fracture around the elbow," said Mercer Rang to emphasize the difficulties inherent in traumatic injuries to the child's elbow (1).

The distal end of the humerus is the second most common site of fracture in children, yet it is the most common indication for surgery. The distal end of the humerus, in addition to its anatomical complexity, is characterized by the presence of numerous ossification nuclei that appear at different times during skeletal maturation (2). These elements are responsible for the many uncertainties in the treatment of traumatic injuries that occur in this anatomical region, in addition to their scientific understanding.

A total of 12 articles and one commentary were selected after selective peer review for the Special Issue of *Elbow Injury in Pediatric Patients* to provide the latest diagnostic and therapeutic strategies for fractures, both common and rare, of the distal end of the humerus in children.

Despite their frequency, not all supracondylar humerus fractures (SHF) require surgical fixation. In particular, Coupal et al. investigated the optimal form of immobilization for the treatment of Gartland-type 1 SHFs and found that there was insufficient high-quality evidence to determine the best option. They reported that children treated with a cuff and collar had delayed return to normal daily life activities and experienced more pain than those treated with a posterior splint. However, no studies directly compared posterior splints with circumferential casts.

Qian et al. assessed the learning curve for successful reduction and fixation of SHFs and reported that 65 procedures are needed to master the surgical technique of closed reduction (CR) and percutaneous fixation; interestingly, they also pointed out that surgical experience significantly impacts the post-operative recovery of children with such injuries.

However, CR and percutaneous fixation are more difficult to achieve in children with an SHF presenting more than 14 days after the initial trauma. Liu et al. reported that CR with a minimally invasive technique followed by external fixation is a potential alternative to manage SHFs presenting 2 or more weeks after the initial trauma; the preliminary results are encouraging with satisfactory functional outcome and low complication rate.

Flexion-type SHFs are extremely challenging to treat due to their instability and rotation of the distal fragment. Sun et al. reported that flexion-type SHFs have a higher rate of ulnar nerve injury and are at a higher risk of open reduction, particularly when lateral displacement and rotation are present simultaneously.

Weng et al. compared the clinical and radiographic outcomes of CR versus open reduction in the treatment of severely displaced lateral condyle fractures (LCFs). They found that despite the relatively long learning curve, CR of severely displaced LCFs is challenging and successful reduction cannot always be achieved. They concluded that although CR of severely displaced LCFs has some advantages, including a smaller scar and lower rate of postoperative infection, open reduction and percutaneous fixation still remain the first-line treatment for such injuries. In their commentary, Rehm et al. highlighted that CR and percutaneous fixation of LCFs with >4 mm displacement are feasible in a significant proportion of cases with relatively good outcomes.

Magnetic Resonance Imaging (MRI) has already been shown to accurately diagnose LCFs and is a valuable tool to properly restore joint anatomy during surgery (3). The use of intraoperative ultrasound (US) to guide both the reduction and stabilization of fractures is steadily increasing in pediatric traumatology (4). Deng et al. reported a novel approach for the treatment of displaced LCFs. They advocated that LCFs should first be reduced by CR and fixed with two to three Kirschner wires (1.5–1.8 mm) inserted under intraoperative US guidance; interestingly, they pointed out that fragments with >4 mm displacement are easier to visualize with US. The reported technique reduces radiation exposure, has a relatively low complication rate, and provides a good functional outcome, even though the results are preliminary and from a single center (4). Similarly, Li et al. investigated the use of intraoperative US guidance in Elastic Stable Intramedullary Nailing (ESIN) for pediatric humeral shaft fractures. They found that US-guided CR and ESIN fixation decreased the risk of radial nerve injury. However, intraoperative US cannot completely replace the role of radiography in humeral fracture surgery, although it can significantly reduce radiation exposure.

Although many surgical techniques have been reported for the management of displaced intercondylar fractures (DIFs) of the humerus in children, there is no specific and accepted treatment protocol for such injuries. Shu et al. reported the results of CR, external fixation, and percutaneous pinning for the treatment of DIFs. They found that fracture stability and acceptable clinical and functional outcomes could be achieved in patients younger than 10 years of age. It has been reported that DIFs in children older than 10 years of age have a higher complication rate and poorer functional outcomes compared to younger children (5). Despite the satisfactory outcome reported by Shu et al. the treatment of such injuries remains challenging and yields unpredictable outcomes.

The group of Monteggia-equivalent fractures (MEFs) has grown steadily over the last 10 years and has complemented Bado's classic classification system. Su et al. evaluated the treatment and outcome of radial head and neck fractures associated with a fracture of the ulna, which is a very rare form of MEF. They recommended anatomic reduction and internal fixation of the ulna to restore its length, and CR and ESIN fixation of the radial neck fracture. If these principles are followed, and early rehabilitation is performed, the functional outcome is very satisfactory in most cases.

Distal forearm fractures have rarely been reported in association with Monteggia type III fractures. In their review of the literature, Gao et al. could only identify four cases of this particular association in children. They reported the case of a 9-year-old boy with a type III Monteggia fracture, ipsilateral forearm fracture, and concomitant radial nerve deficit. The patient underwent open reduction and internal fixation of the distal forearm and proximal ulna. The functional and radiologic outcome of the patient was good with full recovery of the radial nerve injury at 1-year follow-up.

The coronoid process of the ulna is essential for stabilizing the elbow joint. Its reconstruction is recommended in both acute and chronic injuries in order to restore elbow stability and prevent early degenerative changes. Jiang et al. reported the case of a 13-year-old boy with chronic postero-lateral dislocation of the left elbow due to the absence of the coronoid process of the ulna. They reconstructed the coronoid process with the tip of the olecranon and achieved good stability of the elbow joint at a 2-year follow-up. This clinical case demonstrates that the reconstruction of the coronoid process of the ulna with the proximal end of the olecranon provides good mid-term results in children with elbow instability due to the absence of the coronoid process of the ulna.

De Maio et al. performed a systematic review of the literature to identify the best operative treatment for children with displaced olecranon fractures with or without associated injuries. They found that surgically treated fractures generally have a good prognosis and that tension band suture is the preferred fixation, although it is not recommended in older children due to the high risk of fixation failure. They also reported that the outcome was worse in patients with associated injuries.

The presentation, management, and evolution of fractures of the distal end of the humerus in children are complex and require special attention. With this in mind, the articles in the Special Issue *Elbow Injury in Pediatric Patients* offer valuable insight into the diagnosis and treatment of such conditions.

Author contributions

QJ, TL, and FC: research topic editor. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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Elastic Stable Intramedullary Nailing for Pediatric Humeral Shaft Fractures Under Ultrasonographic Guidance: A Retrospective Study

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Objective: Fixation with an elastic stable intramedullary nail (ESIN) is a widely used technique for the treatment of humeral shaft fractures. Ultrasonography (US) is used as an auxiliary tool and alternative to radiography during surgery to reduce radiation damage, but whether it is effective in pediatric patients is not known. In this study we evaluated the utility of US in the treatment of pediatric humeral shaft fractures by closed reduction and fixation with an ESIN.

Methods: Children who were admitted to our hospital with humeral shaft fractures were retrospectively examined from January 2016 to March 2019. The patients were divided into 2 groups, US (treated by US-guided closed reduction and ESIN fixation) and non-US (treated with the same technique but with intraoperative radiography instead of US). The postoperative functional recovery of the 2 groups was compared.

Results: The study population comprised 28 boys and 17 girls (age range: 4–16 years) with humeral shaft fractures. US significantly reduced radiation exposure during the operation ($P = 0.008$), and intraoperative US facilitated the detection of nerve and vascular injury and aided surgical planning. There was no difference between the 2 groups in postoperative recovery based on the Constant–Murley shoulder score (CMS).

Conclusions: These results demonstrate that US-guided closed reduction and ESIN fixation for humeral shaft fractures can limit radiation exposure and help doctors to determine the optimal surgical strategy to avoid radial nerve injury.

Keywords: ultrasonography, humeral shaft fracture, close reduction, pediatric fracture, radiation exposure

INTRODUCTION

Humeral shaft fractures in children are exceedingly rare, accounting for 0.4–3% of all pediatric fractures with higher incidences in children younger than 3 years or older than 10 years (1–4). A conservative treatment approach that includes functional bracing, skin traction, and casts is used in these patients, which is associated with a good prognosis (5); however, there are also certain shortcomings such as skin damage at the traction site, long bed rest and hospitalization for patients with traction, and potential displacement of fractures (6).

Closed reduction and fixation with an elastic stable intramedullary nail (ESIN) is an excellent choice for the treatment of pediatric humeral shaft fractures, especially for older children. The advantages of this approach include minimal invasiveness, rigid fixation of fracture sites, a short hospitalization, and early postoperative functional recovery, although complications such as skin lesions, surgical site infection, and iatrogenic fracture can arise (7, 8). Additionally, both patients and doctors are exposed to high-dose radiation from X-rays used to visualize a closed fracture site with traditional surgical methods (9, 10).

Ultrasonic technology has the advantages of portability, non-invasiveness, and painlessness, and it is now used extensively for the diagnosis and treatment of fractures in children (11, 12). Ultrasonography (US) is superior to radiography for the precise assessment of radial nerve injury in patients with humeral shaft fractures (13). In our clinical experience, US-guided closed reduction and ESIN fixation of pediatric humeral shaft fractures is feasible. The aim of this retrospective study was to evaluate the utility of US for the surgical treatment of ESIN-treated humeral shaft fractures.

MATERIALS AND METHODS

Setting

Children who were admitted to our hospital with humeral shaft fractures from January 2016 to March 2019 were included in this analysis. The inclusion criteria were as follows: (1) <16 years of age; and (2) humeral shaft fracture treated with an ESIN. Exclusion criteria were as follows: (1) multiple fractures, open fractures, or pathologic or comminuted fractures; (2) failure of closed reduction; (3) oblique fractures requiring fixation with a Kirschner wire; (4) incomplete follow-up; and (5) fractures with neurovascular involvement. We started using US to guide closed reduction treatment of humeral shaft fractures with ESIN in February 2018. Patients who were admitted between February 2018 and March 2019 constituted the US group, whereas those who were admitted from January 2016 to February 2018 were the non-US group (without US). All patients underwent routine postoperative follow-up for at least 12 months and were given exercises for functional recovery, which was assessed with the Constant–Murley shoulder (CMS) score (14) at the last follow-up.

Consent for study participation was obtained from the guardian of each patient and the study protocol was approved by the ethics committee of our hospital. Dates in the study were obtained from hospital records.

Surgical Procedure

US was performed using a model CX50 color ultrasonic diagnostic apparatus (Philips, Amsterdam, Netherlands) with an L3-12 high-frequency linear probe and probe frequency of 5 MHz. Bedside C-arm fluoroscopy was performed with a model uMC 560i instrument (United Imaging, Shanghai, China). All surgeries were performed by 3 pediatric orthopedic surgeons who were experienced in the ESIN technique and US, and the same ESIN configuration was used in all patients.

Routine preoperative preparation was performed using a sterile endoscope cover-wrapped probe with iodophor as the ultrasonic couplant. The fracture was examined by US to determine whether there was soft tissue or nerve incarceration and whether closed reduction was feasible. A 1–1.5-cm skin incision was made at the lateral epiphysis of the distal humerus, and the soft tissue was separated. The distal humerus was perforated with a bone cone (Johnson & Johnson, New Brunswick, NJ) while avoiding damage to the epiphyseal plates. A pre-bent ESIN (Johnson & Johnson) of the proper diameter was slowly inserted into the hole, using US to monitor whether the ESIN exited at the fracture site. If the ESIN was difficult to insert or was not observed at the broken end of the fracture, the C-arm X-ray was used to determine its position in the marrow cavity. The bone cortex and ESIN are bright and hyperechoic on US images and are thus easily identified. When the ESIN was detected at the fracture site, it was slowly retracted into the marrow cavity. Closed reduction of the fracture appeared as an approximately straight line of cortical echo by US. The ESIN was subsequently reinserted past the fracture site. US was used to examine the fracture site from all directions to ensure that the ESIN did not protrude from the bone marrow cavity. Sometimes the ESIN in the marrow cavity was also observable at a specific location by US. After the ESIN was advanced to the appropriate site, its position was confirmed by radiography. The operation was repeated at the epiphysis of the medial condyle of the distal humerus, with care taken to avoid damaging the ulnar nerve (**Figure 1**). After surgery, the limb was immobilized with a functional brace or plaster.

Follow-Up

All patients underwent X-ray examination on the first day after surgery and were discharged for follow-up in an outpatient clinic on Day 2 if there were no exceptional circumstances. The incision was verified 7 days after surgery and X-ray examination was performed at 3 and 6–8 weeks and 4, 6, and 12 months. Functional exercises were started 6–8 weeks after the surgery by the patients with the aid of family members who were given instructions on the exercises. Anteroposterior and lateral radiographs of the humerus were reviewed at each visit to evaluate callus formation at the fracture site and identify complications such as secondary displacement, delayed union, nonunion, or malunion. All patients were followed up for at least 12 months and shoulder function was evaluated based on CMS at the last follow-up.

Statistical Analysis

SPSS v25 (IBM, Armonk, NY) was used for statistical analyses. Differences between categorical variables were evaluated with Pearson's $\chi 2$ test. The *P* value threshold for significance was set at 0.05.

RESULTS

Characteristics of the Study Population

The study population comprised 28 boys and 17 girls; 24 children were assigned to the US group and 21 to the non-US group. There

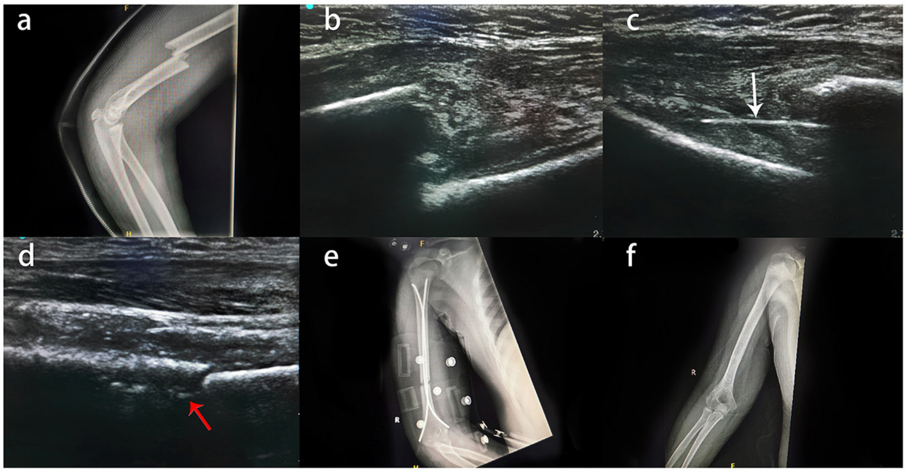

FIGURE 1 | Typical case of an 11-year-old boy with right humeral shaft fracture treated by US-guided closed reduction and ESIN fixation. **(A)** X-ray examination of the child after injury revealed a middle humeral shaft fracture. **(B)** Intraoperative US showed that there was no soft tissue or nerve incarceration at the fracture site, and closed reduction was possible. **(C)** ESIN just past the fracture (white arrow). **(D)** ESIN in the bone marrow cavity after closed reduction (red arrows); it was not detectable in every patient by US. **(E)** Reexamination by radiography on the first day after the operation. **(F)** Good fracture healing was observed by X-ray at the 12-month follow-up.

was no significant difference in sex ratio, age, or fracture location between the 2 groups (**Table 1**). Both groups had a hospitalization time of about 5 days, which was much shorter than for patients treated by skin traction. The average operation time was slightly shorter in the US group than in the non-US group, but the difference was not statistically significant. The average number of radiographs during the operation was 4.9 ± 1.92 (times) for the US group, which was fewer than for the non-US group ($P = 0.008$). Accordingly, radiation exposure was lower for doctors and children in the US group than in the non-US group.

Clinical Outcomes

All patients were followed up for at least 12 months, and limb function was evaluated with the CMS at the last follow-up. The rate of excellent or good CMS scores in the US group was 95.8 vs. 95.2% in the non-US group; there was no significant difference between groups. One of the most common side effects of a humeral shaft fracture is radial nerve damage (13). Because of the pain caused by the fracture, patients did not cooperate with the physical examination and therefore, the degree of radial nerve injury could not be judged solely by physical signs. By US, we could clearly determine whether the radial nerve was ruptured and compressed and evaluate whether open surgery was needed (**Figure 2**). There were 2 children in the US group and 1 in the non-US group with signs of radial nerve injury at admission, but all symptoms of injury in all children disappeared during follow-up. There was no significant difference in hospital satisfaction between the 2 groups, but according to our clinical experience, the cooperation of patients' family members improved when they were informed that radiation exposure during surgery was significantly reduced.

TABLE 1 | Demographic characteristics and clinical data of the patients.

	US group	Non-US group	P
Sex			
Male	15	13	0.967
Female	9	8	
Mean age (years)	9.8 ± 2.78	9.5 ± 2.94	0.782
Fracture location			
Proximal third	6	6	0.493
Middle third	15	11	
Distal third	3	4	
Surgery time (min)	46.0 ± 5.84	54.9 ± 6.70	0.522
Times of X-radiographs	4.9 ± 1.92	20.7 ± 3.45	0.008
Radiation of the X-rays (mGy)	1.36 ± 0.54	5.79 ± 0.97	0.008
Average time to surgery (days)	2.3 ± 0.74	2.5 ± 0.81	0.645
Length of hospital stay (days)	4.6 ± 1.18	4.8 ± 1.17	0.979
Average follow-up (months)	14.8 ± 3.53	16.6 ± 4.99	0.112
CMS			
Excellent (>90)	18	17	0.729
Good (81–90)	5	3	
Fair (61–80)	1	1	
Poor (<60)	0	0	
Complications			
Pin site infection	1	1	1
Radial nerve injury	0	0	
Bone nonunion	0	0	
Patient satisfaction (0–100)	96.0 ± 5.78	96.7 ± 5.99	0.862

Data are shown as mean ± standard deviation unless indicated otherwise.
CMS, Constant–Murley shoulder; US, ultrasonography.

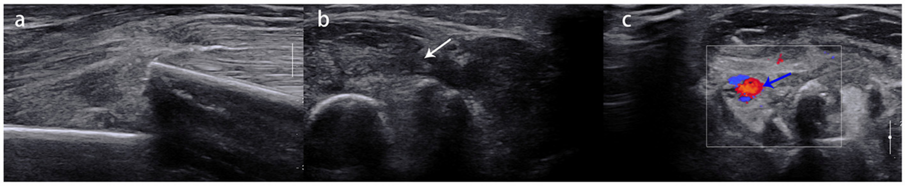

FIGURE 2 | (A) A 9-year-old girl with right humeral shaft fracture. **(B)** Swelling of the radial nerve was observed (white arrow) but there was no rupture or entrapment. **(C)** Good blood supply to brachial artery (blue arrow) was observed at the fracture site.

DISCUSSION

Closed reduction with ESIN fixation of humeral shaft fractures has the advantages of being minimally invasive, providing rigid fixation, and shortening the hospital stay, and is accepted by an increasing number of patients (7, 8, 15). As the fracture site cannot be viewed directly during closed reduction, it is necessary to repeatedly check radiographs during the operation to determine the extent of fracture reduction and position of the ESIN. However, this increases radiation exposure time, which in turn increases the risk of cancers such as thyroid, breast, brain, and skin cancers as well as leukemia, especially in children. Radiation-related cancer risk is greater in younger people and lasts a lifetime (16–18). Thus, examination methods that minimize damage during diagnosis and treatment are desired. The results of this study showed that the use of US reduced the intraoperative radiation exposure of our pediatric patients, and the follow-up results were also satisfactory. Minimally invasive surgery preserves soft tissue and decreases the risk of complications but is associated with greater radiation exposure than open procedures (19). The improved surgical method used in this study could substantially reduce radiation injury and maximize the clinical benefit to children.

Because of its multiplanar real-time imaging capabilities, cost-effectiveness, mobility, and lack of radiation exposure, US is increasingly employed in musculoskeletal system examinations (20, 21). In a study of 201 children with forearm fractures, US had a sensitivity and specificity of 99.5% in identifying fractures (22). Our institution also uses US in the treatment of displaced radial neck fractures; US guidance can reduce X-ray exposure and the risk of posterior interosseous nerve damage (12). We demonstrated that intraoperative US has incomparable advantages over radiography in soft tissue imaging as it can reveal whether the fracture is causing serious soft tissue injury or compression or cutting off the blood supply, which slows fracture healing (23). Additionally, it allows better design of the surgical plan and evaluation of the feasibility of closed reduction.

The radial nerve is one of the most susceptible nerves in a humeral shaft fracture (3); unless it is entrapped or ruptured, in most cases injuries will heal with conservative care (13). In this study, humeral shaft fractures were treated by closed reduction. Because the radial nerve could not be directly viewed, it is possible that it was trapped to the broken end of the fracture, which could aggravate an injury or even lead to sequelae that necessitate open surgery (24). When assessing nerve injury, US has a significant advantage over radiography and can be used to assess radial nerve damage caused by humeral shaft fractures in pediatric patients and predict prognosis (13). By intraoperative US we were able to determine whether the radial nerve was compressed at the fracture end or ruptured and decide whether to perform closed reduction, thereby minimizing the risk of nerve injury associated with this procedure.

Although there are many advantages to using US in the treatment of humeral shaft fractures by closed reduction, ultrasound cannot penetrate the cortical bone to enable visualization of the location of the ESIN. X-ray examination after the nails are implanted or during closed reduction is difficult, and open reduction may be necessary. Extending the operative time and thus prolonging anesthesia to reduce radiation exposure or surgical trauma is not desirable. Thus, US cannot completely replace the role of radiography in surgery.

In the present study, we did not observe that US conferred obvious advantages in terms of avoiding radial nerve injury, possibly because of the small sample size. The subjective factor of patient satisfaction could not be clearly evaluated but in our clinical experience, we feel that the degree of satisfaction among patients' families has improved. There was no significant difference in operative time between the 2 groups. In the early stage of this technique, the operative time was slightly longer than with conventional surgery, but with the increasing proficiency of the surgeons, this gradually improved. The C-arm position should be adjusted, and the surgeons must wait for the anesthesiologist and nurse to leave the operating room before performing the X-ray; however, for US it is only necessary to place the US probe on the skin to obtain images, which reduces operative time.

The main shortcoming of this study was the small sample size and the fact that patients were only followed for a brief period. There was also unavoidable sampling bias in the selection of the cohort.

CONCLUSIONS

The results of this study show that intraoperative US cannot completely replace the role of radiography in humeral fracture surgery but can substantially reduce radiation exposure in pediatric patients and doctors. The detection of radial nerve and soft tissue injury caused by humeral shaft fracture by US can help doctors plan the appropriate surgical method to avoid aggravating radial nerve injury. In summary, US-guided closed reduction and ESIN fixation for humeral shaft fractures is a good surgical approach in pediatric patients.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JL and XLiu wrote the original paper and reviewed, revised it, and the project was conceptualized and designed. JW, YZ, PG, XLi, MZ, PW, and MS acquired the information, performed a preliminary analysis, and updated the paper. All authors agree to be accountable for all parts of the work and accept the final submission.

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frontiers in Pediatrics

CASE REPORT
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Type III Monteggia Injury With Ipsilateral Distal Forearm Fracture in a Child: A Case Report

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Monteggia fracture refers to breakage of the upper third of the ulna combined with dislocation of the radial head. It often occurs in children and adolescents and represents a combined injury. Fracture of the distal forearm is among the most common trauma suffered by children. However, distal forearm fractures have rarely been reported as having an association with Monteggia fractures. We report on a 9-year-old boy diagnosed with a type III Monteggia fracture combined with a distal forearm fracture. He underwent surgery and received rehabilitation training 1 month later. He was followed-up for 1 year. The affected limb functioned well with no sign of radial head dislocation.

Keywords: Monteggia injury, ipsilateral distal forearm fracture, bipolar fracture, child, operative treatment

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INTRODUCTION

A Monteggia fracture is one in which the upper third of the ulna breaks while simultaneously a dislocation of the radial head occurs, representing a combined injury. It is uncommon in children, accounting for only 0.4% of the fractures in childrens' forearms (1). It was first reported by Monteggia, an Italian surgeon in 1814. In 1967, Bado termed this type of injury a Monteggia fracture, with 4 classifications that depend on the direction of the dislocation of the radial head (2). Of these injuries, type I (59%) and type III (26%) are the most common. Because of the high rate of misdiagnosis, the complex mechanism of injury and presentation of challenging complications, Monteggia fracture has been the focus of attention of researchers. Although such fractures have become increasingly recognized in the orthopedics community, the fracture itself remains a challenging clinical phenomenon. In pediatric patients, fractures surrounding the elbow and wrist joints are common. Distal forearm fractures are one of the most common injuries in children, and its incidence is relatively high, accounting for approximately 32.9% of the fractures in children, with a peak incidence at 9.9 years of age (3). However, ipsilateral elbow and wrist fractures are rare (4). The present article reports the case of a 9-year-old boy who was diagnosed with a Monteggia fracture (Bado type III) combined with a fracture of the ipsilateral forearm.

CASE REPORT

A 9-year-old boy complained of pain and swelling with restricted mobility in his right forearm. Three hours earlier, he had accidentally fallen 2 meters from a platform while playing. A pulse from the radioulnar artery was palpable but the right wrist and elbow joints were clearly distorted and swollen, with painful and restricted movement. The child was also unable to perform dorsiflexion of the right first to third fingers. X-ray films indicated fractures of the distal ulna and radius and

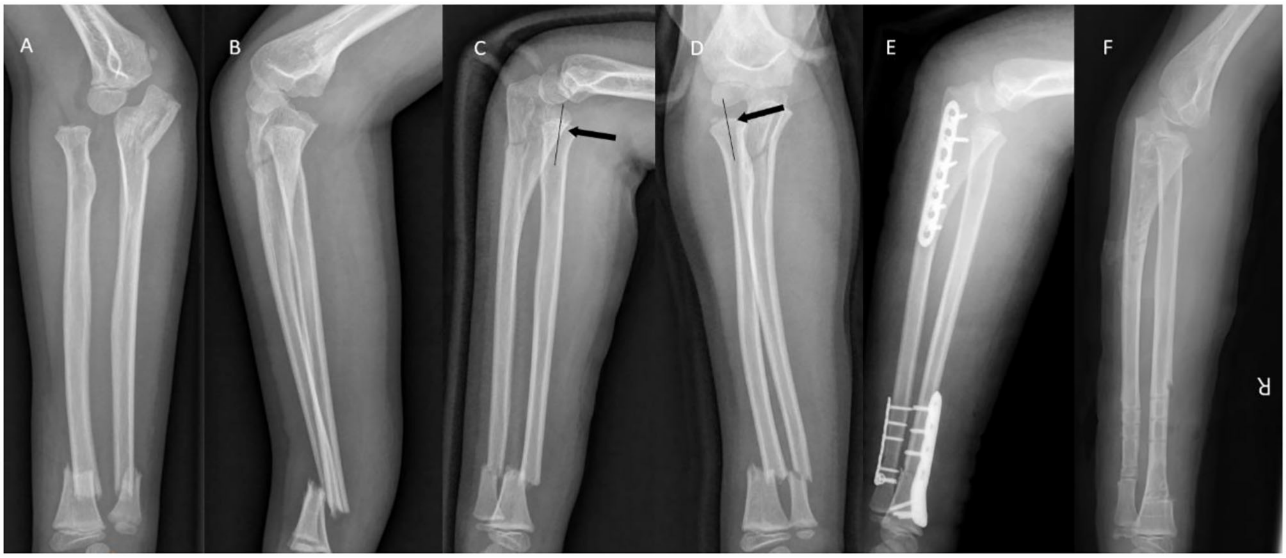

FIGURE 1 | (A,B) X-ray images at initial examination. Bado type III Monteggia fracture and ipsilateral distal forearm fracture were observed. **(C,D)** Following initial traction, the radial axis did not pass the midpoint of the humeral capitulum (black arrow). **(E)** Intraoperative radiographs demonstrated good alignment of the fracture. **(F)** One year after surgery.

proximal ulna, with lateral dislocation of the radial head (**Figures 1A,B**). Considering that the patient displayed symptoms of nerve compression, manual reduction was performed as quickly as possible, with the right elbow joint and forearm placed in a cast. Numbness in the right hand improved significantly after reduction, but dorsiflexion function was poor. After reviewing additional X-rays, it was found that radial head dislocation remained, with poor alignment of the right forearm fracture reduction (**Figures 1C,D**). Four days later, the patient underwent open reduction of the fracture with internal fixation. Surgery was performed following brachial plexus anesthesia, in which the patient was placed in a supine position while a pneumatic tourniquet was utilized. Briefly, two longitudinal skin incisions (∼3cm in length) were created aseptically, with the fracture of the distal ulna and the radius at the center. After separating the skin and fascia, layer by layer, the ends of the fracture were exposed. The incarcerated soft tissue was reduced and the fractured end fixed with miniplates and screws. Intraoperative fluoroscopy demonstrated that the fractured end had been reduced correctly.

A posterior median incision of the elbow joint was created to reduce the proximal ulnar fracture. A compressive comminuted fracture of the proximal ulna was observed. Following removal of the bone fragments, the fracture was fixed with a compression plate. The forearm was subsequently supinated and the elbow joint flexed to reduce the radial head. Intraoperative fluoroscopy indicated that the humeroradial joint was well-positioned, and dislocation of the radial head was corrected (**Figure 1E**). Following surgery, the forearm was immobilized with an above-elbow splint and the patient was discharged from hospital a week later. After discharge, the patient was reexamined in the outpatient department. The plaster cast was removed in the outpatient treatment room after 4 weeks. The forearm could be pronated by 60°, or supinated by 50°, and ∼60° of flexion or extension of the right elbow joint could be achieved (range: 60–120°). The Broberg-Morrey score was 54 points. Dorsiflexion of the fingers had gradually recovered, and was fully restored after 2 months. Following two months of functional exercise, the patient's forearm range of motion had returned to 90° pronation, 80° supination, and 110° movement of the right elbow (range: 0–110°) with a Broberg-Morrey score of 88 points. The plate was removed 1 year after surgery (**Figure 1F**).

REVIEW OF THE CURRENT LITERATURE

Monteggia fracture combined with ipsilateral distal forearm fracture is a rare injury, for which the literature is limited. As described by Odena (5), this type of injury is also known as a bipolar fracture of the forearm. A search of the literature identified 9 previously published cases that were similar (**Table 1**). Patient ages ranged from 5 to 12 years, with a mean of 9 years. The male to female ratio was 3.5:1. All patients sustained injuries by falling from heights ranging from 1.5 to 4.5 meters, with a mean of 2.49 meters. An interesting phenomenon was the presence of a distal forearm fracture with dorsal angulation in each patient, indicating that the wrist was in dorsiflexion and forearm in pronation at the time of injury. Injuries due to falls from a height often result in multiple fractures of the forearm that are clearly misaligned, requiring surgical treatment. Of the cases in the literature, 3 patients received conservative treatment, the remaining 6 undergoing surgery. The duration of fixation ranged

TABLE 1 | Overview of previous bipolar fractures of the forearm.

Article	Specification of Injury	Case Description	Distal fracture fragment	Treatment	Results
Kamudin NAF (6)	Type III Monteggia injury with ipsilateral distal end radius fracture and metaphyseal fracture of the distal ulna	A 12 year old girl fell from a tree of about 15 feet height	Dorsal dislocation	Cast for 4 weeks. The radial head was relocated using closed manipulative reduction. The distal end of the left radius and proximal ulna were fixed with K-wires	After 2 months, full flexion and extension of the elbow and wrist, with full pronation of the forearm, but limited forearm supination (0–60°).
Gaurav Mundada (7)	Type I Monteggia injury with Ipsilateral fracture of the distal radius and epiphyseal injury	A 11 year old boy fell from a tree from about 5 feet	Dorsal dislocation	Cast for 4 weeks. The distal end of the left radius was fixed with Kirschner wire. The proximal ulna was fixed with a 2.5mm plate	6 months post-operatively, elbow (0°-110°), with 30° wrist dorsiflexion and 40°plantarflexion.
Huw LM Williams (8)	Type III Monteggia injury with ipsilateral type II Salter Harris injury	A 5 year old boy fell from a tree from about 5 feet	Dorsal dislocation	Cast for 5 weeks. The radial head was relocated by closed reduction, K-wires were used to stabilize the distal radius fracture. Ulna fracture was treated non-operatively	After 6 months, full range of movement at the elbow and wrist.
Noel Peter (9)	Type I Monteggia lesion with distal radial and ulna metaphyseal fracture	A 5 year old boy fell from a height of ∼2–3 m	Dorsal dislocation	Cast for 4 weeks. Manual reduction	At 12 weeks post injury, no limitation of motion in the affected joints
Asheesh Sood (10)	Type I Monteggia fracture with ipsilateral fracture of the distal radius and ulna	A 11 year old girl fell from a tree from about 1.8 m	Dorsal dislocation	Cast for 6 weeks. The radial neck was reduced with direct observation. The ulna was reduced and fixed with a six-hole dynamic compression plate. The distal wrist fracture was stabilized with K-wires	After 7 months, complete range of motion in both elbow and wrist had been restored
A. Biyani (11)	Ipsilateral fracture of both the radius and ulna at proximal and distal metaphyseal levels	A 10 year old boy fell from a ladder	Dorsal dislocation	Cast for 5 weeks. Manual reduction	After 1 year, complete range of motion in both elbow and wrist had been restored
Hiroshi Maeda (12)	Type III Monteggia fracture with Galeazzi fracture	A 10 year old boy fell from a basketball net from about 3 m	Dorsal dislocation	Cast for 8 weeks. Manual reduction	After 3 years, no limitation of motion in the affected joints
Dhananjay Singh (13)	Type I Monteggia fracture with ipsilateral fracture of the distal forearm	A 11 year old boy fell from a window	Dorsal dislocation	Cast for 6 weeks. Ulna was fixed using a intramedullary nail. Radius fracture was fixed using K-wires	At final follow-up at 6 months, no limitation of motion in the affected joints
Takeshi Inoue (14)	Type III Monteggia Injury with ipsilateral fracture of the distal radius and ulna	A 6 year old boy fell from a climbing pole from about 3 m	Dorsal dislocation	Cast for 2 weeks. Both ulna and radius fracture fixed using K-wires	At final follow-up after 21 years, no limitation of motion in the affected joints

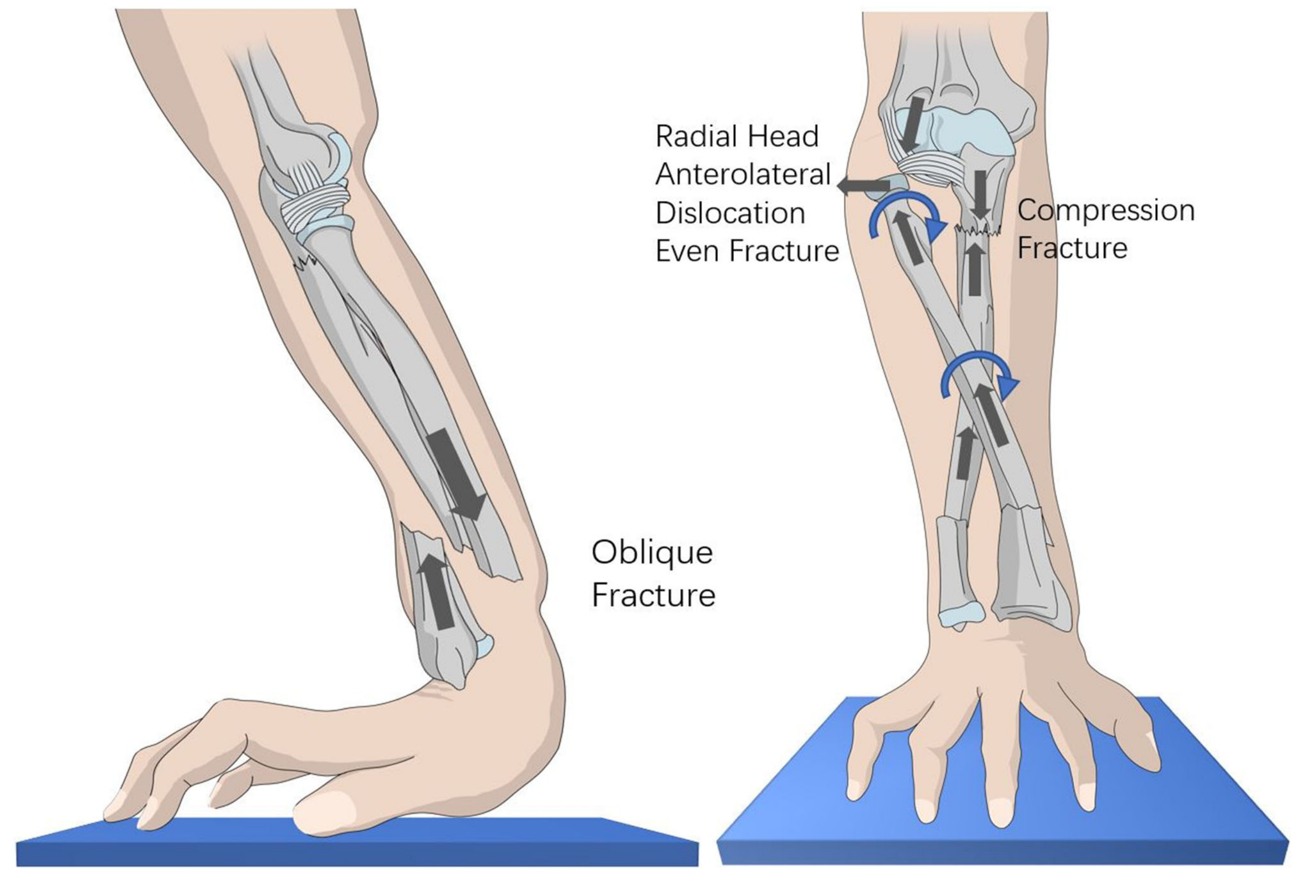

FIGURE 2 | Mechanism of this type of injury.

from 2 to 8 weeks, with 89% (8/9) of patients having a duration ≥4 weeks, and 11% (1/9) with a duration ≤3 weeks.

INJURY MECHANISM

It is often difficult to determine the exact mechanism of an injury in young children because they are often unable to communicate effectively after sustaining an injury (15). However, the type of forearm fracture observed on the X-ray images and the direction of radial head dislocation and ulnar fracture all provide indirect clues to the mechanism of injury (16). Based on our analysis of previous cases, we found that falls are a prerequisite for this type of injury. The mechanisms are as follows: 1. Strong vertical force. 2. The forearm is always pronated when a child falls to the ground with an outstretched hand (17). In this scenario, the ulna is straight and more prone to compression fracture, while the radius is inclined, force more likely to cause anterolateral dislocation of the radial head. In the present case, analysis of X-ray images revealed that vertical impact from falling had fractured the distal forearm (**Figure 2A**), with the force conducting upward along the radius and ulna, respectively, causing dislocation of the radial head and compression fracture of the proximal ulna. Because the radius was pronated, vertical force often results in anterolateral dislocation of the radial head, or even fracture (**Figure 2B**). This explains why the majority of elbow fractures are type I or III Monteggia injuries.

RADIAL NERVE INJURY

Radial nerve injury is the most common complication of Monteggia fractures (18). They often occur in type I and III injuries, of which type III is more common. The reason is that the radial nerve is close to the Frohse arch at the proximal end of the radial head. The arch is thinner in children, possibly causing children's nerves to be damaged more easily. Patients usually present with nerve palsy, although function is quickly restored after reduction of the radial head dislocation. In the present study, the child exhibited injury of the radial nerve, with numbness and limited dorsiflexion of fingers 1–3. After discovering that the radial head was dislocated, it was manually reduced in the emergency department, causing the numbness to disappear, but the child was still unable to perform dorsiflexion of his fingers. Finger movement gradually returned to normal over time. For most patients, function is restored within 6 to 12 weeks of an injury. Where no apparent improvement in function is observed 4 weeks after injury, electromyography can be performed to check whether the radial nerve is damaged. Such patients often require further surgical exploration.

We emphasize that emergency manual reduction of a radial head dislocation is important so that traction of the radial nerve caused by the dislocation does not result in irreversible loss of nerve function caused by long-term compression.

THERAPEUTIC METHOD

In terms of treatment, successful results have been reported with non-surgical approaches (9, 11, 12). Previous studies have demonstrated that conservative treatment is often effective in patients with stable fractures and dislocations. However, for most patients, due to the greater force causing the injury, the fractured ends are often significantly dislocated, and so surgery is required. Stable reduction of ulnar fractures and restoration of the ulnar bow is the key outcome of surgery. When the ulna is reset, the radial head can still be dislocated. This is often due to compression of the annular ligament or bone fragments, and the radial head needs to be reset while observing directly.

CONCLUSION

The present article reports a case of multiple forearm fractures with radial nerve injury. After surgery, the patient recovered well. It can be concluded that satisfactory outcomes for Monteggia fracture and dislocation require early manual reduction, stable anatomical reduction of ulnar fractures, and reduction of the radial head. Although closed reduction can be achieved in the majority of such injuries in children, failure of closed reduction, as in this case, surgical fixation should be performed without hesitation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The parents of patient in our study were informed about the management of this special fracture. They chose operative treatment. They signed a consent form for the participation of their child in the publication and about long-term follow-up. Written informed consent was obtained from the minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

HJZ, JHS, and YYW collected the data. CG wrote the first draft of the manuscript. JC contributed to interpretation of data modified this paper and approved the final version. All authors were involved in the conception of the paper.

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SYSTEMATIC REVIEW
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Management of Gartland Type 1 Supracondylar Fractures: A Systematic Review

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Purpose: Gartland Type 1 supracondylar humerus fractures are stable, non-displaced injuries treated with non-operative management. This systematic review was performed to gather evidence on the optimal form of immobilization to treat these fractures.

Methods: The review process was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. An electronic search was performed in November 2020. Articles were eligible if they included children less than 18 years old, with non-displaced supracondylar fractures, treated non-operatively. Randomized trials, quasi-experimental trials, and prospective cohort studies were included. Outcomes of interest included fracture displacement, pain control, time to return to normal activities, return of range of motion (ROM), child/parent satisfaction, adverse events, and cost. Risk of bias was assessed using the Newcastle-Ottawa scale, Rob-2, and the ROBINS tools.

Results: After duplicate records were removed, 525 records were evaluated with 9 studies meeting the inclusion criteria and 5 reporting clinical outcomes. The studies were heterogenous, in intervention and outcomes, and all at moderate risk of bias. Within the available evidence there were no cases of fracture displacement. Two small studies suggested that cuff and collar treatment provided inadequate pain control and delay in return to normal activities, compared to posterior splints. Two randomized control trials (RCTs) suggested that soft fiberglass casts reduced appointment time and increased parent satisfaction, compared to traditional casts. No studies directly compared posterior splints to circumferential casts.

Conclusion: There is insufficient high-quality evidence to determine the optimal conservative treatment for patients with Gartland type 1 supracondylar fractures. Level of Evidence Level II systematic review of Level II studies.

Systematic Review Registration: [https://www.crd.york.ac.uk/prospero/], identifier [CRD42020144616].

Keywords: pediatrics, systematic review, supracondylar humerus fractures, cast, splint

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INTRODUCTION

Supracondylar humerus fractures are the most common pediatric elbow fracture (1) and account for around 60–70 emergency department visits per 100,000 children annually (2). These fractures are categorized according to the modified Gartland classification system, depending on the degree of displacement, disruption of the posterior cortex, and location of the anterior humeral capitellum line on a lateral radiograph (3). Gartland Type I fractures are non-displaced and are widely accepted as stable fractures that should be treated non-operatively.

The ideal treatment for Type I supracondylar fractures should prevent fracture displacement and result in excellent clinical outcomes while minimizing adverse outcomes, pain, as well as direct and indirect costs to families and healthcare systems. Despite the common nature of these fractures, there remains a lack of consensus regarding which type of immobilization and follow-up care is most appropriate. Emergency department guidelines from Australia and Canada suggest immobilization with an above elbow "backslab" (a posterior splint) and broad arm sling. (4, 5). In comparison, long arm cast immobilization is generally recommended in a number of orthopedic surgery clinical guidelines and textbooks (6).

Given the frequency of the fracture and the existing clinical ambiguity with respect to the type of immobilization, a systematic review was performed to determine the optimal management of Type I supracondylar humerus fractures based on the highest level of evidence available. Our primary objective was to determine which forms of immobilization for Type I supracondylar humerus fractures prevent fracture displacement. Secondary objectives include the determination of relative risks and benefits of different treatment options.

MATERIALS AND METHODS

Study Design

A systematic review was performed to identify publications that reported clinical outcomes and adverse events in pediatric patients with Type I supracondylar humerus fractures treated with immobilization. The review process was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, the details of which are available in **Appendix A**. The review protocol was published on PROSPERO (CRD42020144616).

Search Strategy

The following databases were searched on November 13, 2020: MEDLINE, Embase, and CENTRAL Trials Registry of the Cochrane Collaboration, using the Ovid interface. Search terms for intervention included cast, slab, sling, cuff and collar, splint, non-surgical, and immobilization with the appropriate Boolean operators. Population-specific search terms included supracondylar fracture, or distal humerus fracture and babies, neonatal, infant, child, preschool, adolescent, or pediatric using corresponding Boolean operators. The search was not restricted by language or study design. Our search strategy was designed and conducted by a librarian experienced in systematic reviews, using a method designed to optimize term selection (7). A detailed description of the search strategies is presented in **Appendix B**.

Study Selection

Studies were considered eligible if they met the following criteria: (1) the population included children < 18 years with type 1 (non-displaced) supracondylar fractures; (2) the study type was: randomized trial, quasi-experimental trial (non-randomized interventional study), or prospective cohort; (3) the study involved non-operative fracture management (including: tensor bandage, splint, casting, sling, cuff and collar, no intervention); (4) written in the English language. Fracture displacement was considered the primary outcome, but was not made an explicit inclusion criterion in order to broaden the article pool for reporting on our secondary outcomes. Studies were excluded if they met the following exclusion criteria: (1) narrative and systematic reviews, editorials, letters, surveys, case series and case reports, study protocols, retrospective cohort studies, cross-sectional studies, and studies published only in abstract form; (2) studies that primarily focused on closed reduction, operative management, or traction; (3) studies that primarily focused on adult patients; (3) animal studies; (4) studies that solely focused on patients with displaced (Gartland type II or III) supracondylar fractures, intra-articular distal humerus fractures, or proximal humerus fractures.

Duplicate records were removed, and records retrieved by the electronic search were uploaded to an online systematic review tool (InSight Scope, Ottawa, Canada). Records were appraised against the inclusion and exclusion criteria using a two-step approach. First, two reviewers (KL and SC) independently reviewed the titles and abstracts of the papers for potentially eligible studies. The full-text article of any abstract selected by either reviewer was then reviewed by both reviewers. Conflicts were resolved by the senior author (KL and SC). The reference list from the articles of the included studies was reviewed by KL and SC to identify any further possibly relevant articles. The authors of the included articles were contacted to inquire about additional available data or to clarify results or methodology if unclear.

Data Extraction

Data from the included studies were extracted independently by two authors (KL and SC) and compared for consistency before inclusion in the analysis. Full data extraction included study design details, population, and outcomes including fracture displacement, pain control, time to return to normal activities, return of range of motion (ROM), child/parent satisfaction, adverse events, cost (health care, patient/parent, societal), and additional hospital visits. Discrepancies were investigated and rectified by returning to the original paper. In cases where the study population was heterogenous, data was extracted specifically for Type I or non-displaced fractures, where possible. There was no specific data manipulation required to extract this fracture-specific data.

Quality Assessment

Risk of bias was assessed by two authors (KL and SC) with the Cochrane Rob-2 for randomized control trials (RCTs), Cochrane ROBINS-1 for quasi-experimental studies, and the Newcastle-Ottawa Scale for cohort studies. Discrepancies were resolved with discussion. There is low risk of selection or publication bias across this research topic.

Data Synthesis

We had originally planned to perform a meta-analysis. However, given the heterogeneity of studies and results a descriptive analysis was instead performed.

RESULTS

Study Selection

The primary database search returned 742 records, and 525 records remained after duplicates were removed. Screening of titles and abstracts further excluded 367 records, leaving 126 for full article review with 9 studies meeting all the inclusion and exclusion criteria (see **Figure 1**). Four of the studies did not include clinical or adequate radiological outcome data, and therefore could not be used for data extraction. No additional studies were identified through review of the references of included papers.

Study Characteristics and Methodological Quality

Studies which met the inclusion/exclusion criteria, and contained clinical data, are described in **Table 1**. There were 3 RCTs, 1 prospective cohort study, and 1 quasi-experimental study. Studies were performed in North America, Europe, and Australia and were all published in the last 20 years. Interventions investigated in the studies were posterior splint, long arm cast, cuff and collar, and "Blount's immobilization" (cuff and collar with elbow at 100–120 degrees of flexion). Time of immobilization was inconsistently reported but varied from 2

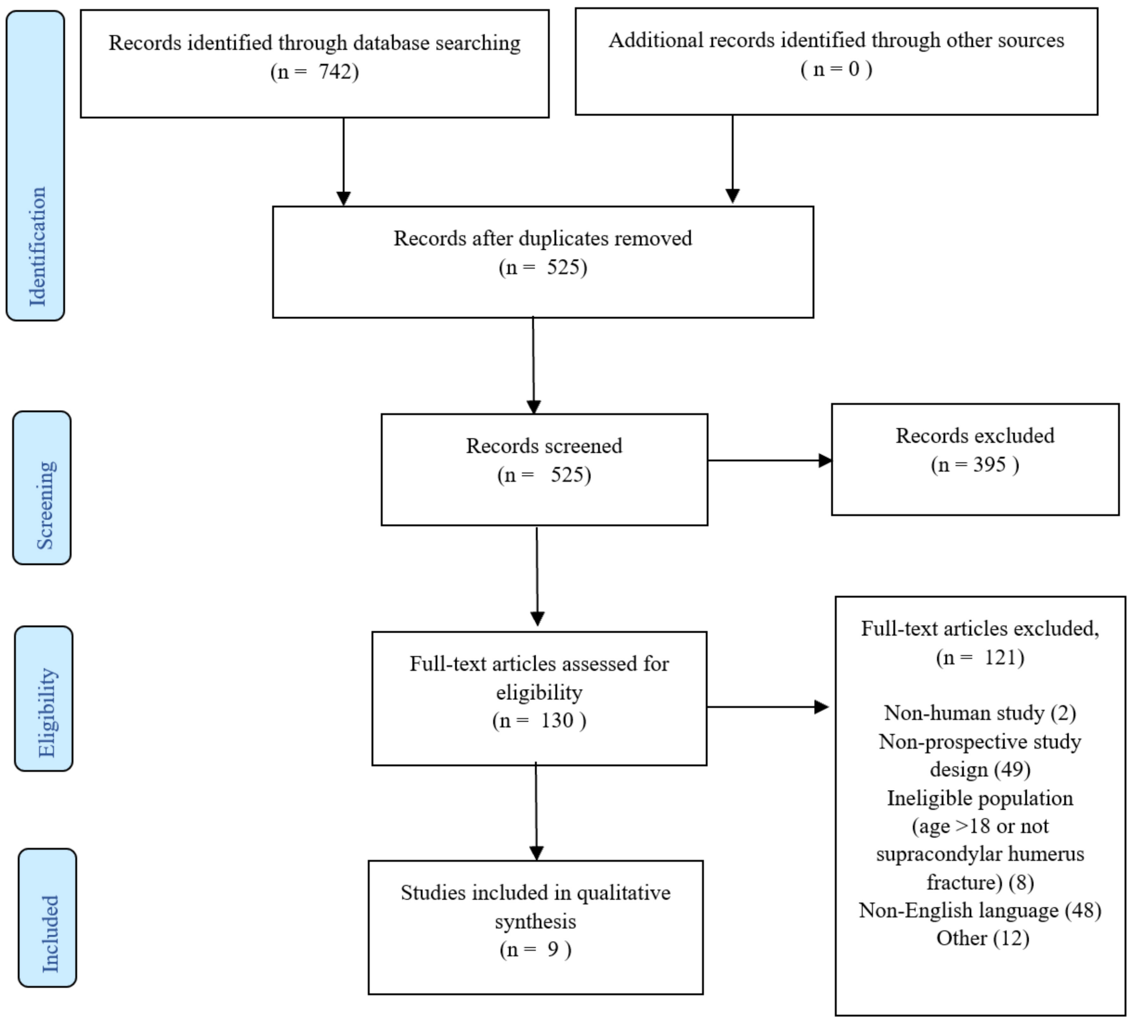

FIGURE 1 | Prisma diagram.

TABLE 1 | Description of studies that met the inclusion criteria and included clinical outcome data.

Author, Year	Design	Location	Type of immobilization	Duration of immobilization	Outcomes reported	Age: Mean (range) in years	Number of participants
Leksan et al. (11)	Prospective Cohort	Europe	Humerus splint, cast, and Blount's immobilization	Not reported	1. ROM	Not reported	38 (18 Type I)
Ballal et al. (7)	Quasi-experimental	Europe	A. Cuff and Collar B. Backslab	Not reported. Patients evaluated 2.67 days from injury (range 1-8 days) and then followed clinically	2. Fracture displacement (no formal radiographic follow-up) 3. Pain	A. 6 (2–14) B. 8 (4–14)	A. 20 B. 20
Oakley et al. (8)	RCT	Australia	A. Collar and Cuff B. Backslab and Sling	14–16 days, plus 2 additional weeks if tenderness/ discomfort remained	1. Fracture displacement 2. Pain 3. ROM 4. Parent satisfaction 5. Time to return to normal activities 6. Costs (indirect)	A. 5.2 (2.9–6.9) B. 6.0 (4.6–8.1)	A. 23 B. 27 (Type I and elbow joint effusion with no visible fracture)
Silva et al. (9)	RCT	North America	A. Long Arm Cast (Traditional Hard Fiberglass) with sling B. Long Arm Cast (Soft fiberglass) with sling	4 weeks (8 week follow-up)	1. Fracture displacement 2. Pain 3. Parent satisfaction 4. ROM	A. 4.8 B. 5.4 Range not reported	A. 50 B. 50 (76% Type 1, other diagnosis include elbow effusion and other occult fracture)
Silva et al. (10)	RCT	North America	A. Long Arm Cast (Soft fiberglass) B Long Arm Cast (Soft fiberglass)	4 weeks (8 week follow-up)	1. Fracture displacement 2. Pain 3. ROM 4. Parent satisfaction 5. Costs (direct and indirect)	A. 5 (1.9 – 10.8) B. 5 (2.6 – 9.4)	A. 26 B. 26 (82% Type 1, other diagnosis include elbow effusion and other occult fracture)

weeks to 4 weeks. Follow-up time ranged from 2 days to 48 weeks. Details of the risk of bias assessment can be found in **Tables 2**, **3**.

Outcomes Associated With Cuff and Collar and Posterior Splints

Two studies directly compared cuff and collar management to the use of a posterior splint (7, 8).

A quasi-experimental study by Ballal (7) included children who presented to a fracture clinic on an average of 2.7 days from injury. The patients had been treated with a cuff and collar or posterior splints based on the emergency physician preference. The posterior splints were placed with the elbow in "at least 90 degrees of flexion." The authors report that "none of the fractures displaced during further management," although there was no specific protocol for radiographic follow-up. The children treated with posterior splints had significantly less pain (3.4/10 vs. 7.2/10, $p < 0.0001$) and decreased regular analgesia use (4 times less, $p = 0.0002$) compared to those treated with cuff and collar. Furthermore, 85% of the patients treated with cuff and collar experienced sleep disturbance, compared to only 45% of the patients in the posterior splint group (7). Range of motion was not compared between the groups. There are moderate concerns with risk of bias since the study protocols were not published *a priori* (**Table 3**).

Oakley et al performed an RCT that investigated cuff and collar, compared to posterior splint (with the elbow placed at 90 degrees) (8). There were no cases of fracture displacement with either treatment, as measured on radiographs performed at the follow-up visit 12–16 days after injury. The primary outcome was the difference in pain intensity and duration and the parental or the patient's willingness to use similar immobilization in the future. There was a trend toward decreased use of analgesia and duration of pain for the posterior splint compared to the cuff and collar (4 vs. 6 days, respectively), but statistical significance was not reported. Time to return to activity was also shorter in the posterior splint group (2 vs. 7 days, respectively). ROM restrictions was 50 degrees in the posterior splint group and 40 degrees in the cuff and collar group (p not reported). Differences in pain, analgesia use, and

TABLE 2 | Risk of bias for prospective cohort studies - Newcastle–Ottawa score.

Study (Author et al., Year)	Selection (max 4 stars)	Comparability (max 2 stars)	Outcome (max 3 stars)
Leksan et al. (11)	0	0	*

participation rates in usual activities had resolved by 4 weeks. Parent satisfaction, harms of immobilization, rates of parents who missed work, duration of missed work, and proportion of patients requiring days off from school/daycare demonstrated no differences between the methods of immobilization. Some concerns for risk of bias were identified for the Oakley study, as again there was no pre-specified, published protocol of outcomes prior to the commencement of the study (**Table 3**).

Outcomes Associated With Long Arm Casts

Long arm casts were investigated in two randomized control studies by Silva et al. (9, 10). In 2018, the authors compared traditional fiberglass to soft fiberglass casts. Both types of casts were placed with the elbow at 90–100 degrees of flexion and the forearm in neutral rotation (9). This study reported no evidence of fracture displacement between the two groups. ROM and parent satisfaction were also found to be equivalent between groups at the 8 week follow-up appointment. Pain scores between the groups showed inconsistent results over time with no difference at 1 week, significant differences at 4 weeks, and no difference at 8 weeks. Overall risk of bias assessment showed some concerns due to measurement of outcome variables, since there was no mention of blinding of the radiographic assessors to intervention (**Table 3**).

In 2019, Silva et al investigated different methods of cast removal to improve parent satisfaction: clinic removal (Group A) was compared to removal at home by parents *via* telehealth appointment (Group B) (10). Soft fiberglass casts were used in both the groups studied. There were no cases of fracture displacement in either group. At latest follow-up there was no significant difference in the mean ROM, with Group A: 147 degrees and Group B: 151 degrees (p = 0.5). Significant difference in the length of appointment time was found between the groups, with Group A: 110.7 min and Group B: 17.6 min ($p < 0.001$). When the parents in the traditional clinic visit learned about the increased appointment time, their satisfaction dropped and was statistically lower than the telehealth group, which was 76.4% for Group A compared to 97.7% for Group B (p = 0.05). Despite this difference in appointment time there was no significant difference in mean professional fee [Group A: $29.22, Group B: $22.51($p$ = 0.19)]. Quality assessment showed some concern for risk of bias for this study due to deviations from the intended intervention; parents from both groups removed the cast prior to the intended date and the data from these patients was not included in the final analysis (**Table 3**). In addition, the radiographic assessors measuring the primary outcome were not blinded to intervention.

Other Forms of Immobilization

Leksan et al. performed a prospective cohort study examining the functional status of the patient's elbow after conservative treatment (11). They included 18 patients with Gartland type 1 fractures treated with a humerus splint, cast, or Blount's immobilization. Results were not separated by the type of

TABLE 3 | Risk of bias for randomized control trials (RCTs) (ROB-2) and non-RCTs (ROBINS-1).

Study	Experimental	Comparator	Primary outcome	Risk of bias tool used	Randomization process	Confounding	Selection of participipants	Classification of interventions	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result/outcome	Overall
Oakley et al. (8)	Cuff and Collar	Backslab	Fracture displacement	ROB-2	🟢	N/A	N/A	N/A	🟢	🟢	🟢	🟡	🟡 Some concern
Silva et al. (9)	Long arm cast (hard Fiberglass)	Long arm cast (soft Fiberglass)	Fracture displacement	ROB-2	🟢	N/A	N/A	N/A	🟢	🟢	🟢	🟡	🟡 Some concern
Silva et al. (10)	Long arm cast (soft Fiberglass) removed at home	Long arm cast (soft Fiberglass) removed in office	Fracture displacement	ROB-2	🟢	N/A	N/A	N/A	🟡	🟢	🟢	🟡	🟡 Some concern
Ballal et al. (7)	Backslab	Cuff and Collar	Fracture Displacement	ROBINS-1	N/A	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡 Some concern

Legend: 🟢 *low risk of bias,* 🟡 *moderate risk/some concerns.*

immobilization, but after completion of treatment, patients had an average ROM of 128.83 degrees, ranging from 110 to 140 degrees with a standard deviation of 8.65 degrees. No other clinical measures or outcomes were reported. This study is not of high quality, despite objective outcome measures. The patients selected were involved in traffic accidents (rollerblading or falling from a bicycle), which is a relatively high energy mechanism. In addition, it was unclear how the type of immobilization was ascertained, as there was no direct comparator, the length of follow-up was not described, and neither was loss to follow-up (see **Table 2**).

Studies Without Clinical Outcome Reporting

Three prospective studies met the inclusion criteria but did not contribute any outcome data to our systematic review, as they did not include radiographic data and the clinical data was not reported specific to Type 1 fractures (i.e., it was grouped with Type 2 and Type 3 fractures treated operatively) (12–14). A small prospective study by Pudas on the utility of MRI in elbow fractures included patients with supracondylar humerus fractures but no clinical or radiographic follow-up data was reported (15).

DISCUSSION

Fracture Displacement

The quality of evidence in these studies is low, and therefore we cannot make strong conclusions on the effect of each type of immobilization on fracture displacement. However, the results of this systematic review suggest that there is no fracture displacement with the use of cuff and collar, posterior splinting, or long arm casts (7–10). These findings are in alignment with other available literature including a retrospective review of 53 cases, which demonstrated that the use of posterior splint resulted in minimal changes in fracture displacement (16). Specifically, they found only 1 case of change in the anterior humeral line (from posterior 1/3 of the capitellum to middle 1/3) and 1 case of change in the humeral capitellum angle by 7 degrees, which is considered to be within the normal interrater measurement variability.

Benefits of Immobilization

Cuff and collar immobilization appears to have fewer benefits for patients, compared to posterior splints. The use of cuff and collar resulted in a delayed return to normal activities (8), more interrupted sleep, and increased average pain scores especially early in the injury phase (7). In addition, the cuff and collar did not result in pain scores at levels considered to be the minimum for adequate pain control ($<$30 mm on a 100 mm visual analog scale), whereas the posterior splint achieved pain levels below this threshold (8). It is therefore reasonable to conclude that the results of this study suggest that immobilization with a splint or cast is significantly better for patients than cuff and collar alone. There were no consistent differences in pain scores between traditional fiberglass and soft cast. When comparing cuff and collar to posterior splints, there was no difference in parent satisfaction. Parent satisfaction for long arm casts was also reported by Silva, with a significant difference in parent satisfaction only when parents were informed of the increased appointment time associated with typical clinic appointments as compared to telehealth visits (9, 14).

Two studies investigated the possible benefits of the use of "soft cast," otherwise known as "peelable fiberglass" casts, utilizing a form of fiberglass which can be removed at the end of a period of immobilization by a parent at home (9, 10). Such "soft cast" has been investigated for immobilization of pediatric buckle fractures (17), and in small studies appear to result in high patient/parent satisfaction (18). The studies included in this review showed a similar improvement in parental satisfaction. However, these studies contained small patient numbers, and patients who removed their cast prematurely at home were excluded from the final analysis. Therefore, the effect of non-compliance during soft cast treatment of supracondylar humerus fractures is unknown. In addition, it is unclear whether "soft cast" treatment option is widely known, available, or considered reasonable to the pediatric emergency medicine and pediatric orthopedic surgery community. For these reasons, future investigation into this treatment method is warranted.

Harms of Immobilization

Orthopedic surgery visits have previously been reported to result in direct costs and societal costs due to loss of productivity for parents (19). Direct healthcare costs were only reported in one study of long arm casts, with no significant difference in cost despite an increased length of appointment in the traditional fiberglass cast (9). The type of immobilization directly impacts the follow-up required, and therefore has downstream societal costs. Rates of missed parental working days, duration of missed work, and proportion of patients requiring days off from school/daycare were only compared between cuff and collar and posterior splint in only one study, but no differences were reported (8).

High rates of improperly placed extremity splints have been reported in other literature, and associated with skin and soft tissue complications (20). However, direct physical harms of immobilization (or lack thereof) were not reported in any of the studies included in this review.

Additional Management Considerations

The ideal length of time required to immobilize Type I supracondylar humerus fractures is not clear from the evidence gathered in this review. In addition, an appropriate type of clinical follow-up care is not well defined. Telehealth has been advocated for delivering orthopedic clinical care during the COVID-19 pandemic (21), and is often used in rural/suburban areas, where it can greatly reduce the appointment times in the form of waiting and travel time (22). One small RCT compared telehealth clinical visits to traditional visits, and more research is warranted prior to changing the clinical follow-up methods.

Limitations

This systematic review is limited in its conclusions by the heterogeneity of the individual studies, which investigated multiple forms of immobilization. There is no study focused on comparing posterior splints and casts, making it impossible to directly compare these two common treatments. The majority of studies also included patients with a variety of elbow injuries (such as occult elbow injuries), which may be more inherently stable than Type I injuries with a visible fracture line. Not all studies included a description of formal radiographic follow-up (8), which restricts the reliability of fracture displacement reporting. In addition, scarce information was presented on adverse events, and therefore it is unclear if these were not present or simply not recorded. A major limitation of the evidence is the short, formal follow-up period (average of 2.7 days to 8 weeks), meaning that long-term ROM and functional data are not available.

CONCLUSION

Despite the ubiquity of the fracture, there remains very limited high-quality evidence on the treatment of Type 1 supracondylar humerus fractures. In addition, there is significant heterogeneity in the intervention and outcome measures in the current literature. Based on the best available evidence, Type 1 supracondylar fractures are stable fractures with no evidence of displacement reported, regardless of the form of immobilization used. Posterior splint and circumferential long arm casts both provide adequate pain control and early return to activity, whereas cuff and collar alone has been shown to be comparatively less effective or even inadequate for pain control. Therefore, immobilization with a splint or cast is reasonable to recommend. It was not possible to determine the optimal duration and type of immobilization for these fractures. Interestingly, soft fiberglass casts may offer the potential of rigid immobilization with the option of cast removal at home, which, in a small study, resulted in reduced appointment times and increased patient/parent satisfaction while maintaining fracture stability. The results of this systematic review clarify the limitations of the existing evidence, and may help to serve as a guide toward the development of more definitive evidence and guidelines. Further research is needed to better determine the optimal management of Type 1 supracondylar humerus fractures in children.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SCo: study design, data capture, measurements, analysis, and manuscript preparation and revision. KL: data capture, measurements, and analysis. AP and MB: study design, analysis, and manuscript preparation and revision. KC: analysis and manuscript preparation and revision. KS: study design and manuscript preparation and revision. SCa: study design, measurements, analysis, and manuscript preparation and revision. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX A

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	Title Page
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	1–2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	3
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	4
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	4
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	4
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	Appendix
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	4–5
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	5–6
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	5–6
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	6 (**Table 2–3**)
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	N/A (descriptive analysis only due to heterogenous studies)
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	N/A
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	6
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	**Figure 1**
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	**Table 1**
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	**Table 2**/3
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	a) 7–11 b) N/A
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	6 (N/A)
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	12–15
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	14–15
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	15
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	N/A

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi: 10.1371/journal.pmed1000097.
For more information, visit: www.prisma-statement.org.

APPENDIX B

Searches were conducted using an Ovid multi-database search, and duplicate records were removed online giving preference to MEDLINE, then Embase, with no field preference. Lines 1–4 are optimized for MEDLINE and the main question constructs are broken out in separate lines for clarity. Lines 5–11 are optimized for Embase and lines 12–15 are optimized for CENTRAL. The next lines associated the records to the database the search was designed for, combine those sets and then remove duplicate records and finally isolate the records from each database again so each can be downloaded and imported into the citation manager using a database-specific import filter.

Database specific: MEDLINE including Epub Ahead of Print, In-Process and Other Non-Indexed Citations (1946- November 13, 2020) and Embase (1947- 2020, November 13) and the CENTRAL Trials Registry of the Cochrane Collaboration (October 20 issue) using the Ovid interface.

1. [(Supracondyl* adj2 fracture*) or gartland].ti,ab,kf.
2. Casts, Surgical/ or Splits/ or [conservative or cast* or immobili* or backslab* or slab* or sling* or (cuff* adj2 collar*) or splint* or non-surg*].ti,ab,kf. or "Referral and Consultation"/
3. (child* or adolescent* or infan*).mp.
4. (1 and 2 and 3) not (femur* or femoral or distal radi* or displaced or type ii or type 11 or type 2 or type two or type 3 or type 111 or type iii or type three).ti.
5. gartland type i supracondylar humerus fracture/ or humerus supracondylar fracture/ or humeral supracondylar fracture/ or distal humeral fracture/ or (distal humerus/ and fracture*.mp.)
6. [(Supracondyl* adj2 fracture*) or gartland].ti,ab,kw. not (femur* or femoral or distal radi*).ti.
7. 5 or 6
8. exp "casts and noninvasive traction devices"/ or exp splint/ or [conservative or cast* or Immobili* or backslab* or slab* or sling* or (cuff* adj2 collar*) or splint* or non-surg*].ti,ab,kw. or patient referral/
9. (baby or babies or newborn* or infan* or neonat* or preschool* or pre-school* or child* or pediatr* or paediatr* or teen* or adolescen*).mp.
10. (7 and 8 and 9) not (femur* or femoral or distal radi* or displaced or type ii or type 11 or type 2 or type two or type iii or type 111 or type 3 or type three).ti.
11. limit 10 to embase
12. [(Supracondyl* adj2 fracture*) or gartland].ti,ab,kw. not (femur* or femoral or distal radi*).ti.
13. [conservative or cast* or Immobili* or backslab* or slab* or sling* or (cuff* adj2 collar*) or splint* or non-surg*].ti,ab,kw.
14. (baby or babies or newborn* or infan* or neonat* or preschool* or pre-school* or child* or pediatr* or paediatr* or teen* or adolescen*).mp.
15. (12 and 13 and 14) not (femur* or femoral or distal radi* or displaced or type ii or type 11 or type 2 or type two or type iii or type 111 or type 3).ti.
16. 4 use medall
17. 11 use emczd
18. 15 use cctr
19. or/16-18
20. 19 use medal
21. 19 use emczd

22 19 use cctr

1. [(Supracondyl* adj2 fracture*) or gartland].ti,ab,kf.
2. Casts, Surgical/ or Splits/ or [conservative or cast* or immobili* or backslab* or slab* or sling* or (cuff* adj2 collar*) or splint* or non-surg*].ti,ab,kf. or "Referral and Consultation"/
3. (child* or adolescent* or infan*).mp.
4. (1 and 2 and 3) not (femur* or femoral or distal radi* or displaced or type ii or type 11 or type 2 or type two or type 3 or type 111 or type iii or type three).ti.
5. gartland type i supracondylar humerus fracture/ or humerus supracondylar fracture/ or humeral supracondylar fracture/ or distal humeral fracture/ or (distal humerus/ and fracture*.mp.)
6. [(Supracondyl* adj2 fracture*) or gartland].ti,ab,kw. not (femur* or femoral or distal radi*).ti.
7. 5 or 6
8. exp "casts and noninvasive traction devices"/ or exp splint/ or [conservative or cast* or Immobili* or backslab* or slab* or sling* or (cuff* adj2 collar*) or splint* or non-surg*].ti,ab,kw. or patient referral/
9. (baby or babies or newborn* or infan* or neonat* or preschool* or pre-school* or child* or pediatr* or paediatr* or teen* or adolescen*).mp.

10. (7 and 8 and 9) not (femur* or femoral or distal radi* or displaced or type ii or type 11 or type 2 or type two or type iii or type 111 or type 3 or type three).ti.
11. limit 10 to embase
12. [(Supracondyl* adj2 fracture*) or gartland].ti,ab,kw. not (femur* or femoral or distal radi*).ti.
13. [conservative or cast* or Immobili* or backslab* or slab* or sling* or (cuff* adj2 collar*) or splint* or non-surg*].ti,ab,kw.
14. (baby or babies or newborn* or infan* or neonat* or preschool* or pre-school* or child* or pediatr* or paediatr* or teen* or adolescen*).mp.
15. (12 and 13 and 14) not (femur* or femoral or distal radi* or displaced or type ii or type 11 or type 2 or type two or type iii or type 111 or type 3).ti.
16. 4 use medall
17. 11 use emczd
18. 15 use cctr
19. or/16-18
20. 19 use medal
21. 19 use emczd
22. 19 use cctr

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A Comparative Study on Closed Reduction vs. Open Reduction Techniques in the Surgical Treatment of Rotated Lateral Condyle Fractures of the Distal Humerus in Children

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Objective: The best approach between closed reduction and open reduction in the treatment of total displaced and rotated LCFs is still being debated. This study aimed to comparatively evaluate the clinical outcomes and complications of closed reduction vs. open reduction in the treatment of displaced and rotated lateral condyle fractures in children.

Methods: We retrospectively evaluated 46 children who underwent surgical treatment for totally displaced and rotated lateral condyle fractures. Thirty-one children underwent open reduction and percutaneous pinning (ORPP). Ten children underwent closed reduction and percutaneous pinning (CRPP). Five children were changed to ORPP procedures because of the failure of closed reduction attempts. Clinical outcomes and complications in the groups were compared.

Results: Among three groups, no significant differences were found in demographic variables, and no differences were detected in the incidence of postoperative complications and clinical parameters. The ORPP group had the shortest surgical duration of the three groups ($p < 0.005$). Patients in CRPP group had faster fracture healing than the patients who underwent open reduction procedures. However, the success of CRPP seemed to be dependent on the earlier surgical intervention.

Conclusion: ORPP is still the first-line treatment for the totally displaced and rotated lateral condyle fractures because of its direct visualization of the joint surface and easy-to-accomplish characteristics. In addition, CRPP may be a feasible option for the treatment of this type of fractures because of it is less invasive and potentially minimizes complications. However, the technical difficulties of CRPP must be taken into account.

Keywords: lateral condyle fractures of humerus, humerus, CRPP, ORPP, children

INTRODUCTION

Lateral condyle fractures (LCF) of the distal humerus are the second most common fracture above the elbow in children and commonly occur between ages 5 and 10 years (1). The incidence of LCF has been reported as 12% to 20% of all pediatric upper extremity fractures (2). The most common reported mechanism of injury is avulsion from a fall onto the outstretched arm with a varus stress at the elbow (3). Timely and appropriate evaluation and treatment are necessary to prevent some intractable complications such as avascular necrosis, nonunion, stiffness, and deformity of the affected elbow.

The widely accepted treatment algorithm for LCF has been established in previous studies (4, 5). Briefly, fractures with < 2 mm of displacement can be treated initially just with immobilization alone; however, careful follow-up is needed to identify further displacement (6). When lateral condyle fractures are displaced more than 2 mm, operative treatment is recommended (5–7). Open reduction and fixation with Kirschner wires or screws has been used for the treatment of displaced LCF for many decades. With the direct visualization of the articular surface, an anatomic reduction can be achieved for this kind of intra-articular fracture (8). However, some recent studies reported satisfactory outcomes of closed reduction and percutaneous pinning (CRPP) in treating displaced lateral condyle humeral fractures (9). This technique is most commonly used for displaced fractures with an intact cartilage hinge or no notable fragment malrotation (10). Generally, CRPP has been advocated for children with LCF displaced more than 2 mm but < 4 mm and without obvious articular surface incongruity under intraoperative arthrography. Otherwise, if the LCF is displaced more than 4 mm with or without fragment rotation, open reduction and percutaneous pinning (ORPP) is seen as the most optimal choice (5, 11).

CRPP has shown several advantages over ORPP, including less dissection of soft tissue around the fragment, low risk of vessel damage, and avoidance of an open incision with an unaesthetic scar (12). In recent decades, CRPP has been utilized to deal with displaced and rotated LCF successfully and seems to be an attractive alternative to ORPP. Song et al. (4) reported excellent results in three of six displaced and rotated LCF with the use of CRPP. Their following study reported more encouraging evidence that 18 of the 24 of displaced and rotated LCFs had achieved satisfactory results (13). However, the unavoidable fact is that the learning curve for this technique is time-consuming, and uncertainty over reduction of a substantially displaced LCF is still a concern. Whether closed reduction or open reduction is the best approach in the treatment of total displaced and rotated LCFs is still being debated. The purpose of this study was to comparatively evaluate the outcomes of closed reduction vs. open reduction in treating displaced and rotated LCFs (Stage-5 LCF according to the Song classification) (4) to provide a reference for treatment selection to peers when encountering this type of injury.

METHODS

Patient Selection

This study was approved by the Institutional Review Board of Children's Hospital of Chongqing Medical University. We retrospectively enrolled consecutive children with displaced LCF surgically treated at our institution from August 2018 to May 2020. The inclusion criteria were (1) patients below 14 years of age, (2) patients diagnosed with displaced and rotated LCF (Stage 5 LCF according to the Song classification), (3) interval from injury to admission <5 days, and (4) more than 6 months' clinical and radiographic follow up. The exclusion criteria were (1) combination with ipsilateral upper-limb fracture and/or dislocation, (2) pathological fracture, and (3) open fracture. In total, 46 patients with displaced LCF were enrolled in this study. Written informed consent was obtained from the parents or guardians of each patient. Closed or open reduction was determined by the consensus reached by the children' guardians and surgeons.

Surgical Techniques

When closed reduction was attempted, the surgical technique reported by Song et al. was employed (4, 13). The procedure was performed under general anesthesia with the children in the supine position. The displacement of the fracture of the affected elbow was reconfirmed under intraoperative fluoroscopy. The rotated displacement of the distal fragment was the first to be reduced. The affected elbow was placed in flexion in an appropriate position to relax the stretching of forearm extensors, usually about 40–60° flexion. Different from the original method described by Song et al. in which a Kirschner wire was used as a joystick to assist reduction, we were accustomed to using a Davis dura dissector as the joystick because its wide tails made it more easily manipulated when reducing the rotated fragment. The Davis dura dissector was inserted into the fracture gap through a minimal lateral elbow incision (about 5 mm in length). Then, an attempt was made to reposition the rotated fragment by using the dissector to pry open the fragment, with a view to make the two fracture surfaces in an opposite position. After the fragment rotation was corrected, the elbow was fully extended with the forearm supine, and direct compression was applied by a surgeon's thumb on the distal fragment medially and anteriorly to minimize the fracture gap. After assurance that the fracture gap was no more than 2 mm either in the AP or oblique internal rotational view, two or three percutaneous K-wires (1.6 or 1.8 mm in diameter) were inserted for fixation. Then an intraoperative arthrogram was used to confirm the congruence of the articular surface of the distal humerus (**Figure 1**). For fractures with > 2 mm of displacement or incongruence of the articular surface following closed reduction, an open reduction was employed. The ORPP technique was undertaken as described by Blasier (14). The patient was placed in the supine position and a tourniquet was utilized. A direct lateral incision was made and care was taken to minimize posterior dissection of the capitellum. Under direct visualization, the articular surface was reduced and stabilized with two to three divergent K-wires with diameters of 1.6 or 1.8 mm that engaged the medial cortex. Thereafter, the

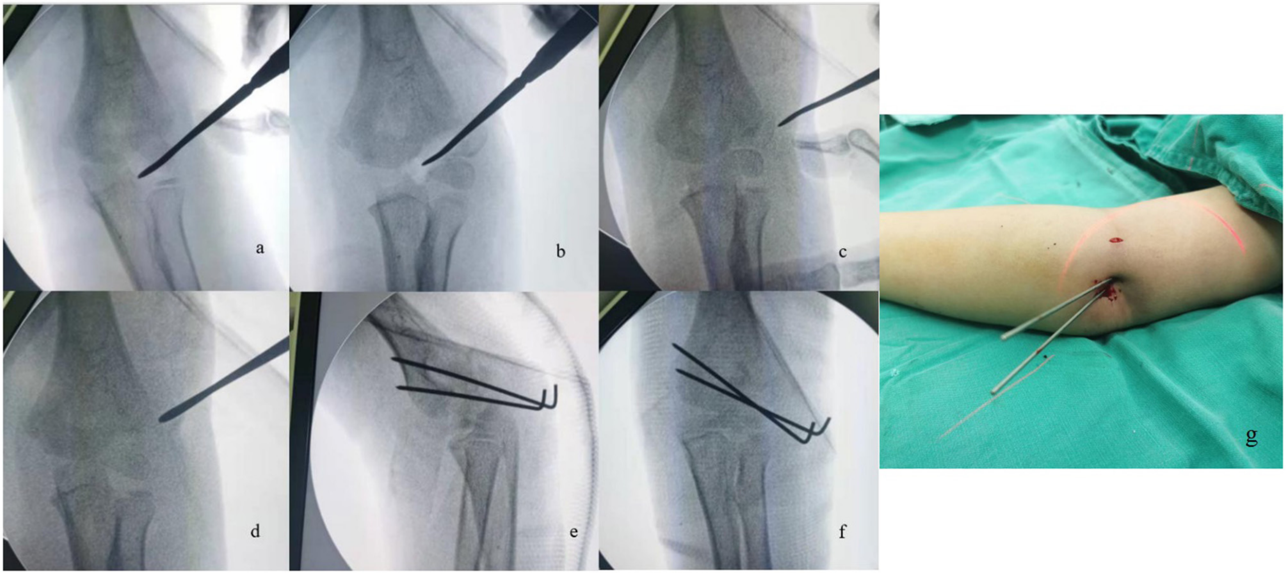

FIGURE 1 | (a) A Dura dissector was placed into the lateral cortex under c-arm fluoroscopy. **(b)** The rotated fragment was reduced by Dura dissector prying. **(c)** The elbow was fully extended with forearm supination, and direct compression was applied by a surgeon's thumb on the distal fragment medially and anteriorly to minimize the fracture gap. **(d)** Assurance that the fracture gap was no more than 2 mm. **(e,f)** Two percutaneous k-wires were inserted for fixation in AP and oblique internal rotational view. **(g)** The minimal lateral incision after the CRPP procedure in the treatment of LCFs.

affected arm was placed in a posterior long-arm cast with a 45° of elbow flexion to immobilize the fracture about 4–6 weeks until the removal of the K-wires. The K-wires were removed in the outpatient clinic when fracture healing was documented on two views. All children had at least six months of follow up and complications were noted.

Clinical Outcomes Evaluation

At the last follow up, the range of motion (ROM) of the elbows and elbow carrying angle were evaluated using a goniometer. The loss of ROM and elbow carrying angle were defined by the difference in values between the affected side and contralateral normal side. In addition, the functional and cosmetic outcomes of the affected elbow were assessed according to Flynn's criteria (15). The occurrences of clinical complications such as infections (superficial/deep), late ulnar neuritis, and conspicuous incision scar after surgery were also recorded. More specifically, the superficial infection was defined as the infection involving only skin and subcutaneous tissue of incision, with little or no tissue reaction. The deep infection involved deep tissues, such as fascial and muscle layers, even at the fracture site.

Radiographic Outcomes Evaluation

The radiographic outcomes were evaluated in AP and lateral radiographs of elbows at each follow up in all the patients. Osseous union was confirmed by the presence of bone bridging on AP and lateral radiographs. Cases with delayed union, nonunion, and malunion were recorded. Furthermore, avascular necrosis of the humeral capitulum, fishtail deformity at distal humerus, and lateral spur formation were also assessed from the postoperative radiographs. The radiographic carrying angle were measured on the AP radiographs.

Statistical Analysis

All variables were analyzed by the SPSS 22.0 statistical software, continuous data were indicated by mean ± SD, and the ANOVA analysis and independent sample t-test were used for the comparison of continuous variables. The chi-square test was used for categorical variables. The Kruskal-Wallis test was used for ranked variables. The level of statistical significance was set at $p < 0.05$.

RESULTS

A total of 46 patients who met the inclusion criteria underwent surgical treatment for the diagnosis of a displaced and rotated LCF from August 2018 to May 2021. There were 26 males (56.5%) and 20 females (43.5%) included in this study. Thirty-one fractures were directly treated with ORPP and all the fractures achieved successful reduction. In April 2020, we began to use CRPP to treat LCF with complete displacement and rotation of fragments. To sum up, treatment of 15 fractures was initially attempted with CRPP. Of these, 10 (10/15, 66.7%) fractures were successfully treated with CRPP, but the other 5 fractures (5/15, 33.3%) needed to be changed to the ORPP procedure because the fracture gap was more than 2 mm or there was incongruence of the articular surface on the arthrogram after closed reduction efforts. In addition, the patients who were

TABLE 1 | General descriptive data of three groups.

Variables	Treatment						
	ORPP	CRPP	Converted group	P	#P	&P	%P
No. of children	31	10	5				
Age at the presentation (years)	5.39 ± 2.03	4.90 ± 2.33	5.00 ± 2.00	0.782			
Sex							
Male	17	6	3	>0.999			
Female	14	4	2				
Side of injury							
Left	16	6	3	0.92			
Right	15	4	2				
Neurovascular involvement	0	0	0				
Interval from injury to surgery (days)	3.23 ± 0.72	2.50 ± 0.53	3.60 ± 0.55	**0.005***	**<0.001***	0.275	**0.002***
Surgery duration (minutes)	36.00 ± 9.16	56.1 ± 9.99	81 ± 8.43	**<0.001***	**<0.001***	**<0.001***	**<0.001***
Fracture healing (weeks)	5.84 ± 1.34	4.50 ± 0.53	6.20 ± 0.84	**0.007***	**0.004***	0.566	**<0.001***
Follow up (months)	9.81 ± 3.53	10.20 ± 4.83	10.40 ± 2.70	0.923			

*ORPP, open reduction and percutaneous pinning; CRPP, closed reduction and percutaneous pinning; Converted group, CRPP converted to ORPP; P, statistical significance among three groups; #P: ORPP vs. CRPP; &P: ORPP vs. Converted group; %P: CRPP vs. Converted group; *statistical significance and P-value was less than 0.05.*

converted to open reduction were the first, second, fifth, sixth, and tenth patients in the CRPP cohort. All the conversions occurred in the first 10 patients. A summary of variables compared by treatment types is shown in **Table 1**. No differences were found among any of the groups in age, sex, follow-up duration, and side of injury. The interval from injury to surgery, surgery duration, and fracture healing time had differences among groups. A shorter interval time from injury to surgery was found in than CRPP group than in the ORPP ($p < 0.001$) or converted groups ($p < 0.001$). The ORPP group had the least time, 36.00 ± 9.16 min, for surgical completion, and the converted group had the longest time, 81 ± 8.43 min, to finish the surgery. The mean fracture healing time in the CRPP group was 4.50 ± 0.53 wk, which was shorter than those in the other two groups.

Data were collected on complications including infections (superficial/deep), delayed union, nonunion, malunion, late ulnar neuritis, lateral spur formation, avascular necrosis, fishtail deformity, and conspicuous incision scar after surgery. No differences in these variables were found among the three groups (**Table 2**).

At the last follow up, the loss of ROM and radiographic elbow carrying angle were defined by the difference in values between the affected side and contralateral normal side. Regardless of the treatment methods, all the injured elbows had a slight decrease either in extension, flexion, and movement arc when compared to the normal contralateral elbow. However, no differences were found among the three groups in these parameters. Moreover, no differences were observed among the three groups in the radiographic carrying angle. In addition, the clinical outcomes were classified as excellent, good, fair, or poor according to Flynn's criteria (15). No significant differences were observed among groups in the cosmetic outcome and functional outcome according to Flynn's criteria (**Table 3**).

DISCUSSION

The foremost goal of treatment for LCF in children is to restore the anatomical articular surface. For this reason, open reduction and Kirschner wire fixation has long been considered the preferred method for LCFs. Most of the published studies addressing surgical treatment of LCFs have focused on techniques utilizing an open approach. According to the displacement and congruity of the articular surface of the LCF fractures under arthrography, a classification was proposed by Weiss et al. (5) to guide treatment decision making. Type I fractures are fractures with < 2 mm displacement that can be managed with observation and casting. Type II fractures are displaced more than 2 mm but with congruence of the articular surface, which can be managed with closed reduction. Type III fractures have articular surface displacement and open reduction is recommended, although most pediatric orthopedic surgeons do not recommend closed reduction for the treatment of the displaced and rotated lateral condyle fractures (6). This technique for displaced LCFs has received increasing attention. In the last decade, CRPP has still been favored by other surgeons when joint congruity can be confirmed because it is less invasive and potentially minimizes complications, and some promising results have been found (16). The present study also found that the LCFs treated by CRPP had a shorter fracture healing time than those treated by ORPP.

Song et al. conducted a prospective study of CRPP for treating unstable lateral condyle fractures, and achieved a high success rate (73%). However, only three of six (50%) with displaced and rotated lateral condyle fractures were reduced to < 2 mm of residual displacement and needed a further open reduction procedure (4). Silva et al. also confirmed that CRPP is a safe and effective alternative when considering the treatment of pediatric LCFs with limited displacement (between 2 and 4 mm) (17). However, after accumulating experience, Song and colleagues

TABLE 2 | Complications in three groups.

Complications	ORPP	CRPP	CRPP converted to ORPP	*p*
Superficial infection	4/31	0/10	1/5	0.725
Deep infection	2/31	0/10	0/5	>0.999
Delayed union	0/31	0/10	0/5	
Nonunion	0/31	0/10	0/5	
Malunion	0/31	0/10	0/5	
Tardy ulnar neuritis	0/31	0/10	0/5	
Lateral spur formation	23/31	7/10	3/5	0.783
Avascular necrosis	0/31	0/10	0/5	
Fishtail deformity	0/31	0/10	0/5	
Conspicuous incision scar	5/31	0/10	0/5	0.459

TABLE 3 | Radiographic and clinical outcomes of three groups.

	Treatment			
	ORPP	**CRPP**	**CRPP converted to ORPP**	***p***
Radiographic carrying angle (°)				
Affected side	8.58 ± 5.19	8.90 ± 4.56	5.20 ± 1.64	0.325
Contralateral side	9.03 ± 3.34	10.00 ± 3.27	8.4 ± 1.14	0.601
Loss of carrying angle	0.46 ± 3.35	1.10 ± 3.21	3.20 ± 2.59	0.221
ROM of elbow (extension, flexion, arc)				
Extension (°)				
Affected side	1.45 ± 1.65	1.50 ± 1.08	1.60 ± 0.89	0.978
Contralateral side	3.16 ±1.68	4.30 ± 1.16	4.20 ± 0.84	0.08
Loss of extension	1.71 ± 1.74	2.80 ± 1.14	2.60 ± 1.14	0.129
Flexion (°)				
Affected side	131.29 ± 7.05	126.00 ± 4.81	128.20 ± 5.63	0.081
Contralateral side	136.16 ± 6.48	131.70 ± 4.81	133.40 ± 5.94	0.126
Loss of flexion	4.87 ± 2.51	5.70 ± 2.00	5.20 ± 1.10	0.615
Arc (°)				
Affected side	132.74 ± 7.53	127.50 ± 4.84	129.8 ± 5.76	0.111
Contralateral side	139.32 ± 6.99	136.00 ± 4.19	137.60 ± 6.07	0.356
Loss of flexion	6.58 ± 2.94	8.50 ± 2.12	7.80 ± 2.17	0.141
Flynn's criteria (cosmetic, functional)				
Cosmetic outcome				
Excellent	24	8	3	0.668
Good	7	2	2	
Fair	0	0	0	
Poor	0	0	0	
Incidence of "excellent" or "good"	100%	100%	100%	
Functional outcome				
Excellent	7	0	0	0.206
Good	19	7	4	
Fair	5	3	1	
Poor	0	0	0	
Incidence of "excellent" or "good"	83.90%	70%	80%	

achieved a tremendous success rate of 85.7% (18/21) in such fractures using CRPP (13). More recently, a study by Xie et al. (12) demonstrated that CRPP is an effective technique for treating LCFs with severe displacement. The overall success rate of closed reduction was 78% (36/46) regardless of the displacement grade. In addition, 14 of 18 (78%) with displaced and rotated LCFs were also successfully treated with CRPP. In the present study, we used CRPP for 15 lateral condyle fractures with complete displacement and rotation. Only 10 of the 15 (66.67%) fractures were satisfactorily reduced, as defined by the fracture gap being < 2 mm either in anteroposterior (AP), lateral, and oblique radiographic views, and the congruent articular surface was confirmed by intraoperative arthrography. This success rate of closed reduction was lower than that in previous studies. We considered that the principal reason for our failure in reduction was the high degree of displacement of fractures in the present study. All the LCFs was displaced and rotated, which indicated that more soft tissue around the fracture fragment had been destroyed. In particular, the massive disruption of the lateral periosteum in this type LCF could give rise to the lack of a support point during manual reduction, which made the surgeons convert to open reduction after unsuccessful closed reduction attempts.

CRPP has been widely accepted as the standard treatment for unstable supracondylar fractures. It was reported that delaying surgery more than 8 h was associated with an increased rate of open reduction (18). The present study focused on CRPP for the treatment of LCFs and also found that increased time from injury to surgery led to a trend toward open reduction. The failure can be ascribed, at least in part, to the significant swelling from delayed treatment making the fracture fragments hard to palpate (19). Moreover, coagulated blood clots between the fracture gap and contracted soft tissues might also have hampered the reduction.

Undoubtedly, accumulated experience is necessary for the skilled manipulation during closed reduction (16). For the same reason, we had a limited success rate (66.67%) for rotated LCFs with CRPP in this study. Among patients who underwent closed reduction attempts, 5 of the 15 patients underwent conversion to open reduction, 3 of them occurred in the first five cases (60%), and all of them occurred in the first 10 patients. The time-consuming learning curve of closed reduction for the rotated LCFs cannot be ignored. More experience and training may help us to be more proficient with this technique.

The open reduction procedure allows direct visualization of the joint surface, and for this reason, getting a congruent joint surface and maintaining reduction can be easily guaranteed (20). Closed reduction has been favored by some colleagues because it requires less dissection of soft tissue and avoids incision and a conspicuous scar, with lower risk of complications (4). However, in the present study, using open reduction internal fixation (ORIF) to treat rotational LCFs did not increase the risk of complications when compared to the fractures treated by CRPP. Moreover, comparable satisfactory functional outcomes and cosmetic outcomes have been obtained by both open reduction and closed reduction. Interestingly, unlike the previous reports that CRPP had a shorter operating time than open reduction procedures in treating LCFs, the present study found that the CRPP procedure in treating rotational LCFs takes a significantly longer time than that in ORIF to achieve a satisfactory reduction and fixation. In our experience, technical difficulty might be the main reason for the long duration of CRPP in treating this type of rotational LCFs. In addition, repeated intraoperative confirmation of the reduction and secure maintenance of percutaneous K-wires are also time-consuming processes. According to present outcomes, we still hold the cautious view that the ORPP might be still the first-line treatment for total displaced and rotated LCFs.

Lateral spur formation was the most common complication in the present study, but almost all of them were asymptomatic. Our results were consistent with the previous studies (21). In addition, we observed a comparable incidence of lateral spur formation among the three groups. Regardless of the surgical methods, all the LCFs in present study were fixed with the K-wires, which is not a rigid fixation system. As a result, micromotion between the bone fragments at the fracture site enhanced the bone formation and led to the lateral spur formation.

In conclusion, both CRPP and ORPP in treating total displaced and rotational LCFs yield good clinical outcomes and acceptable complication incidences on the basis of successful reduction and fixation achieved intraoperatively. However, because of the standardization of the operative process and straightforward characteristics, open reduction and fixation remains the "gold standard" for displaced and rotated LCFs, especially for patients with a longer interval between injury to first treatment. Nevertheless, with the intrinsic advantages such as faster healing time without risk of conspicuous incision scar and lower surgical infection rate, CRPP should be still taken into consideration in the decision-making process for the treatment of this type LCF, and surgeons should be prepared for the time-consuming learning process.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This was a retrospective study of patient data, and IRB approval was obtained from Children's Hospital of Chongqing Medical University (2020196). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LW, XL, and YZ were involved in the conception, design of the project, and made the critical revisions. YZ, LW, HZ, and GZ participated the surgery implementation. LW and YC collected and extracted the data. XL, YC, and YZ conducted the analysis and data interpretation. YZ drafted the manuscript. All authors read, provided feedback, and approved the final manuscript.

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Commentary: A comparative study on closed reduction vs. open reduction: Techniques in the surgical treatment of rotated lateral condyle fractures of the distal humerus in children

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A Commentary on
A comparative study on closed reduction vs. open reduction: Techniques in the Surgical treatment of rotated lateral condyle fractures of the distal humerus in children

By Weng L, Cao Y, Zhang G, Zhou H, Liu X, Zhang Y. (2022). Front. Pediatr. 10:891840. doi: 10.3389/fped.2022.891840

We read with interest the article by Weng et al. Neither the Jakob (1) nor the Song (2) classification considers the anatomic variations of lateral humeral condyle fractures (LHCF). Both (1, 2) do not differentiate between Milch (3) type I fractures (fracture line runs through the capitello-trochlear sulcus or lateral to it) and type II fractures (fracture line runs through the trochlea). Song et al.'s (2) illustration of stage 1 to 5 fractures depicts only Milch type II fractures of increasing severity, which only applies to avulsion fractures caused by forearm adduction injuries. These limitations have possibly resulted in the classification having been abandoned by Song et al. (4) two years after its publication.

Weng et al. included only Song stage 5 fractures which are the same as Jakob type III (displaced and rotated fragment) and did not differentiate between Milch type I and II.

Xie et al. (5) reported an overall closed reduction and percutaneous pinning (CRPP) rate of 74% for LHCFs with >4 mm displacement. There was no difference in the CRPP rate between Song stage 4 (75%; 15 of 20 cases) and stage 5 cases (73%; 22 of 30 cases) but there was a significant difference between Milch type I (50%; 6 of 12 cases) and II

(82%; 31 of 38 cases) fractures. All 30 Song stage 5 patients had an initial attempt of closed reduction. In 11 of the latter patients a 2 mm K-wire was used as a joystick which resulted in a closed reduction in 6 patients but in 5 it had to be proceeded to an open reduction. Information on the length of the individual procedures was not provided. Xie et al. (5) concluded that a closed reduction should always be attempted and that the fracture anatomy, as identified by the Milch classification, is more important for the success rate than the Song classification. We would like to ask Weng et al. if they could identify the Milch types for their fractures and if there was an association between Milch type I and increased ORPP rate?

Most of the fracture healing happens within the bone and is in our opinion impossible to measure or judge accurately, so that we generally leave children in a cast for about 5 weeks and then take radiographs after cast removal. It would have been necessary for Weng et al. to have had a fixed follow-up and clearly defined bone healing assessment protocol (which does not exist for these fractures) to identify a difference in the fracture healing time between the groups, with cast removal, taking of radiographs and cast re-application (where necessary) on a weekly basis from 4 weeks until it was judged for the fractures to have healed. Since the authors did not describe such protocol, we assume that the casting times and reported bone healing times were purely dependent on the surgeon's preference, with the different bone healing times only reflecting the arbitrary choice of casting times. Do Weng et al. agree that their study design and provided evidence does not support their statement that CRPP is associated with a reduced bone healing time compared to open reduction?

We would also like to ask Weng et al. how they explain their high superficial (x5) and deep (x2) infection rate in their open reduction and percutaneous pinning group (ORPP) in comparison to Nazareth et al. (6) who reported 1 superficial and no deep infection in 30 patients with >4 mm displacement who had ORPP. Deep infections create a lot of hardship for the children and their parents, requiring intravenous antibiotics *via* a PICC-/long line and sometimes wound and/or joint washout. This creates a lot of costs for the health provider which might outweigh the costs for the extended operating time needed for CRPP reported by Weng et al.

Weng et al. reported that CRPP of Song stage 5 LHCFs was generally difficult, not possible in 33% of cases and was associated with a time-consuming learning process and therefore identified open reduction and fixation as their "gold standard", indicating that CRPP is a technique which requires acquired experience and skills and should probably be left to those who perform such procedures regularly.

In conclusion, Weng et al. identified that CRPP of LHCF is technically difficult but the data provided by the latter and other authors (1, 2) support that closed CRPP of LHCF displaced >4 mm is possible in a high proportion of fractures with good outcomes. Therefore, the way forward might be to attempt CRPP of all fractures, considering the high infection rate reported by Weng et al. for ORPP (19.4%), the larger scars from ORPP and the very low infection rate reported by Bloomer et al. (7) for CRPP of supracondylar humerus fractures with (0.6%) and without antibiotic (0.4%).

Author contributions

AR contributed to the literature review and manuscript preparation. EA contributed to the literature review and manuscript preparation. PLN contributed to the literature review and manuscript preparation. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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Learning Curve of Closed Reduction and Internal Fixation for Supracondylar Fractures of the Humerus in Children

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Background: This study aimed to identify the threshold for success in supracondylar humeral fracture surgery by describing the learning curve for beginners and exploring the relationship between the learning curve and the prognosis of supracondylar fractures of the humerus.

Methods: Surgical information was collected of the first 100 humeral fractures treated by four pediatric orthopedic surgeons. The relationship between operation time, wire placement success rate, and surgical experience was determined using the restricted cubic strip (RCS). The inflection point in the curve and other risk factors that may affect fracture prognosis were collected and subjected to multiple logistic regression to clarify the relationship between the learning curve and prognosis of supracondylar fractures of the humerus. After the training, the four fresh surgeons were interviewed in the form of questionnaires to get feedback from the trainees.

Results: A total of 400 supracondylar fractures of the humerus from four pediatric orthopedists were included in the study. On an RCS analysis, 65 surgical experiences were the inflection point of the learning curve. Before and after these 65 surgical experiences, there were significant differences in the patients' anatomical reduction (186 vs. 122, $P < 0.001$), conversion to incision (33 vs. 6, $P = 0.008$), and supervising physician guidance (28 vs. 2, $P < 0.001$). In the multiple logistic regression analysis, functional recovery after supracondylar fractures of the humerus was significantly associated with surgical experience, intraoperative conversion to incision, and post-operative infection. Four surgeons and a supervisor were interviewed. They believed that self-confidence establishment requires the experience accumulation of about 30 operations. The most critical surgical technique is the reduction of fractures.

Conclusions: Although the accumulated experience of 30 operations can establish the self-confidence of trainers, fresh surgeons must accumulate experience with 65 operations to master closed reduction and internal fixation for supracondylar fractures. Surgical experience significantly impacts the post-operative recovery of patients with fractures.

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INTRODUCTION

Just as pilots learn to fly an aircraft, a learning curve is required for surgeons to master surgical skills. Pilots can prove mastery of technology by accumulating simulated flight time and completing mock exams, and airlines can determine the practice time required for pilots to master various aircrafts. However, surgeons cannot test their skills by collecting experiences with real patients. Before becoming proficient in surgical techniques, the medical team must give novice surgeons knowledge and technical support in practice and bear the medical risks of surgical failure. At present, the research on surgical learning curve often focuses on innovative surgery, difficult surgery and robotic surgery (1, 2). In orthopedics, there was also a large number of research on the learning curve of spine, pelvic fracture, congenital hip dysplasia and arthroscopic (3–5). There was no report on the learning curve for more elementary surgery. Thus, we asked, is it possible to change the way of thinking, starting with simple routine surgery, and explore a method of accurately calculating the learning curve?

Supracondylar fractures of the humerus account for two-thirds of all elbow injuries in children requiring surgery (6). Closed reduction and internal fixation of fractures with a Kirschner wire are not difficult, with minimal damage, fewer incisions, and accelerated healing (6). It should involve surgical skills that fresh pediatric orthopedists can master quickly so that pediatric orthopedists can build confidence in surgical success and lay the foundation for subsequent difficult operations.

This study aimed to explore the learning curve characteristics of pediatric fracture surgery by collecting the experience of four pediatric orthopedic surgeons in our center using surgeries treating supracondylar fractures, determining the learning threshold point, and exploring the relationship between the learning curve and prognosis of supracondylar fractures of the humerus.

MATERIALS AND METHODS

Surgeon Selection

The surgeons were the four residents of the hospital, all of whom had completed 2 years of pediatric orthopedic resident training. During training, they were required to master all the methods of diagnosing and treating pediatric orthopedic-related diseases and were required to study all aspects of pediatric orthopedic-related surgical techniques as an assistant. After training, they began to perform common orthopedic surgeries in children.

Patient Selection

The study included the first 100 patients with supracondylar fractures of the humerus that the above four residents were the chief surgeons in chronological order. Patients with multiple fractures, refractures, pathological fractures, congenital bone disease, neurovascular-related complications, and those assessed by the department requiring treatment by a more experienced physician were excluded.

Surgical Plan Formulation and Implementation

The diagnosis of the patient's disease and the formulation of the surgical plan were jointly formulated by all orthopedic surgeons in the center after discussion. After confirming that the chief surgeon was one of the new residents mentioned above, the center designated an supervising doctor for the patient to prepare in the ward so that he/she could take over at any time in the event of an accident. Moreover, at the end of the operation, the supervising doctor confirmed the fracture reduction and internal fixation position on an intraoperative radiograph.

Surgical Procedure

We will give priority to the closed reduction to correct the dislocated supracondylar fracture. When the closed reduction failed, the chief surgeon will switch to open reduction with the permission of the supervising doctor. Different K-wire arrangement schemes will be adopted according to the stability of the fracture (sector fixation with 2–3 Kirschner wires on the radial side or cross fixation with 2 Kirschner wires on the radial side and one Kirschner wire on the ulnar side) (7). After internal fixation, the supervising doctor will evaluate the position of fracture and internal fixation through observation in the operating room and intraoperative radiography (Due to the excellent shaping ability of supracondylar fracture, we do not require anatomical reduction of fracture at this time). Finally, we cut and bend the tail of the Kirschner wire, wrap it with gauze and leave it outside the skin.

We recorded each patient's operation time and the Kirschner wire placement success rate after each operation, and these two data were the main exposure variables for further research. We also recorded whether each operation was converted to open reduction during the operation and whether the intraoperative guidance of the supervising doctor was requested. Post-operatively, radiographs of the elbow joint were used to assess whether the fracture was anatomically reduced.

Post-operative Complications

The supervising surgeon and the chief surgeon performed regular outpatient follow-up (every 2 weeks) for all cases. Fracture healing, wound infection, neurovascular function, and internal fixation loosening were evaluated and recorded at each follow-up visit.

Prognosis

When a patient's fracture healed, the K-wire was removed and elbow joint function was exercised at home under the guidance of the chief surgeon. We evaluated and recorded the range of flexion and extension of the elbow joint 1 month after removal of the internal fixation. We considered the patient's recovery satisfactory if the elbow flexion and extension range of motion reached 80% of normal. If recovery was poor, we provided the patient with further rehabilitation guidance.

Definitions and Standards for the Collected Data

Operation time: The operation time includes the whole process of disinfection, operation and wound dressing. It does not include the duration of induced anesthesia and anesthesia recovery.

Wire placement success rate: Number of K-wire used/ number of internal fixed attempts.

Anatomical reduction: The deformity and displacement of the fracture were completely corrected and the normal anatomy of the humerus was restored.

Functional reduction: The fracture was not completely reduced. We can accept a certain degree of rotation or radial displacement. However, on lateral radiographs, anterior humeral line must contact the capitulum humeri. Significant rotational displacement, ulnar displacement, and absence of contact with the humeral capitulum at anterior humeral line are not acceptable.

Infection: Including osteomyelitis, cellulitis and skin infection.

Fracture union: No local tenderness and abnormal activity; X-ray showed that the fracture line was fuzzy and there was continuous callus passing through the fracture line.

Delayed union: The fracture do not reach the union standard within 2 months after operation.

Implant related complications: Including internal fixation looseness and fracture displacement caused by internal fixation looseness.

Elbow function recovery: The range of motion of the normal elbow is about 135°-150°. We will take the patient's healthy elbow as the control. When the range of motion of the injured side reaches 80% of the control side, we will define it as good recovery.

Statistical Analysis

We collected the data recorded above as well as the demographic and comorbidity variables for each patient, including age, sex, affected side (left or right), and fracture classification (8).

We used restricted cubic splines with four knots (9) to model the relationship between surgical experience, surgical time, and wire placement success rate after the adjustment for fracture classification, age, sex, and affected side (left or right). We examined the non-linear relationship between surgical experience and operative time and the wire placement success rate to identify any inflection point that could be used to dichotomize operative experience into categories in a clinically meaningful way. Once a reasonable inflection point was identified, the differences in the various data before and after the inflection point were used to verify its accuracy. Subsequently, we used multivariable logistic regression to determine the area under the curve for the models relating various surgical experience cutoff points to functional recovery. The surgical experience with the maximum area under the curve was selected as the cutoff point to dichotomize the surgical experience.

The final multivariate models were constructed in a stepwise backward manner. The model initially included all independent variables and sequentially excluded the variable with the highest P-value until only those of $P < 0.20$ remained. Values of $P < 0.05$ were considered statistically significant. Variables with P-values of 0.05–0.20 were left in the model to control for potential confounding.

Interviews With the Four Surgeons

After surgical training, each surgeon will complete a simple questionnaire. The questionnaire includes the following 7 questions: (1) time for confidence building; (2) conditions for confidence building; (3) the most worried events during the operation; (4) the most worried events during the follow-up; (5) what is the most frustrating thing in the treatment process; (6) list an event that makes you grow fastest; (7) list one of the most critical technologies. Then, we will summarize their questionnaire results.

RESULTS

General Results

In 2015–2021, 400 patients were included in the study; all were operated upon by the four surgeons mentioned above. The average patient age was 59.38 ± 21.15 months; 242 were male, 158 were female; and fractures included type II (45.5%) and III (54.5%). The average operation time was 34.00 ± 13.80 min, the average wire placement success rate was 57.75 ± 20.33%, and the anatomical reduction rate was 77%. Of all children, 9.8% required conversion to open reduction and 7.5% required intraoperative superior surgeon guidance. The fractures of all children eventually healed, while 8.8% required more than 2 months to heal. There were no post-operative neurovascular-related complications, while the infection rate was 3.5%. Two infected patients were eventually treated with surgical debridement and healed thereafter. Internal fixation loosening occurred in 12.5% of cases; no other complications occurred. One month after Kirschner wire removal, 81% of the children showed good recovery of elbow function (**Table 1**).

Comparison of Surgeons Background and Operation Experience

The learning experience and internship experience of the four surgeons are shown in **Table 2**. The average age of the four doctors participating in the training is 27.5 years old, and they are all male. Tow of them have a master's degree and the others have doctor's degrees.

The four surgeons successfully completed their first 100 supracondylar fractures of humerus during training. Patient information for each surgeon is shown in **Table 3**. The patients treated by the four surgeons had no significant difference in age ($P = 0.907$), gender ($P = 0.871$), Wire placement success rate ($P = 0.154$), side ($P = 0.795$), Gartland classification ($P = 0.612$), conversion to open reduction ($P = 0.803$), intraoperative guidance ($P = 0.387$), infection ($P = 0.687$), internal fixation loosening ($P = 0.290$)and delayed union ($P = 0.66$). There were differences in operation time and anatomical reduction among the four doctors.

Regression Splines of Relationship of Operation Time and Wire Placement Success Rate

The restricted cubic splines for surgical experience to time and rate had similar inflection points at ~65 procedures, after which point, with the continued accumulation of surgical experience, the trend of increasing operation time and decreasing success rate flattened (**Figures 1**, **2**).

TABLE 1 | Medical and admission characteristics of 400 eligible patient of supracondylar fractures before surgery and subsequent complications.

General results		
Age (month)	59.38 ± 21.15	
Sex	Male: 242	39.5%
	Female: 158	60.5%
Side	Left: 230	42.5%
	Right: 170	57.5%
Type	Type II: 182	45.5%
	Type III: 218	54.5%
Accumulation of surgical experience	Before 65: 263	65.8%
	After 65: 137	34.2%
Operation time (min)	34.00 ± 13.80	
Wire placement success rate (%)	57.74 ± 20.33	
Anatomical reduction	Yes: 308	77.0%
	No: 92	23.0%
Conversion to open reduction	Yes: 39	90.3%
	No: 361	9.8%
Intraoperative superior surgeon guidance	Yes: 30	7.5%
	No: 370	92.5%
Infection	Yes: 14	3.5%
	No: 386	96.5%
Internal fixation loosening	Yes: 50	12.5%
	No: 350	87.5%
Delayed union	Yes: 35	8.8%
	No: 365	91.3%
Degree of recovery	Good: 324	81.0%
	Not good: 76	19.0%

We dichotomized the surgical experience according to a volume of 65 procedures (≤65 or >65). Before and after the accumulation of surgical experience, the two groups of patients were compared in terms of age (58.19 ± 25.18 vs. 61.66 ± 30.54 months), sex (male, 154 vs. 88; female, 109 vs. 49), and classification (type II, 139 vs. 79; type III, 124 vs. 58). In terms of post-operative evaluation, the operation time, anatomical reduction (186 vs. 122, $P < 0.001$), conversion to incision (33 vs. 6, $P = 0.008$), and superior physician guidance (28 vs. 2, $P < 0.001$) were significantly different. Regarding post-operative complications, there was no significant difference in infection (12 vs. 2, $P = 0.153$) or delayed union (28 vs. 7, $P = 0.065$). There were significant differences in internal fixation loosening (41 vs. 9, $P = 0.01$) and poor post-operative functional recovery (67 vs. 9, $P < 0.001$) (**Table 4**).

Multivariate Logistic Regression Analysis of Post-operative Functional Recovery

Subsequently, we conducted analysis of variance with the accumulation of surgical experience as an independent risk factor affecting post-operative functional recovery and found that the effect of surgical experience was significant. Similarly, an analysis of variance was performed for other continuous variables (age, duration of surgery, and wire placement success rate). The chi-square test was performed of the risk factors of the dichotomous variables, and the results showed no difference between the sexes, affected side, or type. However, significant differences were observed in conversion to open reduction, infection, and delayed healing (**Table 5**).

After excluding risk factors with values of $P > 0.2$ (type, side, intraoperative guidance, and implant loosening), we performed multivariate logistic regression of post-operative functional recovery. Surgical experience, infection, and conversion to incision significantly affected the prognosis of closed reduction and internal fixation of supracondylar fractures of the humerus (**Table 6**).

Interviews With the Four Surgeons and One Supervisor

We were fortunate to receive the response from four surgeons and one of the oldest supervisors. As shown in **Table 7**, the interviewees' answers to most questions have something in common: (1) it usually takes about 3 months to establish surgical self-confidence (about 30 supracondylar fractures); (2) the opportunity to establish self-confidence is usually to successfully complete difficult surgery independently; (3) the surgeons are most worried about the difficulty of intraoperative reduction and

TABLE 2 | Surgeons background.

	Surgeon 1	Surgeon 2	Surgeon 3	Surgeon 4
Age (y)	28	28	27	27
Sex	Male	Male	Male	Male
Education	Master of Medicine	Master of Medicine	Doctor of Medicine	Doctor of Medicine
Internship experience	General hospital	Children's general hospital	General hospital	Children's general hospital

TABLE 3 | Patient characteristics for each surgeon.

	Surgeon 1	Surgeon 2	Surgeon 3	Surgeon 4	*P*-value
Sex (*n*)					
Male	62	57	62	61	0.871
Female	38	43	38	39	
Age	60.2 ± 26.93	59.4 ± 24.32	60.44 ± 20.41	57.72 ± 30.4	0.907
Side (*n*)					
Left	57	54	61	58	0.795
Right	43	46	39	42	
Type (*n*)					
Type II	49	46	40	47	0.612
Type III	51	54	60	53	
Operation time (min)	36.54 ± 14.01	37.48 ± 12.84	29.32 ± 13.75	32.66 ± 13.21	<0.01
Wire placement success rate (%)	56.92 ± 20.72	56.58 ± 18.64	55.9 ± 22.27	61.57 ± 19.3	0.183
Anatomical reduction (*n*)	72	77	71	88	0.021
Conversion to open reduction (*n*)	9	10	12	8	0.803
Intraoperative superior surgeon guidance (*n*)	10	7	9	4	0.387
Infection (*n*)	5	4	2	3	0.687
Internal fixation loosening (*n*)	8	13	17	12	0.29
Delayed union (*n*)	7	10	11	7	0.66

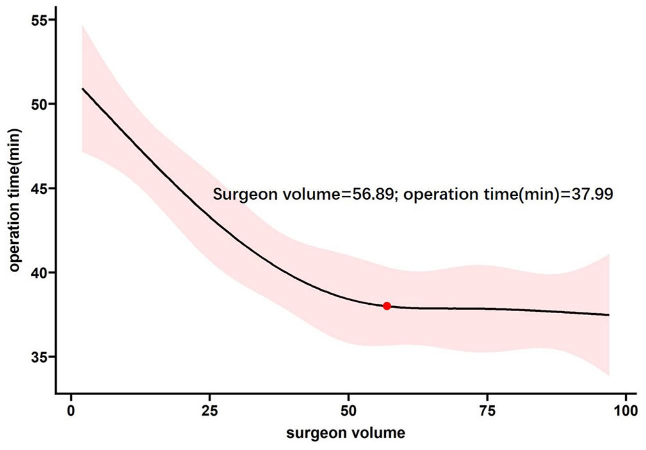

FIGURE 1 | Probability of operation time for supracondylar fractures according to surgeon volume.

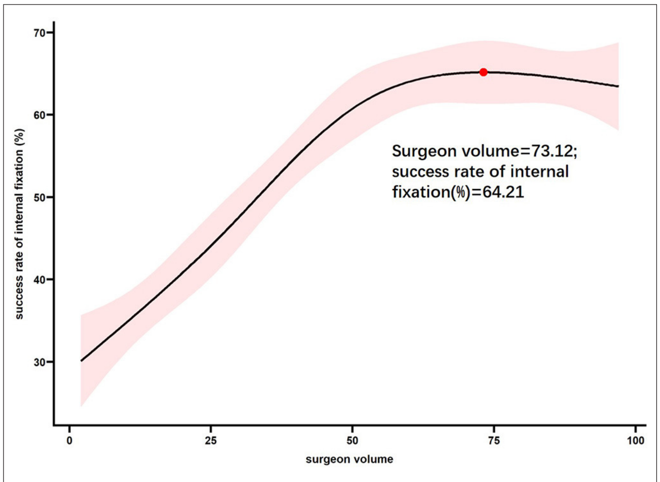

FIGURE 2 | Probability of success rate of internal fixation according to surgeon volume.

post-operative complications; (4) the most frustrating thing is the poor functional recovery of patients after operation; (5) manual traction and closed reduction is considered to be the most critical surgical technique.

DISCUSSION

RCS is a commonly used method to explain the non-linear relationship between variables and outcomes, whether it is the research on disease mechanism (10, 11), treatment methods (12), health management (13) or hospital management (14). To our knowledge, this study is the first application of RCS in surgical learning curve.

Supracondylar fractures of the humerus are suitable candidates for fresh pediatric orthopedists because the treatment of this disease is very mature and it involves a standardized diagnosis and treatment process (6, 15–17). Just as a pilot learns to fly a plane, he must start with the most productive, most commonly used, and safest aircraft. The treatment options for supracondylar fractures of the humerus were described in detail in a 1997 review by Otsuka and Kasser (7). Closed reduction and internal fixation of fractures are suitable for most patients with type II and III fractures, and it is already a very mature treatment plan. For the four surgeons in this study, there were no differences in diagnosis or treatment plan (all patients were treated after discussions with all doctors in the department). The

TABLE 4 | Comparison of characteristics of patient, before, and after accumulation of surgical experience.

Results	Before 65	After 65	*P*-value
Sex (*n*)			
Male	154	88	$P = 0.238$
Female	109	49	
Age	58.19 ± 25.18	61.66 ± 30.54	$P = 0.225$
Side (*n*)			
Left	153	77	$P = 0.749$
Right	110	60	
Type (*n*)			
Type II	124	58	$P = 0.398$
Type III	139	79	
Operation time (min)	35.39 ± 15.05	31.32 ± 10.59	$P = 0.005$
Wire placement success rate (%)	52.74 ± 19.76	67.34 ± 17.87	$P < 0.001$
Anatomical reduction			
Yes	186	122	$P < 0.001$
No	77	15	
Conversion to open reduction (*n*)			$P = 0.008$
Yes	33	6	
No	230	131	
Intraoperative superior surgeon guidance (*n*)			
Yes	28	2	$P < 0.001$
No	235	135	
Infection (*n*)			
Yes	12	2	$P = 0.153$
No	251	135	
Internal fixation loosening (*n*)			
Yes	41	9	$P = 0.01$
No	222	128	
Delayed union (*n*)			
Yes	28	7	$P = 0.065$
No	235	130	
Good functional recovery (*n*)			
Yes	196	128	$P = 0.001$
No	67	9	

center did not allow these four surgeons to perform operations that required neurovascular exploration, which would involve more severe fractures, the intraoperative operation review would be more complex, and the learning curve would be steeper, an unsuitable course for beginners.

Following the outcomes of the cases in the study, we believe that supracondylar fracture of the humerus was an appropriate disease for studying the learning curve, although for these 400 children, our department always provided them with senior orthopedic physicians on duty in case rescue became necessary. However, the research process was safe and no accidents occurred. The 400 patients included in this study had no neurovascular complications or requirement for revision after delayed union. There were patients with loose fixation, but none required re-fixation. There was one case of infection, but it did not require ongoing treatment. Thus, closed reduction and internal fixation with a Kirschner wire for supracondylar fractures of the humerus is a safe, effective, and suitable surgical technique for beginners.

The children in this study were equally distributed to each suregon in age, sex and classification. This suggests that our study population did not suffer from selection bias. Through the RCS fitting curve of the number of surgical cases, operation time, and success rate of wire placement, the operation time and wire placement success rate were moderated in the plateau period after the accumulation of experience with 60–70 procedures. Therefore, we considered the experience accumulation of 65 operations as the inflection point for supracondylar fracture surgeries. We also compared data on surgical technique and post-operative prognosis before and after the 65 operations and found statistically significant differences in operation time, wire placement success rate, and converted to open reduction, indicating that the accumulation of experience in 65 operations was reasonable.

Multiple logistic regression analysis revealed that, although the operation time and wire placement success rate included in the RCS mapping could reflect accumulation of surgeon experience, they did not affect post-operative functional recovery. Similarly, our study found that the guidance of supervising surgeons did not affect post-operative recovery. Before obtaining the help of supervising surgeons, the intraoperative operation of fresh resident surgeons may include multiple steps such as disinfection, traction reduction, and internal fixation with a Kirschner wire. However, the inability to complete the reduction or experience of several failed attempts at implant placement did not affect patient prognosis. This conclusion can also increase fresh surgeon confidence.

Loosening of the internal fixation, a common complication of percutaneous Kirschner wire fixation, had no effect on post-operative functional recovery. The usual incidence was about 5–8%, and our incidence was 12%, which was slightly higher than that reported by other centers (18, 19). This may be related to the novice's proficiency at mastering internal fixation. In addition, we also found that loosening of internal fixation may be more common in fractures without anatomical reduction. Because the position of K-wire shown on the anteroposterior and lateral radiographs of the fracture that did not achieve anatomical reduction may be false, misleading the surgeons to confirm the position, resulting in the loosening. The author suggests that when anatomical reduction cannot be achieved, taking multi angle radiography can help the surgeons better determine the position of K-wire.

The accumulation of surgical experience, intraoperative conversion to open reduction, and post-operative infection were risk factors affecting functional recovery after surgery. Intraoperative conversion to open reduction often indicates that the fracture is difficult to reduce and unstable and that the periosteum is severely torn. Moreover, the broken ends of fractures are usually embedded in soft tissues such as muscles, blood vessels, and nerves. Moreover, in the process of open reduction, the soft tissue near the fracture will be destroyed iatrogenically, further causing post-operative recovery

TABLE 5 | Univariate analysis of functional recovery in eligible patient.

	Recovery		OR	*P*-value
	Good	Not good		
Operation time (min)	32.86 ± 12.61	38.85 ± 17.28		<0.001
Wire placement success rate (%)	59.04 ± 20.51	52.20 ± 18.67		0.005
Age (month)	71.84 ± 28.91	60.03 ± 23.19		0.001
Sex				
Male	193	49	Female/male = 0.812	0.515
Female	131	27	CI: 0.483–1.365	
Side				
Right	134	36	Left/right = 1.276	0.368
Left	190	40	CI: 0.773–2.107	
Type				
Type II	151	31	Type II/Type III = 0.789	0.373
Type III	173	45	CI: 0.475–1.310	
Surgical experience				
<65	197	66	Before 65/after 65 = 4.255	<0.001
>65	127	10	CI: 2.110–8.581	
Anatomical reduction				
Yes	259	49	0/1 = 2.196	0.006
No	65	27	CI: 1.276–3.778	
Conversion to open reduction (*n*)				
Yes	22	17	0/1 = 0.253	<0.001
No	302	59	CI: 0.127–0.505	
Intraoperative superior surgeon guidance (*n*)				
Yes	22	8	0/1 = 0.619	0.330
No	302	68	CI: 0.261–1.450	
Infection (*n*)				
Yes	8	6	0/1 = 0.295	0.032
no	316	70	CI: 0.099–0.878	
Internal fixation loosening (*n*)				
Yes	38	12	0/1 = 0.709	0.338
No	286	64	CI: 0.351–1.432	
Delayed union (*n*)				
Yes	23	12	0/1 = 0.408	0.023
No	301	64	CI: 0.193–0.861	

difficulties. Therefore, the use of open reduction should be reduced as much as possible. At present, supracondylar fractures of the humerus increasingly require open reduction, and many reports have reported reduction methods for refractory supracondylar fractures (20, 21). However, these are advanced techniques for fracture reduction that are difficult for beginner to master. Combined with this study's findings, we found that anatomical reduction was not a risk factor for poor prognosis. Therefore, blindly pursuing anatomical reduction may not be necessary for fresh surgeons.

Infection, a common complication that affects the prognosis of all fractures, is divided into intraoperative and post-operative. Intraoperative infection requires attention to intraoperative aseptic technique. It has been suggested that surgical procedures can be performed after local disinfection without increased infection rates, which may be possible for experienced physicians. However, for new surgeons, we still recommend that they strictly grasp the concept of aseptic technique to avoid intraoperative infection. In this study, the infection eventually progressed to osteomyelitis in two patients who underwent debridement. During the debridement operation, we found that the source of infection was the part where the tail of the wire contacted the skin. This reminds us that guidance is also required for handling K-wire tails. In future teaching, we must remember to emphasize the importance of infection control.

As shown in **Figure 3**, we may clearly see the progress of the four surgeons. The experience accumulation of 65 operations was beyond our expectations. From our data, we can find that earlier than 65 operations, our four fresh surgeons have rarely needed supervisors to guide the operation. Therefore, we believe that the experience accumulation of 65 operations is not the time required to learn one operation, but the time required to achieve the stability of personal surgical techniques. Just like the arthroscopic learning curve in the literature you provided, the experience accumulation of 170 surgeries can reach the level of consultant (5). Our experience in 65 operations may not be learning a technique, but mastering a technique.

In our interview, we found that the accumulation of experience required by fresh surgeons to build their confidence is generally less than the inflection point obtained in this study. But this does not mean that the calculation of our inflection point is wrong. Every operation has key techniques that can be perceived by the trainer and those that cannot be perceived. This key technology that cannot be perceived can be called "hidden points". Fracture reduction, for example, is a key perceptible technique. This has attracted the attention of our center. Teachers will focus on the guidance of key technologies mentioned in the questionnaire.

However, the imperceptible key technology may exist in theory, skills, psychology and so on. So we invited a psychologist to describe the characters of the five respondents only based on their questionnaires, and provided them psychological guidance. We believe that if psychological intervention is regularly added in the process of surgical training, it will be more conducive to the growth of young doctors (**Supplementary Material**).

In the subsequent resident training, we will pay more attention to the number and time of the supervising doctor's guidance when the resident is an assistant. We have added an additional "preparatory period" of 6 months for fresh surgeons. During the preparatory period, our fresh surgeons will follow supervising doctors on duty in the entire ward the next day to complete emergency operations. Intraoperatively, the fresh one learns to

TABLE 6 | Multivariate logistic regression analysis of post-operative functional recovery in eligible patient.

	Good	Not good	*P*-value
Age (month)	71.84 ± 28.91	60.03 ± 23.19	0.448
Operation time (min)	32.86 ± 12.61	38.85 ± 17.28	0.344
Wire placement success rate (%)	59.04 ± 20.51	52.20 ± 18.67	0.831
Surgical experience			
<65	197	66	0.001
>65	127	10	
Anatomical reduction			
Yes	259	49	0.456
No	65	27	
Conversion to open reduction (*n*)			
Yes	22	17	0.025
No	302	59	
Infection (*n*)			
Yes	8	6	0.042
No	316	70	
Delayed union (*n*)			
Yes	23	12	0.343
No	301	64	

TABLE 7 | Interview contents after the training.

Supervisor	Surgeon 4	Surgeon 3	Surgeon 2	Surgeon 1	
3 months 30 operations	15–20 operations	3 months 34 operations	2–3 months 21–30 operations	About 2 months 22 operations	Time for confidence building
Operation completed within 30 min	Continuous successful operation	Successful reduction of irreducible supracondylar fracture	After completing some difficult operations independently	Presence of Supervisor	Conditions for confidence building
The patient was over 10 years old with obvious swelling	Fracture reduction failed without supervisor's help	Open reduction failure • Need intraoperative guidance	• Repeated fracture reduction failure • Iatrogenic neurovascular injury	Iatrogenic neurovascular injury	The most worried events during the operation
Neurologic complications	Various post-operative complications	Infection	• Fracture displacement • Infection	Infection	The most worried events during the follow-up
Transfer to open reduction	Poor functional recovery in case of good reduction, fixation and healing	Infection	Poor functional recovery due to anatomical reduction failure	Poor recovery of elbow function	What is the most frustrating thing in the treatment process
Solo the operations without any assistant	Successful operation of first flexion supracondylar fracture	Hands on guidance of supervisors	Successful operation of first flexion supracondylar fracture	Success of the first open reduction and internal fixation	List an event that makes you grow fastest
Close reduction	Close reduction	Theoretical basis of supracondylar fracture	Percutaneous K-wire fixation	Close reduction	List one of the most critical technologies

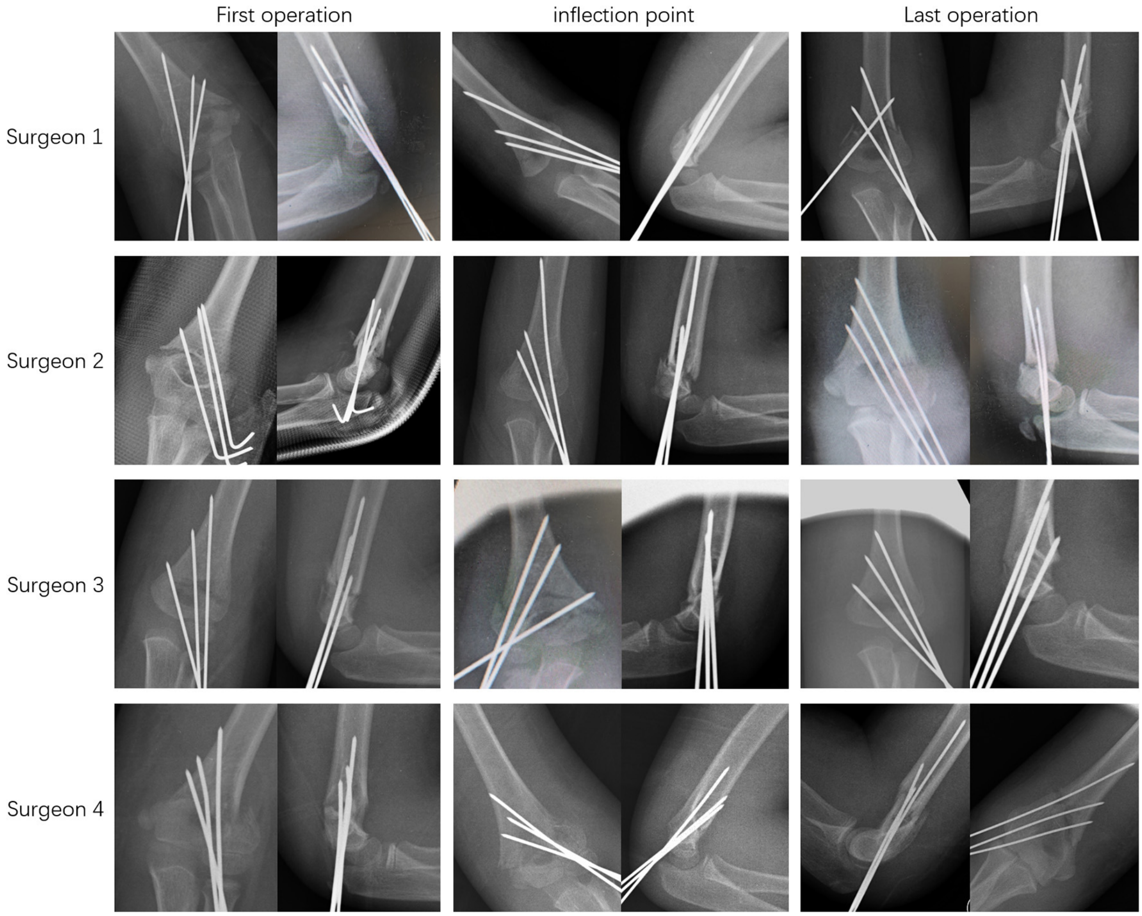

FIGURE 3 | Progress in surgical skills of the four surgeons: Both the fracture reduction and K-wire arrangement of the four surgeons tend to be perfect with the accumulation of surgical experience.

operate in the position of chief surgeon, but the supervising doctor must function as an assistant. According to the total number of operations in our center, two fresh surgeons can each participate in treating ∼60 humerus supracondylar fractures in 4 months of training, and the amount of training in the preparatory period has reached the learning curve required for this study. In a follow-up study, we will compare the performance of new orthopedic surgeons after the adjustment for the training method.

However, there was still a lack of attention to patients in this study. We found that operations with an operation time >90 min occurred before the accumulation of experience with 65 units. Therefore, we added the indicators of active intervention by the superior surgeons in the following medical arrangements: (1) existing combined neurovascular injury and suspected compartment syndrome; (2) irreducible supracondylar fracture of the humerus; and (3) surgery time >60 min. This can avoid excessive damage to the patient without putting pressure on new surgeons, although the time of the operation does not affect the surgical prognosis. In this way, we can shorten the time limit for higher-level surgeons to prepare shifts from 1 year to half a year, which greatly saves medical resources and affords patients better treatment.

CONCLUSION

Although fresh surgeons can establish self-confidence in surgery through 30 operations, we still insist on accumulating experience in 65 operations to master closed reduction and internal fixation of supracondylar fractures. The accumulation of surgical experience, infection and conversion to open reduction are the risk factors affecting the recovery of elbow function. Strengthening the supervisor's guidance on the key techniques and regular psychological guidance to find hidden point may help fresh surgeons master the surgical techniques as soon as possible.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

CQ and YZ: operations, data collection, performed measurements, and manuscript preparation. JM and YM: operations, data collection, and performed measurements. JS: psychological evaluation. HL: study design, statistical analysis, and manuscript preparation. DW: study design and manuscript preparation.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fped.2022.945616/full#supplementary-material

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ORIGINAL RESEARCH
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Treatment of Pediatric Intercondylar Humerus Fracture With External Fixation and Percutaneous Pinning After Closed Reduction

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Background: It is uncommon for young children to suffer an intercondylar fracture of the distal humerus. Although many approaches have been described to manage, there is no specific and accepted treatment protocol for such fracture patterns. This study aimed to identify the incidence of intercondylar fracture of the distal humerus in the pediatric population and report the clinical outcome of external fixation and percutaneous pinning in such injury patterns.

Methods: Pediatric patients under the age of 14 years who had an intercondylar fracture of the distal humerus treated with external fixation and percutaneous pinning between January 2013 and December 2018 at the author's Wuhan Union Hospital were retrospectively evaluated. The detailed baseline information of the patients, operating time, time to union time, and carrying angle difference (CAD) of the injured extremity were collected. During the follow-up visit, clinical results were evaluated using the Mayo Elbow Performance Score (MEPS) and the Flynn criteria.

Results: A total of eight patients (2 women and 6 men) with an average age of 8 years (5–12 years) who had an intercondylar fracture of the distal humerus (1 C2 and 7 C1) were included. All the patients achieved union, and the average MEPS score was 95 points 24 months after the surgery.

Conclusion: The intercondylar fracture of the distal humerus in children is rare, and closed reduction and external fixation is a viable treatment option, especially for the C1 type of fracture pattern.

Keywords: closed reduction, external fixation, intercondylar fracture, distal humerus, children

INTRODUCTION

The intercondylar fracture of the distal humerus in children is considered to be a rare entity (1–10). Maylahn and Fahey reported an overall incidence of 6 (2%) among 300 elbow injuries in children (10). In this injury pattern, the medial and lateral condyles are often separated into independent fragments in a "T" or "Y" shape and lose contact with the humeral shaft causing rotational displacement.

In the past years, open reduction with internal fixation (ORIF) has been considered an effective treatment method for such fractures (8). Commonly reported surgical approaches are olecranon osteotomy, triceps-sliding, and triceps-splitting approaches. The most common short-term and long-term complications following ORIF are transient neuropathy (16.3%) and elbow stiffness (9.6%), respectively (9). With the recent trend toward the utilization of a minimally invasive approach in most surgical procedures, closed reduction with external fixation has been reported to provide satisfactory clinical results in pediatric fractures also (10, 11). So, most pediatric orthopedic surgeons have the discretion of using the closed method as much as possible.

This study aimed to identify the incidence of intercondylar fracture of the distal humerus in the pediatric population and report the clinical outcome of external fixation and percutaneous pinning after closed reduction in such injury patterns.

PATIENTS AND METHODS

Pediatric patients under the age of 14 years who had an intercondylar fracture of the distal humerus treated with external fixation and percutaneous pinning between January 2013 and December 2018 at the author's Wuhan Union Hospital were retrospectively evaluated. All the surgeries were performed by a consultant pediatric orthopedic surgeon or under his direct supervision.

The baseline information, including age, gender, and AO classification of fracture, was recorded preoperatively (**Table 1**). All fractures were diagnosed as per definition by the AO classification system relying on a radiograph or a CT scan (**Figure 1**). The postoperative data were collected during the follow-up visit. The clinical results were evaluated using the criteria of Mayo Elbow Performance Score (MEPS) (12) and Flynn degree (13). The authors assessing these patients' clinical outcomes did not participate in the treatment. The Ethics Committee of the authors' institute approved the study. Written informed consent was obtained from the legal guardians.

Surgical Technique

All the procedures were performed under general anesthesia. Initially, the first Schanz pin (2.7 or 3.0 mm) was inserted into the lateral condyle fragment distal to the physis under fluoroscopic guidance. The pin was placed parallel to the elbow joint and perpendicular to the longitudinal axis of the bone in order to avoid injuring the physis. The second Schanz pin was then inserted 2 cm proximal to the fracture line laterally and parallel to the first pin. This pin was tightly secured with the bicortical purchase, but great care was taken to avoid radial nerve injury. The lateral fragment was reduced with the proximal fragment by closed manipulation. After an acceptable reduction was achieved, the fracture fragments were held tightly together with clamps and rods. An anti-rotation K-wire (1.5–2 mm) was inserted in a retrograde fashion from the distal end of the lateral condyle and passed through the fracture line.

Another K-wire (1.5–2 mm) was inserted onto the distal medial condyle of the humerus, which acts as the joystick for the manipulation. After an acceptable alignment and reduction were achieved, the third K-wire was inserted from the medial condyle to the proximal fragment in a crisscross fashion. Then, the joystick pin was inserted further across the fracture line. The stability of the fixation and elbow movements were assessed in the anteroposterior (AP) and lateral views *via* fluoroscopy with gentle stress in maximum extension and flexion. The operated arm was immobilized with a posterior slab in a supine position with the elbow at 90° flexion (Operative stages are shown in **Figure 2**).

Postoperative Care and Follow-Up

After the surgery, patients were discharged from the hospital once their condition allowed. The caregivers were taught to perform daily pin care. The plaster was removed after 3 weeks post-operation, and then, the child was allowed to start free elbow mobilization, but weight-bearing was avoided. AP and lateral radiographs of the operated elbow were taken at 3, 6, and 9–12 weeks and 6, 12, and 24 months. All the K-wire and external fixators were removed at 6 weeks in the outpatient visit. The weight bearing was allowed only after 12 weeks. The radiological union was considered once 3 out of 4 cortices were united (14), whereas radiological delayed union was considered if the visible gap were evident in 2 or more cortices at 12 weeks (14). The final clinical and radiological evaluations, including MEPS, Flynn criteria, CAD difference, and other complications, were performed at the last follow-up.

RESULTS

A total of 8 patients (2 women and 6 men) with an average age of 8 years (range, 5–12 years) were included in the study. According to the AO classification, 1 patient had a C2 type

TABLE 1 | Preoperative demographics of the patients.

No.	Age (years)	Gender	AO classification
1	7	W	C1
2	6	M	C1
3	10	M	C1
4	5	M	C1
5	7	W	C1
6	8	M	C1
7	9	M	C2
8	12	M	C1

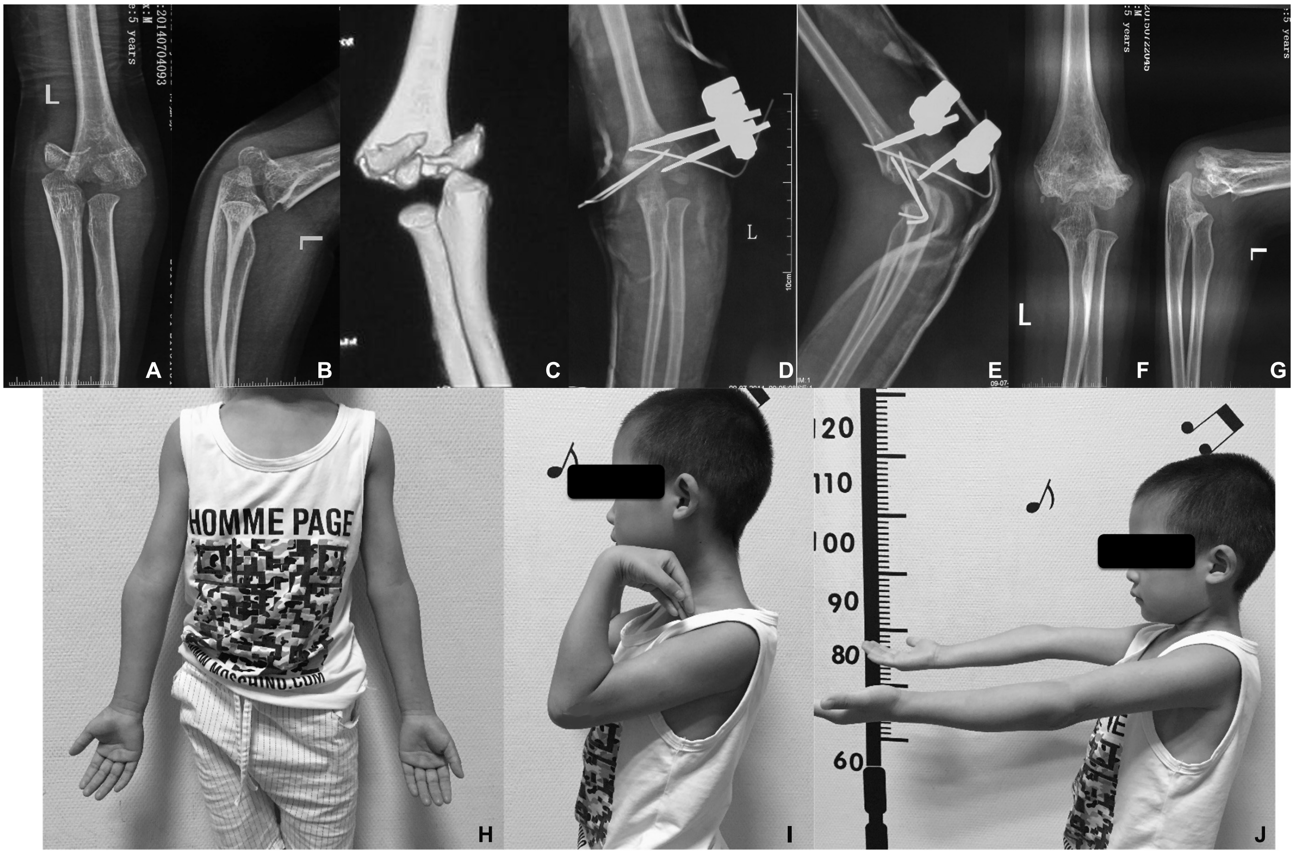

FIGURE 1 | (A) Anteroposterior and **(B)** lateral radiographs of a 6-year-old boy with an intercondylar fracture of the distal humerus; **(C)** CT scan showing C1 type of AO classification; **(D)** anteroposterior and **(E)** lateral radiographs post-operation; **(F)** anteroposterior and **(G)** lateral radiographs at 12 months post-operation; and the follow-up in 24 months after surgery show excellent cosmetic results **(H)** and the functional appearance **(I,J)**.

fracture and the rest of the other patients had C1 type fractures. Demographic details of the patients are shown in **Table 1**. The average duration of the surgery was 53.5 min (range, 46–60 min). All the fractures were clinically and radiologically united before 12 weeks (**Table 2**). At the last follow-up, all the patients showed satisfactory functional results on the MEPS score with an average of 95 points. All the patients' carrying angle difference of the affected elbow was within 4 degrees, and they all showed good to excellent elbow function as per the Flynn scale (**Table 2**). Only two patients with superficial pin-site infection were identified during the follow-up visit, which resolved after 2–3 days of oral antibiotics. There were no non-union, neurovascular injury, myositis ossificans, or other surgery-related complications requiring further revision.

DISCUSSION

The most important finding of this study was that satisfactory fracture stability with acceptable postoperative outcomes could be achieved by external fixation and percutaneous pinning following a closed reduction in pediatric intercondylar humerus fracture.

There is no available consensus on the treatment of intercondylar fracture of the distal humerus in the pediatric population (1–11). Some surgeons insist that the open reduction and internal fixation is the ideal treatment for a pediatric T-condylar fracture of the humerus, which allows early elbow mobilization preventing stiffness (8, 10, 15). However, it cannot be denied that open reduction will bring more damage to the soft tissues and increase the risk of elbow stiffness (16–19). On the other hand, some authors advocate that the pediatric intercondylar fractures of the distal humerus can be treated with closed reductions and percutaneous pinning to obtain a satisfactory clinical outcome (16). Opinions vary as per the surgeon's experience, but most surgeons accept that the goal of the treatment is to reconstruct the normal relationship of the joints and obtain good alignment.

To our knowledge, this is the first case series of pediatric humerus intercondylar fractures treated with external fixation and percutaneous pinning. Previously only the case report has been documented (20). The satisfactory result in our study may be attributed to most of the fractures (87.5%) in our series being the AO C 1 type. This type of fracture is a "T" shaped fracture with good bone quality where closed reduction can be performed successfully. As Ducic summarized, T-condylar fractures of the

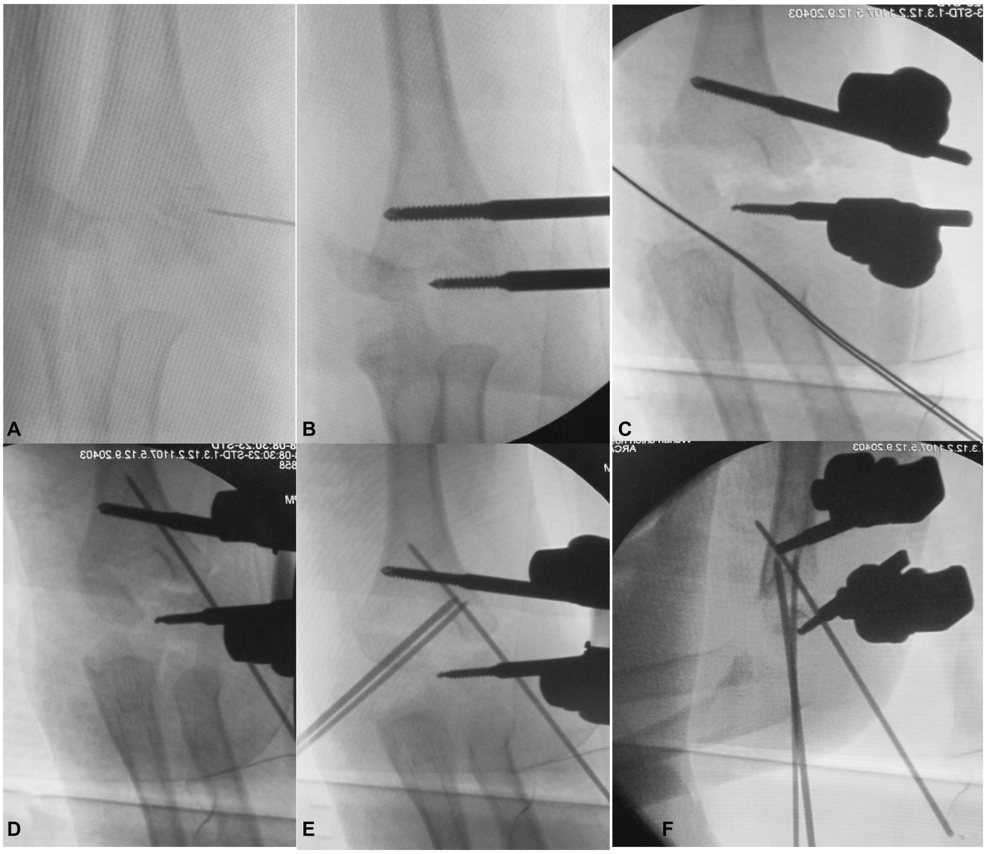

FIGURE 2 | The C-arm x-ray during operation showed: **(A)** the distal lateral condyle fragment located with a syringe needle; **(B)** placement of radial unilateral external fixation; **(C)** reset the lateral side of the distal humerus by closed reduction and tightened external fixation; **(D)** placement of the radial side anti-rotation K-wire to stable the lateral fragment; **(E)** placement of the ulnar K-wire to stable the medial fragment; **(F)** lateral view of the elbow after fixation.

humerus are rare in children (21). A CT scan plays a significant role in the surgical plan in such a fracture pattern.

ORIF is an established surgical treatment method in adult and skeletally immature patients with intercondylar fractures of the humerus (21–24). However, surgical treatment for such fracture patterns in pediatric patients is controversial and has not been described in the literature. We adopted external fixation and percutaneous pinning, which led to a shorter duration of surgery and fracture union. Regardless of whether the patient population was subjected to olecranon osteotomy or triceps sparing surgery, the average duration of surgery was more than 77 min (21, 22). It is also worth emphasizing that there was only a negligible amount of bleeding in this series due to its minimally invasive nature. In the previous literature, the average time of fracture union following an ORIF was more than 11.5 weeks in previously published studies (21, 22), which is longer than the 10.6 weeks in this study. Similarly, 7 out of 8 patients had an MEPS score of the operated elbow of 95 points and above, and only 1 patient had an MEPS score of 90 points at the final follow-up, which is higher than the average MEPS score in other studies (21–23, 25). Compared to open reduction, closed reduction causes minimal damage to the skin and soft tissue, so the risk of postoperative joint stiffness is minimal (19). Percutaneous pinning after closed reduction is less invasive and does not increase the risk of complications. This technique may be an excellent alternative to open reduction for intercondylar fracture of the humerus (26). Due to the fact that there is minimal soft tissue and periosteal striping during surgery, the chance of bone healing is faster. The external fixator technology was initially proposed by Slongo (27), which has a fixation strength better than the simple K-wires providing sufficient

TABLE 2 | Perioperative and follow-up data.

No.	OD (min)	FLT (month)	CAD	MEPS	UT (week)	Flynn
1	56	36	2	95	12	Excellent
2	60	37	3	95	10	Excellent
3	52	24	3	90	12	Good
4	55	48	2	95	9	Excellent
5	57	45	0	95	10	Good
6	49	27	4	95	10	Good
7	52	39	3	100	10	Excellent
8	46	42	3	95	12	Good

OD, operation duration (min); FLT, follow-up time (month); CAD, carrying angle difference; MEPS, Mayo Elbow Performance Score; UT, union time.

stability to ensure early postoperative functional rehabilitation. Beck et al. (28) reported that early elbow Range of motion (ROM) following T-condylar fracture management produces a better final ROM with high patient satisfaction. Our technique provides better fracture stability allowing early ROM, resulting in better patient satisfaction. Another advantage of this technique is that the removal of the external fixation system can be completed in the outpatient setting and no secondary operation for implant removal is required (29).

The key points to remember for closed reduction and external fixation in patients with pediatric intercondylar fracture of the distal humerus are as follows: 1. Choosing an appropriate size Schanz pin: The surgeon should measure the size of the lateral condyle fragment in orthogonal x-ray views and then an appropriate sized (2.7 or 3.0 mm) Schanz pin should be inserted from the lateral condyle fragment parallel to the joint line and perpendicular to the longitudinal axis of the humerus under fluoroscopy guidance. 2. Avoiding nerve injury: there is always a chance of injuring the ulnar nerve during this procedure. The elbow should be placed in extension while inserting the K-wire in the medial condyle in order to avoid iatrogenic injury to the ulnar nerve.

Although the fracture pattern is rare in the pediatric population, this study still adopts the limitations of retrospective case series, such as a small sample size with no control group.

CONCLUSION

The intercondylar fracture of the distal humerus in children is rare, and closed reduction and external fixation is a viable treatment option, especially for the C1 type of fracture pattern.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Tongji Medical College, Huazhong University of Science and Technology (IORG No: IORG0003571). Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

RZ, ZY, XL, and GJ involved in data collection and follow-up assessments. XT, SR, and HZ were responsible for the literature search and study design and finalized the manuscript. WS and RZ drafted the manuscript. All authors contributed to the article and approved the submitted version.

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Rotation of both X- and Y-axes is a predictive confounder of ulnar nerve injury and open reduction in pediatric lateral flexion supracondylar humeral fractures: A retrospective cohort study

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Background: Rotation of the distal fragment often occurs in flexion-type supracondylar humerus fractures (SCHFs), potentially leading to ulnar nerve injury (UNI) and open reduction. We analyzed the correlation between the rotations and UNI or open reduction and then assessed the risk factors associated with these rotations.

Methods: Data of Wilkins type III lateral flexion SCHFs were collected over a 10-year time period (1 January 2012 to 31 December 2021) in Children's Hospital of Fudan University Anhui Hospital. We defined the rotation of the distal fragment on the coordinate axis as two types, IIIA (*X*-axis rotation) and IIIB (the rotation of both *X*- and *Y*-axes) on X-ray radiography. Demographic data, the incidence of the two-type rotation, odds ratios (ORs) of UNI and open reduction, and risk factors of the rotation of both *X*- and *Y*-axes were analyzed.

Results: Totally, 152 patients were found (50 with IIIA vs. 102 IIIB). The UNI rate was 13%, and the open reduction rate was 22%. The UNI rate of the IIIB was five-fold higher than that of the IIIA [OR, 5.143; 95% confidence interval (CI), 1.414–23.125; $p = 0.019$], and the open reduction rate of the IIIB was nearly five-fold higher than that of the IIIA (OR, 4.729, 95%CI, 1.584–14.495; $p = 0.003$). In these two types, patients with UNI had a higher risk of open reduction than those without UNI (OR, 9.816; 95%CI, 3.503–27.508; $p = 0.001$). In the multiple regression analysis, a high level of fracture was identified as a risk factor for the rotation of both *X*- and *Y*-axes.

Conclusion: Type IIIB lateral flexion-type SCHFs have higher rates of UNI and open reduction, and a high level of fracture is a risk factor associated with this type.

KEYWORDS

supracondylar fracture of the humerus, SCHFs, lateral flexion, ulnar nerve injury, open reduction, fracture lever

Introduction

Supracondylar fracture of the humerus (SCHFs) is one of the most common elbow fractures in children, and flexion-type SCHFs accounts for 2%—4% of all SCHFs (1–3). Flexion-type SCHFs are usually laterally deviated, which are divided into three subtypes by Wilkins in 1990, according to the mirror image relationship with the classical extension-type proposed by Gartland (4, 5). Type I is minimally displaced with both anterior and posterior cortex integrity; type II is a simple anterior displacement with anterior cortex integrity; and type III is displaced without cortex integrity (5). The classical treatment algorithm, which was recommended in the flexion type, was similar to the extension type from cast immobilization to open reduction and pinning (6, 7).

Flexion-type SCHFs are often associated with higher risks of ulnar nerve injury (UNI) than extension-type (8–11). For a higher incidence of UNI, the two major reasons are: (1) the direction of anterior lateral translocation of the distal fragment leading to excessive tension of ulnar nerves in the posterior medial side and (2) the fractured fragment posssibly being shaped as a medial spike, which can compress or puncture ulnar nerves. For a higher incidence of open reduction, the fragment spike can puncture muscles and the ulnar nerve can be an entrapment, which does not facilitate closed reduction. In addition, several surgical techniques have been used, but open reduction is still unavoidable in some severe rotational cases (12–14). According to the anatomical rotation characteristics of type III flexion SCHFs, the distal fragment would rotate on the X-axis or both *X*- and *Y*-axes. However, the correlation between the two rotations and UNI or open reduction remains unclear.

Therefore, we hypothesized the two rotations of the distal fragment as two new subtypes of type III flexion SCHF and analyzed the correlation between the rotations and UNI or open reduction and then assessed the risk factors associated with the rotations of both *X*- and *Y*-axes.

Materials and methods

Subjects

This study was approved by the institutional review board of Children's Hospital of Fudan University, Anhui, in accordance with the Declaration of Helsinki, and the consent of patients or their guardians was obtained.

In total, 4,831 patients with SCHFs in our hospital between January 2012 and December 2021 were screened. According to inclusion and exclusion criteria, 152 patients were included. Gender, domination hand, body mass index (BMI), age, and the level of fracture were analyzed. The inclusion criteria were flexion-type III SCHFs; available preoperative initial anteroposterior (AP) and lateral X-ray radiographs; and medical records including height, weight, medical history, and operation documents. The exclusion criteria were SCHFs with an ulnar deviation; manipulation before original X-ray radiography; patients' or their guardians' refusal; and open fractures.

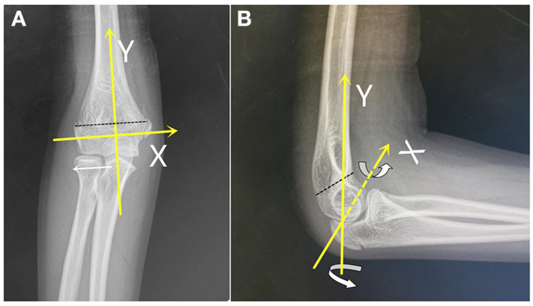

FIGURE 1
Translocation and rotation schema on the coordinate axis (yellow line) on normal anteroposterior (AP) and lateral radiographs. The *Y*-axis is parallel to the humeral shaft, the *X*-axis is perpendicular to the *Y*-axis crossing both supracondylar, and the black dotted line indicates the fracture line. In **(A)**, the white arrow indicates lateral translocation; in **(B)**, the rotate arrows indicate the rotation along the *X*- or *Y*-axes of the distal fragment.

Classification and analysis of x-ray radiography

The definition of the coordinate axis

In this study, the coordinate axis was drawn on AP and lateral films of SCHFs, and the center of the normal olecranon fossa location was defined as the coordinate center. The longitudinal axis of the humerus was defined as the *Y*-axis, and the line perpendicular to the *Y*-axis through the medial and lateral epicondylar was defined as the *X*-axis. The distal fracture fragment rotations were determined along the *X*- and *Y*-axes on the coordinate axis with reference to the proximal humeral shaft (Figure 1). Patients were divided into two types by the spatial rotation characteristics of the distal fracture fragment on preoperative initial AP and lateral X-ray images.

The fracture levels were classified as high or low according to Kang's description of the fracture line above or below the isthmus of the distal humerus (15), respectively.

The classification of two subtypes

The final results of the two types were identified by two senior orthopedic specialists.

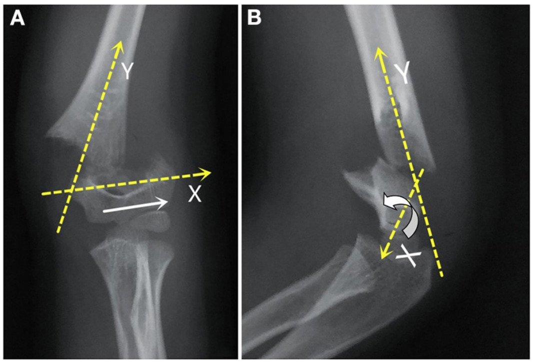

FIGURE 2
In the AP view **(A)**, the distal fragment (white arrow) was anterior-lateral translocation. In the lateral view **(B)**, the distal fragment was the rotation on the *X*-axis without an obvious *Y*-axis rotation.

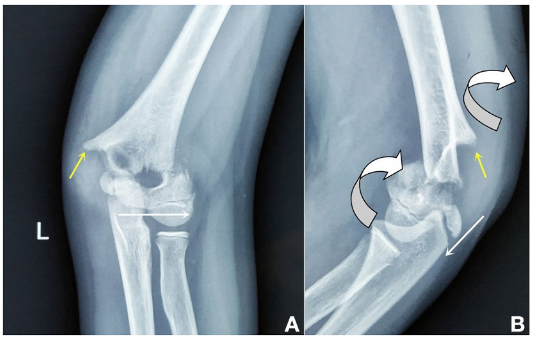

FIGURE 3
In the AP view **(A)**, the distal fragment (white arrow) was anterior-lateral translocation. In the lateral view **(B)**, the distal fragment was obviously rotation both on *X*- and *Y*-axes (rotation arrow), and the proximal fragment spike was obvious (yellow arrow).

- IIIA: The distal fracture fragment was with only a rotation on the *X*-axis, and there was no proximal metaphyseal medial spike on a lateral film (AP tilt, Figure 2).
- IIIB: The distal fracture fragment was with a rotation on both *X*- and *Y*-axes, and there was usually a proximal metaphyseal medial spike on a lateral film (Figure 3).

Statistical analysis

Statistical analysis was conducted using SPSS version 24.0 (IBM, Armonk, New York, USA). Statistical methods included standard descriptive summaries of demographic data; these were analyzed using the Chi-squared test, thew Fisher's exact test, or the two-sample *t*-test. Regression analysis was used to identify the risk factors of type IIIB.

Results

Demographic data

The average age was 8.78 ± 2.51 (2–15) years in 152 children with lateral flexion SCHFs. Of these, 50 were type IIIA and 102 were type IIIB. There was no significant difference between the two types in gender, domination hand, and BMI. The age and fracture level had a significant difference between the two groups ($p = 0.015$; $p = 0.001$; see Table 1).

UNI rate

Among the 21 patients with nerve injury, 20 (95%) were UNI and one had a radial nerve injury. Among the 20 cases, two (10%) were classified as type IIIA and 18 (90%) were type IIIB. The odds ratio (OR) of UNI showed that the type IIIB group was five-fold higher than the IIIA group [OR, 5.143; 95% confidence interval (CI), 1.414–23.125; $p = 0.019$]. The results are shown in Table 2.

Open reduction rate

Open reduction was performed in 34 patients (22%), including four cases of type IIIA and 30 cases of type IIIB (30/34). The OR of open reduction showed that the type IIIB group was nearly five-fold higher than the type IIIA group (OR, 4.729; 95%CI, 1.584–14.495; $p = 0.003$; Table 2). There were 13 cases (IIIA, 1; IIIB, 12) with UNI in the 34 patients receiving open reduction, and seven cases with UNI in the other 118 patients treated by closed reduction. In all patients, patients with UNI had a significantly higher risk of open reduction than those without UNI (OR, 9.816; 95%CI, 3.503–27.508; $p = 0.001$). Type IIIB patients with UNI had a higher risk of open reduction than type IIIA patients with UNI (OR, 6.000; 95%CI, 0.509–70.668; $p = 0.264$).

Risk factors associated with IIIB rotation

Totally, there were 114 cases of high-level and 38 cases of low-level SCHFs. A high level of incidence was 58% in IIIA and 83% in IIIB. Age and the level of fracture were significantly different in the two groups (IIIA and IIIB). According to the results of multiple logistic regression analysis, a high level of fracture was identified as an independent risk factor of type IIIB rotation (OR, 3.210; 95% CI, 1.470–7.011; $p = 0.003$; Table 3).

TABLE 1 Injury characteristics of 152 skeletally immature patients with lateral flexion supracondylar humerus fractures (SCHF).

Characteristics	IIIA (50 cases)	IIIB (102 cases)	t or χ^2	p-Value
Male gender, n (%)	29 (58)	56 (55)	0.031	0.718‡
Domination hand, n (%)	33 (66)	58 (57)	1.166	0.280‡
Mean BMI (kg/m^2)	20.87 ± 5.19	21.83 ± 5.12	1.093	0.276†
Mean age at surgery (years)	8.08 ± 2.30	9.13 ± 2.54	2.462	0.015†
Fracture level (high:low)	29:21	85:17	11.484	<0.001‡
Ulna nerve injury, n (%)	2 (4)	18 (18)	5.469	0.019‡
Open reduction, n (%)	4 (8)	30 (29)	8.858	0.001‡

† Student t-test.
‡ χ^2 test.

TABLE 2 Univariate odds of SCHF in different rotation fracture types.

Type	Ulnar nerve injury			Open reduction	
	Referent	OR (CI 95%)	p-Value	OR (CI 95%)	p-Value
IIIB	IIIA	5.143 (1.414–23.125)	0.019	4.792 (1.584–14.495)	0.003

TABLE 3 The results of multiple logistic regression analysis of risk factors associated with type IIIB rotation.

Variables	IIIB rotation		
	OR	CI 95%	p-Value
Fracture level	3.210	1.470–7.011	0.003
Age	1.155	0.994–1.343	0.060

Discussion

Type III flexion SCHF is an important fracture in pediatric orthopedic clinical practice, and most of them are laterally deviated (16). It has attracted special attention from surgeons due to the high rates of UNI and open reduction, especially for those with a medial spike in the proximal fragment (8–11, 16, 17). We classified the rotation of the X-axis or both X- and Y-axes of the distal fracture fragment into two subtypes of type III flexion SCHF, and we proposed that these two subtypes could be helpful for an orthopedic to evaluate UNI and make a better decision between close and open reduction in daily clinical practice.

Ulnar nerve injury is caused by several reasons: the direction of anterior lateral translocation of the distal fragment leading to excessive tension of the ulnar nerve on the posterior medial side; and the proximal medial metaphyseal spike, which posteriorly compresses or punctures the ulnar nerve and in some cases can be even entrapped between the two fragments in flexion SCHFs (11, 16, 17). An early and precise evaluation is required for UNI; traditionally, the clipping test and the Forment's sign are clinically used. However, these two traditional methods could be affected by tissue swelling, pain, and muscle impact. Therefore, our subtype could be helpful in these situations. In our study, we also found that the total UNI rate in type III flexion SCHFs was 13%, and the UNI rate in the type IIIB group (18%) was increased significantly than that in type IIIA (4%). Due to the lack of patients with type III flexion SCHF, few previous studies focused on the UNI rate in this type. Usually, UNI rates in the total flexion SCHF have been reported with a wide range of 10.5%—26% (8, 9, 11, 18, 19). In a meta-analysis study, the UNI rate was calculated as 14% in flexion SCHFs, and type II and type III patients were not separated for an analysis (20). To our knowledge, our study presented an innovative and detailed understanding of type III flexion SCHFs. According to the results of our subtype UNI rate, we suggested that more attention should be paid to patients with subtype IIIB fracture for UNI. Furthermore, due to the instability of fractured fragments in both X- and Y-axes, closed reduction overtime should be avoided in this subtype because it could cause iatrogenic UNI (21).

Open reduction is an alternative treatment in SCHFs in case of failure of closed reduction. According to the study by Flynn et al. (9), the flexion type had a 15-fold higher risk of open reduction than the extension type; furthermore, we found in type III that type IIIB had a higher incidence of open reduction. Type IIIB flexion SCHF normally comes with a rotated proximal fragment spike, which detaches from the periosteum sheath and pierces the triceps muscle. Although some techniques are used in closed reduction, such as "joystick" and "push–pull," the proximal spike may still remain irreducible or even have unsatisfactory alignment after reduction, which could cause restricted elbow function in older children with limited distal humerus remodeling and cubitus varus (22, 23). Based on our open reduction rates in the two subtypes, we thought that subtype IIIB had more unstable fractured fragments, which were more difficult to reduce by closed reduction. This is because, in type IIIB, most of the proximal fragment spikes rotated toward the triceps muscle and some compressed the ulnar nerve, and this led to swelling of the nerve epithelium, tortuous bleeding, and even breaking off of a few nerve fiber bundles in our study. Furthermore, we found four cases (4/34) with ulnar nerve entrapment in a fracture gap that impedes reduction, which was similar to Steinman's finding (11), and all of the four cases were in the type IIIB group. Therefore, our findings could provide more confidence for orthopedic surgeons in decision-making of reduction of type IIIB flexion SCHFs.

Additionally, some studies showed that UNI could increase the incidence of open reduction (8–11, 18). A 6.7-fold higher risk of open reduction was found in patients with UNI than in those without UNI (9). These are similar to our finding, which found an almost 10-fold higher risk of open reduction in the UNI group than in the non-UNI group, and most of the patients with UNI (12/13) were in the type IIIB group.

Furthermore, we found that a high level of fracture was the only risk factor for type IIIB, which may be related to anatomical characteristics of the distal humerus in the transverse fracture. A high level of fracture usually has a smaller fracture "contact area" than the low type, which decreases the force of sliding friction and is more unstable (24, 25). Therefore, type III flexion SCHFs with a high level of fracture are more likely to combine with the rotation of both X- and Y-axes.

This study has some limitations. First, this is a retrospective single-center study and lacks long-term follow-up of UNI outcomes and elbow function. Second, patients were difficult to homogenize on a nonstandard X-ray. Finally, the sample size of patients with UNI or open reduction is not large enough to analyze the risk factors for UNI or open reduction.

In conclusion, lateral flexion-type type IIIB SCHFs have higher rates of UNI and open reduction, and a high level of fracture is a risk factor associated with this type. Our findings could support further studies on a deeper understanding of type III flexion SCHF in UNI or open reduction and on analyzing the risk factors of them in both subtypes. Thus, prospective multi-center studies are needed in the future.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Children's Hospital of Fudan University Anhui Hospital. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

JSu wrote the article. JSh and LM collected data and analyzed statistics. TL and EW reviewed the article. GJ designed and reviewed the article. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Small incision reduction and external fixation for the treatment of delayed over fourteen days supracondylar humeral fractures in children

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Background: Supracondylar humeral fractures (SHF) are the most common type of fracture occurring at the distal humerus in children. In patients with delayed presentation of SHF, closed reduction is challenging to achieve with traditional reduction maneuvers. This study aimed to report the clinical results of pediatric SHF delayed over 14 days treated by closed reduction with a minimally invasive technique and external fixation and evaluate the efficacy of this technique.

Methods: Between October 2010 and September 2018, children with delayed presentation of SHF over 14 days were retrospectively included in this study. The patients received closed reduction with a minimally invasive technique followed by external fixation. The demographics and radiographic data were collected. The Mayo Elbow Performance Score (MEPS) and the Flynn criteria were used to evaluate the clinical outcomes of treatments.

Results: A total of 11 children (aged 4–13 years) with delayed presentation (range, 14–22 days) were recruited. They received surgery using closed reduction with a minimally invasive technique followed by external fixation. None of the surgery was done with the open method. After surgery, the patients' carrying angle returned to normal. The radiological union was evident in 8 to 12 weeks in all fractures without complications. Every patient had a good to excellent score on the MEPS and the Flynn criteria.

Conclusions: The results of this series indicated a satisfactory outcome in children with delayed more than 14 days of supracondylar humeral fractures. The closed reduction with a minimally invasive technique followed by external fixation is an alternative treatment for such injury.

KEYWORDS

close reduction, minimally invasive technique, external fixation, delayed presentation, supracondylar humeral fracture, children

Introduction

Supracondylar humeral fracture (SHF) is an extra-articular fracture that passes through the olecranon fossa, encompasses the distal humeral condyles, and is one of the most common elbow injuries in children (1). Delayed presentation of SHF is defined if the patient presents to the hospital after 2 days of injury (2, 3). Patients with delayed presentation (>1 week) may present with callus formation, union, nonunion and/or malunion with varying degrees of elbow deformity and dysfunction (4).

Treatment of delayed SHF aims to attain anatomic reduction, stable fixation, comprehensive function and good cosmetic results. However, there is no consensus regarding the appropriate treatment method for delayed SHF among orthopedic surgeons (5). Treatment includes closed reduction or open reduction with fixation. Closed reduction and percutaneous fixation has become the preferred treatment option for pediatric SHF but usually fails in patients presenting more than 7 days after injury (4). On the other hand, open reduction and internal fixation may cause iatrogenic neurovascular injury, wound infection, elbow stiffness and other complications (6).

This study aimed to report the clinical results of pediatric SHF delayed over 14 days treated by closed reduction with a minimally invasive technique and external fixation and evaluate the efficacy of this technique.

Patients and methods

Children diagnosed with delayed SHF between October 2010 and September 2018 at the authors' hospital were retrospectively reviewed. The inclusion criteria were: (1) patients with delayed SHF more than 14 days after injury, (2) visible callus formation on the radiographs with failed manual reduction, (3) carrying angle of more than −15°, (4) availability of the complete clinical and radiological data, and (5) minimum follow up of 24 months. The exclusion criteria were: (1) patients with metabolic bone disease and (2) concomitant neurovascular injury needing exploratory surgery. Demographic data included age, gender, Gartland classification and time between injury and surgical intervention. All the patients' parents or legal guardians were fully informed of the surgical procedure and gave consent to be included in the study. It was informed that closed reduction might not be achieved and minimally invasive incision might be necessary. All patients were operated on by the same surgical team as per the standard protocol. This study was approved by the ethical review board of the corresponding author's institution.

Surgical technique

All the procedure was performed under general anesthesia. The patient was positioned supine with the injured extremity close to the edge of the operating table. The fracture line with the callus was located under fluoroscopy (**Figure 1A**). A 5 mm skin incision was made from the medial aspect of the humerus, closed to the fracture line with callus and guided by the intraoperative fluoroscopy. A hemostat was inserted, and soft tissue was mobilized away from the callus. Lateral, anterior, and posterior calluses were removed from the humerus horizontally along the fracture line with the

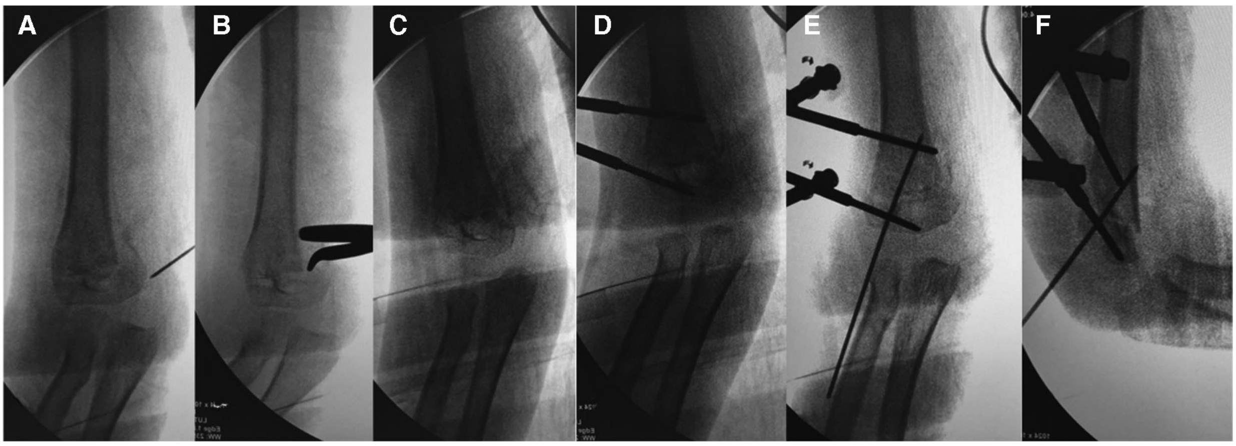

FIGURE 1
C-arm image during the surgical procedure of a 5-year-old boy with delayed supracondylar fracture of right humerus: (A) the fracture line with callus was located with a needle; (B) lateral, anterior, and posterior calluses were removed from the humerus horizontally along the fracture line with the hemostat; (C) manual reduction of fractures was performed to correct the abnormal carrying angle; (D) external fixation with two schanz pins was used; (E) placement of K-wire was served as a de-rotational wire to stabilize the fracture; (F) lateral view of the elbow after fixation.

hemostat in order to loosen the fracture (Figure 1B). Manual reduction of fractures was performed in order to correct the abnormal carrying angle, rotation and shortening after the fracture was loosened (Figure 1C).

External fixation was used for patients as per the technique reported by Slongo T et al. (7) The first Schanz pin (3.0–4.0 mm) was placed perpendicular to the longitudinal axis of the proximal humerus and buried in the medial cortex, keeping 2 cm above the fracture line. The second pin was placed perpendicular to the longitudinal axis of the distal fragment and parallel to the elbow joint, keeping 1–2 cm below the fracture line (Figure 1D). It was regarded as an adequate and stable reduction without malrotation following manual reduction when these 2 pins became parallel. A 1.5–2.0 mm K-wire was passed retrograde from the lateral epicondyle crossing the fracture line as a de-rotational wire (Figure 1E,F). The stability of the fixation was then tested in maximum flexion and extension, and a check x-ray was obtained. The surgical procedure of a typical case is presented in Figure 1.

Postoperative care and follow-up

All patients were discharged 2–3 days after surgery without a cast. Free range of motion with non-weight-bearing was allowed 48 h post-operation. The external fixation was removed 6 weeks postoperatively. Every patient returned for clinical and radiographic evaluations at 6 weeks, 12 weeks, 6 months, 12 months and 24 months. The elbow joint function was evaluated with the Mayo Elbow Performance Score (MEPS) and the criteria of Flynn at the last follow-up (8, 9). The typical case in fellow up was presented in Figure 2.

Results

A total of 11 patients (8 boys and 3 girls) with an average age of 7 years (range, 4–13 years) were included in this study. Closed reduction with a minimally invasive technique

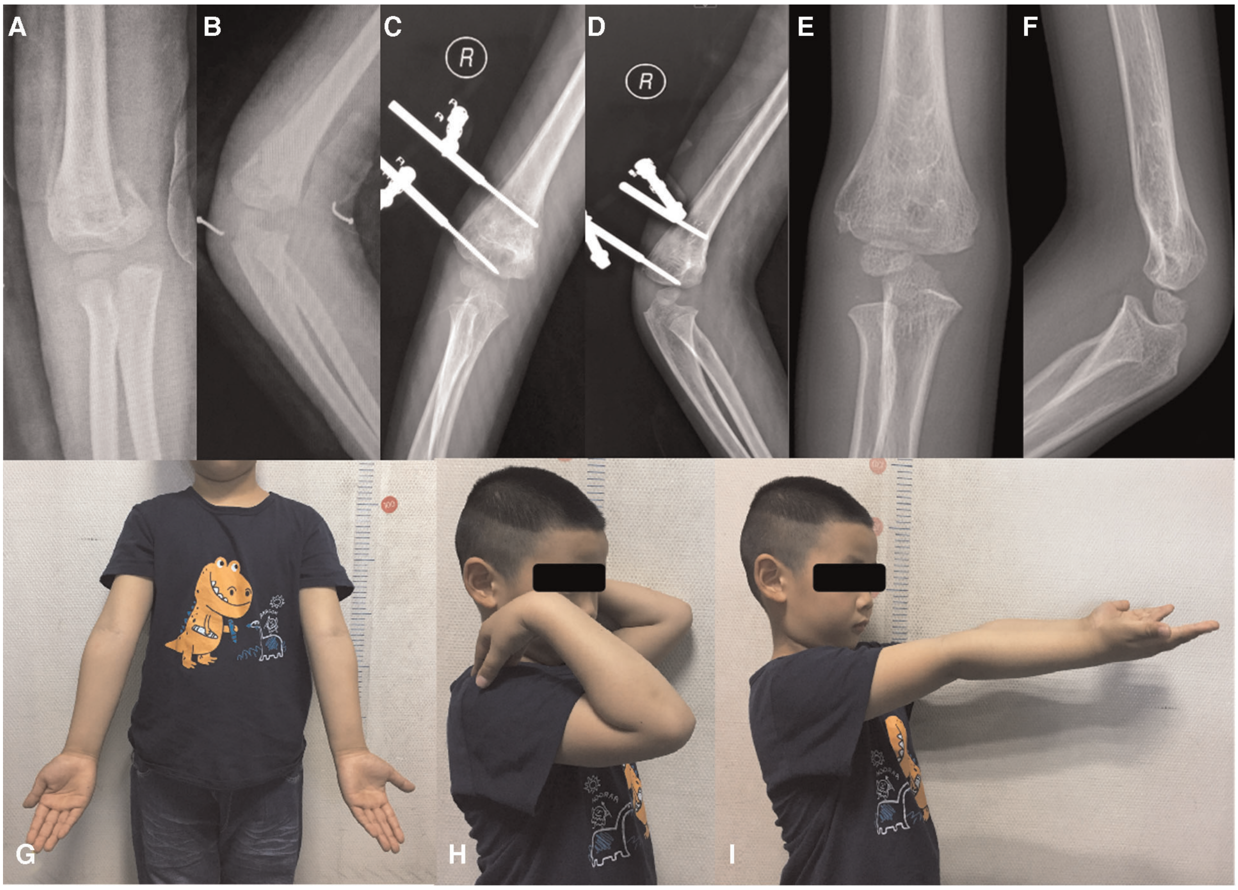

FIGURE 2
(A) anteroposterior and (B) lateral radiographs of the 5-year-old boy with delayed supracondylar fracture of right humerus; (C) anteroposterior and (D) lateral radiographs at 6 weeks post-operation; (E) anteroposterior and (F) lateral radiographs at 12 months post-operation; and the follow-up in 24 months after surgery show excellent cosmetic results (G) and the functional appearance (H,I).

achieved a satisfactory reduction in all patients. All cases were classified as Gartland type III and underwent surgery with an average of 17.7 days after injury (Table 1). The average duration of the surgery was 56 min (range, 50–65 min). The radiological union was evident in 8 to 12 weeks in all fractures. No complications such as Volkmann ischemic contracture, infection, nonunion, myositis ossificans, iatrogenic neurological injuries or residual vascular deficits were noted. The carrying angle difference between fractured and uninjured sides was less than 4°, and cosmetic results in all patients were excellent (Table 2). At the last follow-up, all patients reported 90 points or more on MEPS and good to excellent outcomes on Flynn criteria (Table 3). The therapeutic effect was satisfactory in all patients. Neither revision surgery after the initial fixation nor change in muscle power in the injured limb relative to the uninjured limb was reported at the last follow-up.

TABLE 2 Carrying angle of injured and uninjured sides before and after the operation.

Serial No.	Carrying angle of the operated side before the operation	Carrying angle of the operated side after the operation	Carrying angle of the uninjured side	Carrying angle difference between fractured and uninjured sides after the operation
1	−23°	13°	12°	1°
2	−18°	13°	11°	2°
3	−15°	15°	13°	2°
4	−15°	14°	12°	2°
5	−38°	8°	10°	−2°
6	−22°	10°	12°	−2°
7	−20°	8°	5°	3°
8	−15°	12°	13°	−1°
9	−17°	14°	11°	3°
10	−16°	15°	15°	0°
11	−16°	14°	10°	4°

Discussion

To our best knowledge, this was the first study reporting the outcome of pediatric supracondylar humerus fractures treated with closed or mini-open reduction and external fixation after 14 days of injury. SHF accounts for 55% to 80% of total elbow fractures in children and up to two-thirds of pediatric elbow injuries require hospitalization (10). This type of fracture usually occurs as a result of a fall from height and the incidence is estimated to be 177.3 per 100,000 (11). Delayed presentation of SHF is defined if the patient presents to the hospital after 2 days of injury in developed countries (4). Prabhakar P et al. reported that surgical treatment of low-severity Gartland type III SHFs might be delayed without increasing surgical time and reduction difficulty, but only if the delay time was about 18.5 h, which was hardly a delay in developing countries (12). Silva M et al. showed that anatomic reduction of type II humeral supracondylar fractures could be achieved probably even when closed reduction and percutaneous pinning was performed 7 days after the original injury, but the risk of avascular necrosis of the humeral trochlea must be considered (13). In developing countries, the delayed duration always exceeds 7 days, and the reasons for a delay in interventions are quackery, lack of medical facilities, cost, poor economic status, lack of awareness, delayed referral from the rural hospital, fear of surgery, and various

TABLE 1 Demographics of patients.

Serial No.	Age (years)	Gender	Gartland classification	Time between injury and surgical intervention (days)
1	7	F	type III	20
2	6	M	type III	16
3	6	F	type III	18
4	4	M	type III	17
5	13	M	type III	15
6	5	M	type III	21
7	5	M	type III	22
8	7	F	type III	17
9	8	M	type III	16
10	9	M	type III	19
11	12	M	type III	14

TABLE 3 Perioperative and follow-up data.

Serial No.	Operation duration (min)	Time to union (weeks)	Follow-up time (months)	Flynn	MEPS
1	56	12	40	Excellent	95
2	60	10	34	Excellent	95
3	52	10	40	Excellent	95
4	50	8	52	good	90
5	65	12	70	Excellent	90
6	55	9	41	Excellent	95
7	54	8	36	Excellent	95
8	57	10	27	good	95
9	59	10	27	good	95
10	52	10	26	Excellent	100
11	56	12	27	good	95

MEPS, mayo elbow performance score.

indigenous forms of treatment, which bring difficulty for closed reduction (14–16).

Optimum treatment of SHF is essential in order to avoid serious complications. It is well recognized that the Gartland type III and type IV fractures should be treated surgically (17). To date, closed reduction and percutaneous pinning is the gold standard for all displaced fractures (10). The advantages of closed reduction are the preservation of blood supply to the fracture site, shortening of hospital stays and reduction of risk of infection (18). However, controversy remains with regard to the timing of emergency reduction, whether reduction can be safely delayed, the adequate reduction technique, the risk/benefit ratio of open reduction and the long-term consequences of a cubitus varus deformity (19). It is a challenge for surgeons to improve the success rate of closed reduction, especially for delayed supracondylar humeral fractures. Displaced supracondylar fractures had been traditionally treated as surgical emergencies for the reason that delayed surgery often required open reduction rather than closed reduction (20). In the case of delayed presentation, especially for Gartland type III fractures which is a statistically significant independent risk factor for closed reduction failure, the probability of fracture swelling is significantly increased, for which open reduction is needed to achieve better outcomes and avoid complications such as iatrogenic neurovascular injuries, stiffness, delayed union, malunion and nonunion (14, 15, 21, 22). A meta-analysis conducted by Farrow L et al. showed that there was no statistically significant difference in the risk of complications between immediate and 91-h delayed treatment for patients with SHFs undergoing open reduction (23). However, all the patients in this study were Gartland type III fractures and were delayed over 14 days. All achieved a satisfactory result with reduction with a minimally invasive technique.

The formation of intraperiosteal bone begins immediately after the fracture, but proliferative activity in the cells appears to cease before 2 weeks. By the time the endochondral process has reached the stage of chondrogenesis, a large number of woven bone forms near the fracture site. Once the fracture coalesces through the bone-bridging gap, the callus (composed entirely of woven bone) remodels to form a mechanically capable layered structure (24). Callus formation occurs even faster in children, which is why closed reduction over 14 days often fails and open reduction is the only option left. Close reduction avoids complications related to open reduction, such as wound infection or elbow stiffness (18, 25, 26). However, the closed reduction could not be achieved in a single patient presenting more than 7 days after injury in Tiwari A et al.'s study because closed reduction and cast fixation were not feasible in late-presenting SHFs. The injury is usually accompanied by severe swelling that prevents rapid and safe flexion, and soft tissue scabbed at the end of the first week precludes reduction of the fracture (4). All the patients achieved a satisfactory reduction using the minimally invasive technique in this study. Traditional K-wires fixation of SHF was not performed in this series because without removing the callus from the fracture site, the fixation could not be stable only by K-wires. Instead, the external fixator could provide better stability than K-wires. Sufficient stability following the use of an external fixator allowing an early functional exercise was indicated by good to excellent functional outcomes. Also, none of the cases underwent revision surgery in our series.

The carrying angle of the elbow is used to assess varus or valgus deformity (19). The patients' carrying angles in this study were over −15° pre-operation, with a high risk of cubitus varus deformity that might lead to a second corrective osteotomy. After the operation, the carrying angle difference between fractured and uninjured sides was less than 4°, indicating that the reduction of fracture by minimally invasive technique and application of external fixation corrected the preoperative cubitus varus effectively. Masumbuko CK et al. showed that delaying surgery for more than seven days resulted in reduced elbow range of motion (27). In contrast, midterm follow-up results of the elbow function were satisfactory in our study. The advantages of external fixation include stable fixation avoiding delayed healing and early mobilization, which may contribute to good functional results (7, 28). This method reduced the risk of complications of open reduction, such as neurovascular injury, elbow stiffness, wound infection and ugly scarring, as well as complications due to unsatisfactory closed reduction, including triceps fibrilization and limited elbow mobility.

Limitations of this study were the small number of cases, failure to follow-up until the closure of physes, and its retrospective nature. This case series could not provide a control group because none of the parents or guardians chose to wait for a long-term outcome with a high risk of cubitus varus. They all chose a one-stage procedure in view of carrying angle >−15°.

Conclusions

The results of this series indicated a satisfactory outcome in children with delayed more than 14 days of supracondylar humeral fractures. The closed reduction with a minimally invasive technique followed by external fixation is an alternative treatment for such kind of injury.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by The Ethics Committee of Tongji Medical College, Huazhong University of Science and Technology (IORG No: IORG0003571). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

JTL, ZXO and ZZW were involved in data collection and follow-up assessments. XT, SR and WFL were responsible for literature search and study design, SL and YYP drafted the manuscript. XT, WFL and SR finalized the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A novel approach for the treatment of Jacob II and III fractures of the lateral humeral condyle in children: Percutaneous Kirschner wire fixation with ultrasound localization

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This research investigated the effectiveness of percutaneous Kirschner wire fixation in children with Jacob II and III lateral humeral condyle fractures. 28 children with Jacob II and III lateral humeral condyle fractures were treated with percutaneous Kirschner wire fixation under ultrasound localization, followed by cast immobilization for 4–5 weeks at our institution from January 2018 to April 2022. X-rays were evaluated on the first postoperative day to assess fracture reduction and Kirschner wire fixation. After 2 and 4 weeks, x-rays were taken to assess fracture healing and the presence of discomfort and infection was evaluated. After confirming fracture healing and callus formation, the cast and Kirschner wire were removed. Rehabilitation exercises were conducted following removal to restore elbow function. At the last follow-up, most results were excellent ($n = 25$) and good ($n = 3$) according to Flynn's criteria. Moreover, according to the Mayo Elbow Functional Score Scale (MEPS), all 28 children had excellent scores, with no significant difference in MEPS scores between the lesion and healthy sides ($t = 1.533$, $p > 0.05$). The present study substantiated that our novel approach is more convenient and effective, brings less trauma and complications and no radiation and deserves clinical promotion.

KEYWORDS
ultrasound, children, lateral humeral condyle fractures, minimally invasive, treatment

Background

It is well-established that fractures of the lateral condyle of the humerus are common elbow fractures in children, second only to supracondylar fractures, occurring mostly between ages 5 and 10 and are responsible for 15 to 20% of elbow fractures in this patient population (1, 2). The mechanism of injury generally involves forearm varus or valgus stress exerted by the elbow in extension. Heavy, obese children are at greater risk for lateral humeral condyle fractures (3). Jacob's classification is clinically used to classify lateral humeral condyle fractures according to the fracture displacement: type I: articular surface continuity; type II: articular surface fracture; type III: fracture fragment rotation. Jacob type I fractures are treated conservatively with cast immobilization, while Jacob type III fractures generally require open reduction with Kirschner wires, screws, or cannulated nails due to considerable displacement. However, much controversy surrounds the optimal treatment for Jacob type II fractures, with inconsistent reports on open or closed reduction treatment.

Manual reduction with percutaneous Kirschner wire fixation under arthrography is the mainstay of treatment. However, arthrography requires repeated x-ray fluoroscopy, which increases the risk of iatrogenic radiation damage and is an invasive procedure with hazards such as allergies to contrast agents. In recent years, ultrasound has been widely employed in treating lateral condyle fractures in children due to its ability to visualize cartilage hinges, properly determine re-displacement risk, and avoid iatrogenic harm (4, 5). Therefore, the clinical efficacy of percutaneous Kirschner wire fixation for children with Jacob II and III fractures of the lateral humeral condyle under ultrasound localization was assessed in the present study.

Patients and data

A total of 28 cases of Jacob II ($n = 21$) and III ($n = 7$) fractures of the lateral humeral condyle were included, with a mean age of 5.5 ± 2.1 years (range 2–10 years) and consisting predominantly of males ($n = 20$). The mean time from injury to surgery was 2.6 ± 0.8 days (range 1–4 days). The same surgical team completed all surgical operations in this study, and the legal guardians of the children agreed to participate and signed the informed consent form. A Hitachi F31 ultrasound instrument with an 8 MHz high-frequency probe (Hitachi, Japan) was used in this study (**Table 1**).

This retrospective study was approved for publication by the ethics committee of Jiangnan Hospital Affiliated with the Zhejiang University of Traditional Chinese Medicine (Hangzhou Xiaoshan Hospital of Traditional Chinese Medicine). (XSZYY2081115) and conducted based on the tenets of the Declaration of Helsinki. Copies of the written consent form are available for review by the editors of this journal. The study is reported in agreement with the principles of the CAse REport (CARE) guidelines.

Inclusion and exclusion criteria

Inclusion criteria

1. Age ≤ 10 years old; 2. x-ray imaging (including frontal and lateral films) showing Jacob II and III fractures of the lateral condyle of the humerus; 3. Absence of vascular and nerve damage at the time of injury; 4. Follow-up duration >6 months.

Exclusion criteria

1. Age > 10 years old; 2. x-ray imaging (including frontal and lateral films) showing Jacob type I fracture of the lateral condyle of the humerus; 3. Patients with concomitant elbow injuries, including supracondylar and intercondylar fractures of the humerus, olecranon fractures, and radial head and neck fractures. 4. Presence of neurovascular complications; 5. Refusal of surgery; 6. Loss to follow-up.

Treatment methods

Preoperative treatment

After admission, the child received symptomatic treatment for analgesia and detumescence. All children underwent preoperative examinations to assess the surgical risk.

Surgical methods

Operation process: After a combination of brachial plexus block with general anesthesia, the surgical site was draped. Hematomas in the joint cavity were aspirated with a needle when present. Preoperative sterile probe preparation, apply sterile medical ultrasonic couplant on the probe surface and wrap it with sterile membrane (**Figure 1**). During intraoperative ultrasound, the probe was predominantly placed along the transverse and coronal plane. When the elbow was in a flexed position, the ultrasound probe was used to visualize the lateral elbow in the coronal plane and assess the condition of the cartilage at the distal humerus (**Figure 1**). Total separation, articular surface displacement, or lateral condyle rotation could be observed. Sufficient traction should be given before reduction and rotated type III fracture pieces should be reduced by gentle manipulation. Under ultrasound guidance, the rotationally displaced fracture fragments were reduced, and the reduced type III fracture was transformed into a type II fracture. Simultaneously, valgus pressure was applied, the elbow joint was flexed and stretched to align the articular surfaces, and the “steps” on ultrasound disappeared, indicating effective articular surface reduction (**Figure 2**). Under ultrasound guidance, 2–3 Kirschner wires (size 1.50–1.80 mm) were inserted parallel from the lateral condyle and the proximal end of the fracture at an angle of 45° to the articular surface, with extra caution to avoid nerves and blood vessels (**Figure 3**). The fractured end was reduced under x-ray fluoroscopy, and elbow flexion and extension

TABLE 1 Patients and data.

Case	Age	Sex	Jacob's type	K-wires number	K-wires Size (mm)	Time from injury to surgery (day)	operation time (min)	Plaster removal time (day)	limited flexion	carrying angle	Evaluation
1	7	1	2	2	1.6	3	30	35	3°	3°	Excellent
2	8	1	2	2	1.6	4	30	35	2°	3°	Excellent
3	8	1	2	2	1.6	1	32	30	0°	0°	Excellent
4	8	1	2	2	1.6	2	30	32	3°	2°	Excellent
5	6	2	2	2	1.6	3	33	30	0°	0°	Excellent
6	2	2	2	2	1.4	4	30	32	3°	2°	Excellent
7	6	1	2	2	1.6	3	30	32	0°	0°	Excellent
8	7	2	2	2	1.6	3	30	35	5°	3°	Excellent
9	3	1	2	2	1.4	3	30	34	0°	0°	Excellent
10	4	2	2	2	1.6	2	35	35	3°	3°	Excellent
11	6	2	2	2	1.6	2	35	35	0°	0°	Excellent
12	2	1	2	2	1.6	2	30	35	5°	5°	Excellent
13	6	1	2	3	1.6	4	30	35	0°	0°	Excellent
14	10	1	2	3	1.6	3	35	35	2°	2°	Excellent
15	4	2	2	3	1.6	2	30	35	2°	2°	Excellent
16	4	1	2	2	1.4	2	30	34	0°	0°	Excellent
17	4	1	2	2	1.6	2	34	35	3°	5°	Excellent
18	6	1	2	2	1.4	2	30	35	0°	0°	Excellent
19	4	1	2	3	1.6	1	30	35	2°	2°	Excellent
20	8	1	2	3	1.8	4	30	35	3°	3°	Excellent
21	5	1	2	3	1.6	2	35	35	4°	5°	Excellent
22	5	1	3	3	1.6	3	35	35	9°	9°	Good
23	6	1	3	3	1.6	3	38	35	5°	4°	Excellent
24	3	2	3	3	1.6	3	35	35	8°	6°	Good
25	10	2	3	2	1.6	3	35	35	4°	3°	Excellent
26	5	1	3	3	1.6	3	35	35	5°	3°	Excellent
27	3	1	3	3	1.6	2	35	34	3°	4°	Excellent
28	6	1	3	3	1.6	2	35	35	9°	6°	Good

Sex: 1: male, 2: female.

were excellent. After the operation, the needle port was cleaned, and the Kirschner wire was bent and cut for outpatient removal. The average intraoperative blood loss was about 10.00 ± 5.00 ml.

Postoperative management

X-rays were taken on the first day after surgery to assess fracture reduction and Kirschner wire fixation. After 2 and 4 weeks, x-rays were repeated to assess fracture healing and patients were assessed for any discomfort or signs of infection. The cast and Kirschner wires were removed after a mean duration of 34.21 ± 1.52 days after confirming fracture healing and callus formation. After removal, the patients underwent rehabilitation exercises to improve recovery of elbow function.

Results

Efficacy evaluation indicators

At 2, 4 weeks, 3, and 6 months after surgery, anterior and lateral elbow x-rays were collected to assess fracture healing. The Flynn and Mayo Elbow Score (MEPS) was used to evaluate the children's postoperative functional recovery.

Flynn's criteria (6) is commonly used to evaluate outcomes into four grades based on the carrying angle and motion loss. Excellent, Good, Fair, and Poor results were associated with a 0–5°, 6–10°; Fair, 11–15° and over 15° motion loss and carrying angle.

The Mayo Elbow Joint Function Rating Scale (7) scores the function of the affected limb based on pain, range of motion, stability, and daily functional activities, with a full score of

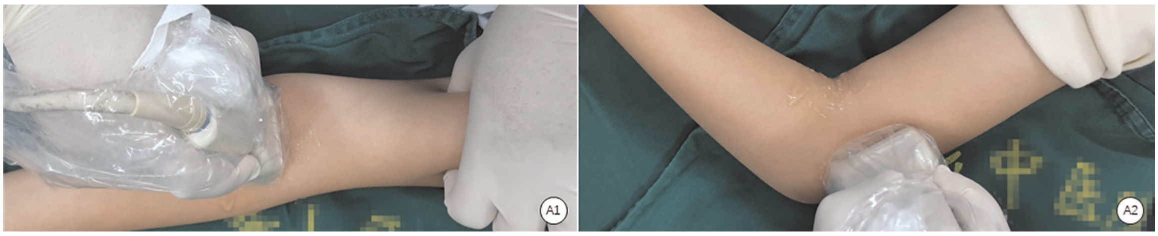

FIGURE 1
(A1) The transverse plane. (A2) The coronal plane.

FIGURE 2
Intraoperative K-wire insertion angle.

100. Excellent, good, moderate and poor outcomes were associated with scores of over 90, 75–89, 60–74, and below 60, respectively.

Treatment results

Elbow joint function

All 28 children were observed for 6–12 months (mean 8.40 ± 2.30 months). The average operation duration was 32.39 ± 2.60 min. No infection, fracture displacement, delayed union, fishtail deformity, early epiphyseal closure, growth arrest, nonunion, functional impairment, or postoperative arthritis complications were detected. All fractures healed after Kirschner wire removal. The average recovery time was 5.40 ± 0.50 weeks (**Figure 4**).

At the last follow-up, according to Flynn's criteria, results were excellent in 25 cases and fair in 3 cases. No children presented with a loss of carrying angle of 11–15° or >15° (**Table 1**).

At the final follow-up, all 28 children had excellent MEPS scores. There was no significant difference in MEPS (99.80 ± 0.39) between the lesion side and the healthy side (99.92 ± 0.17) (t value = 1.533, p value > 0.05) (**Table 2**).

Discussion

The benefits and drawbacks of ultrasound localization in the treatment of lateral humeral condyle fractures in children.

It is well-established that ultrasound localization is better than arthrography for treating lateral humeral condyle fractures in children (8) for the following reasons: 1. The absence of ionizing radiation minimizes radiation damage from frequent x-ray fluoroscopy. 2. This approach is more convenient and fracture fragments can be seen from multiple directions and joint planes. 3. Ultrasound guidance provides greater precision, avoiding unnecessary surgery for children with mildly displaced lateral humeral fractures. 4. Nerve and blood vessel damage can be seen before or during the operation. 5. Epiphysis and cartilage injury can be

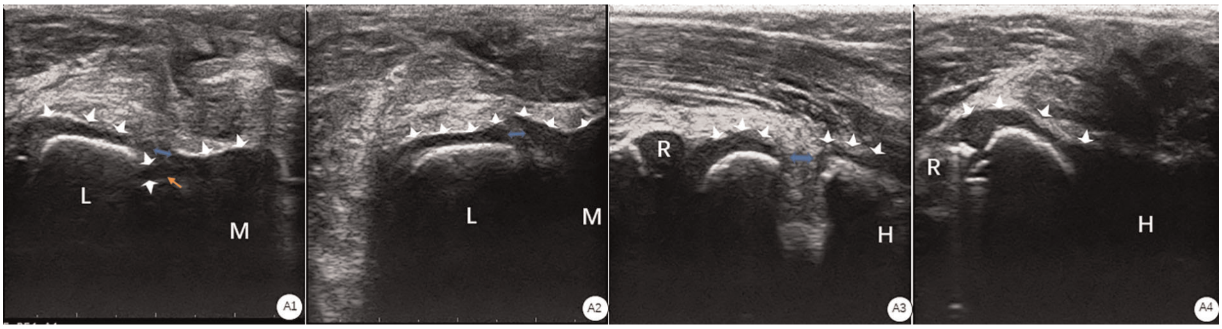

FIGURE 3
(A1) Ultrasonography on the transverse plane showed that the cartilage hinge (white arrow) was broken (blue arrow), the "step sign" was seen at the broken end, and the triangular bone fragment (yellow arrow) at the broken end was free from the cartilage articular surface. (Note: L the humerus Lateral condyle; M: the medial condyle of the humerus). (A2) Ultrasonography on the transverse plane showed that the cartilage hinge (white arrow) was broken (blue arrow), and the "step sign" was seen at the broken end. (A3) Ultrasonography on the coronal plane showed that the cartilage hinge (white arrow) was broken (blue arrow), and the "step sign" was seen at the broken end. (Note: R: radial head; H: humeral shaft). (A4) Ultrasonography on the coronal plane shows the continuity of the cartilage hinge (white arrow). (Note: it radial head; humeral shaft).

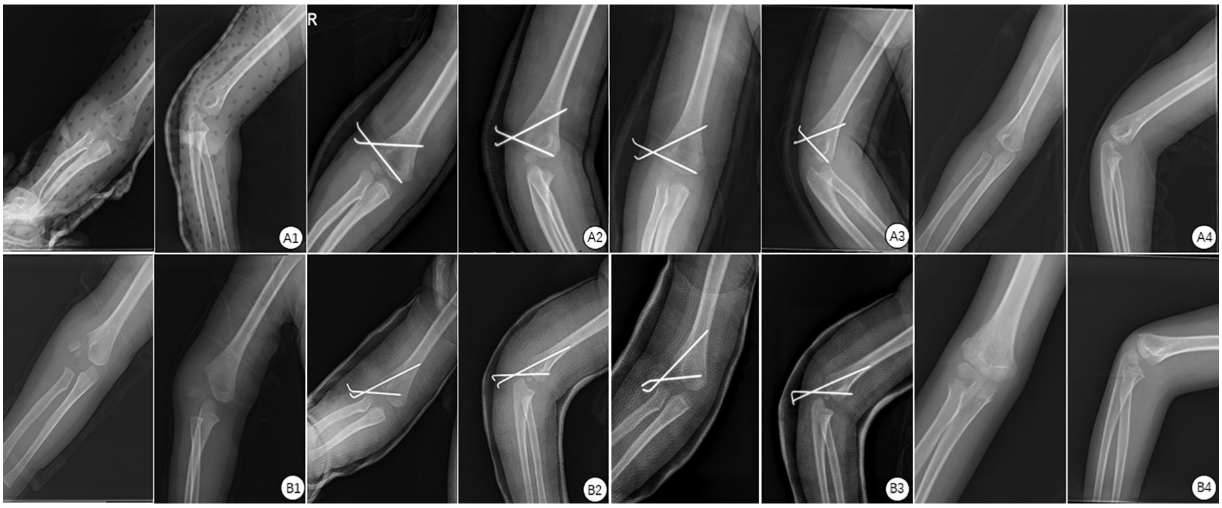

FIGURE 4
(A1) Pre-operative type II frontal and lateral view: fracture of the articular surface, displacement <2mm. (A2) Frontal and lateral view on the first day after operation of type II: the Kirschner wire was stable and the articular surface was continuous. (A3) Frontal and lateral view of type II one month after operation: the Kirschner wire was stable and the callus formed at the fracture end. (A4) Frontal and lateral view two weeks after the plaster removal of type II after operation: the fracture healed well.B1. Pre-operative type III frontal and lateral view: fracture of the articular surface, rotational displacement >2 mm. (B2) Frontal and lateral view on the first day after operation of type III: the Kirschner wire was stable and the articular surface was continuous. (B3) Frontal and lateral view of type III in the second week after operation: the Kirschner wire was stable and the callus formed at the fracture end. (B4) Frontal and lateral view twelve months after the removal of the plaster of type III after operation: the fracture healed well.

prevented. 6. Intraoperative dynamic monitoring of the cartilage hinge. 7. Intraoperative trauma is minimal, with relatively lower bleeding and reduced iatrogenic harm. The short surgery duration promotes early fracture repair and functional recovery of the elbow joint.

Although percutaneous Kirschner wire repair of lateral humeral condyle fractures in children under ultrasound localization has numerous benefits, many drawbacks have been reported (9). For instance, ultrasonography requires experienced operators with professional training. Accordingly, the high learning costs may hinder the wide implementation of this approach. Moreover, it should be borne in mind that ultrasound cannot be used to identify fracture displacement during plaster immobilization, unlike an x-ray.

TABLE 2 Percutaneous Kirschner wire fixation of children with Jacob II and III fractures of the lateral humeral condyle under ultrasound localization in 28 children with MEPS comparison at the last follow-up.

Side	Pain	AROM	Stability	ADL	Score
lesion	45.00 ± 0	19.96 ± 0.18	9.92 ± 0.26	24.91 ± 0.27	99.80 ± 0.39
healthy	45.00 ± 0	19.98 ± 0.09	9.96 ± 0.13	25.00 + 0	99.92 ± 0.17
T value		0.447	0.645	1.724	1.533
p value		0.657	0.522	0.096	0.134

AROM, active range of motion; ADL, activities of daily living.

Treatment experience and study limitations

The lateral condyle fracture of the humerus is the second most frequent elbow fracture in children. Ultrasound technology has become extremely popular clinically, given its convenience, non-invasiveness, and ability to visualize neurovascular and soft tissues (4). Kirschner wire fixation with ultrasound localization represents a more effective approach consistent with the contemporary concept of minimally invasive surgery. During closed reduction, emphasis should be placed on the following points: 1. Gentle manipulation is essential to avoid epiphyseal injury in children leading to exacerbation of trauma and unintentional healing. 2. The Kirschner wire should be fixed at the correct angle to meet biomechanical criteria and accelerate fracture healing. 3. The tip of the needle should reach the contralateral bone and an adequate should be left outside the skin to facilitate removal.

In this research, 28 children with Jacob II and III fractures of the lateral humeral condyle were treated with percutaneous Kirschner wire fixation under ultrasonography. All fractures exhibited fast healing after surgery. At follow-up, there was no infection, deformity, or other complications. In children with type III injuries, elbow joint function scores were slightly worse than type II. For type III fractures with a displacement of >4 mm, the degree of trauma and soft tissue injury is considerable, and the chance of postoperative joint adhesion is higher than in type II children. Following long-term follow-up and correction, some children with type III trauma exhibited poorer postoperative functional recovery than type II trauma. Notwithstanding that the efficacy of type III trauma is inferior to type II trauma, excellent results have been reported in recent years with the use of ultrasound. Based on our experience, cases with displacement >4 mm and type III trauma can be more objectively visualized. Indeed, more research is warranted for the application of ultrasound in cases with minimal displacement or type II fractures.

In conclusion, percutaneous Kirschner wire fixation in children with Jacob II and III lateral humeral condyle fractures under ultrasound localization is more convenient and effective, brings less trauma and complications and no radiation and deserves clinical promotion.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by the ethics committee of Jiangnan Hospital Affiliated with the Zhejiang University of Traditional Chinese Medicine (Hangzhou Xiaoshan Hospital of Traditional Chinese Medicine). (XSZYY2081115). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

CD, ZS, and KW collected the data and wrote the manuscript. CD was a major contributor to writing the manuscript. WD, WX, and WZ contributed to the conception and design of the study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Treatment of olecranon fractures in childhood: A systematic review

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Background: Literature over the last 20 years provides evidence for a surgical treatment of displaced olecranon fractures in children, this is usually obtained with commonly proposed methods, although there is no general agreement about the best recommended technique.
Aim: Identifying the best surgical technique in displaced olecranon fractures in children and the role of associated fractures in the prognosis of these lesions, by analyzing the most relevant studies on this topic.
Methods: A literature search was performed in MEDLINE database and Scopus database. Articles reporting clinical outcomes of pediatric patients affected by olecranon fractures treated surgically were identified.
Results: The initial search produced 111 studies, with 8 fulfilling the eligibility criteria of our study. Selected articles (2002–2022) included 122 patients overall.
Conclusion: Displaced olecranon fractures, occurring during skeletal growth and surgically treated, generally have good results, although we are unable to recommend the best surgical treatment based on our review. In most cases, they are intra-articular fractures; thus, the overall goal is to get an anatomic reduction that in some cases cannot be obtained by percutaneous techniques. Tension band suture is the preferred device, although it is not recommended in adolescence for the high risk of fixation failure. Associated lesions may affect results.

KEYWORDS
olecranon, fracture, children, surgery, upper limb, surgical procedures, surgical treament, pediatric

Introduction

Fractures of the olecranon are rare and account for 5% of all elbow fractures during skeletal growth (1). These fractures generally occur between 5 and 10 years of age and the most common mechanism of injury is trauma onto either an outstretched hand or a flexed elbow; they are commonly associated with additional fractures of the radial head or the distal part of the humerus. Fractures with displacement greater than 2 mm generally require surgical treatment (2). In 2002, we reported a long-term follow-up study with an average follow-up of 23.8 years, on 39 cases, the majority of which were treated conservatively. We conclude that the long-term prognosis of olecranon fractures in children is related to the anatomic site of the fracture line, to the interfragmentary displacement and to the presence of an associated lesion that represent a negative prognostic factor (3). Classification of these rare lesions is still debated and to the best of our knowledge, there is no universally accepted classification in the literature. Generally, in all the classification systems reported, the possible presence of the intra-articular displacement more than 2 mm and the presence of associated injuries are considered (4, 5). In our study we proposed a classification in 5 types, on the basis of the anatomic site of the fracture line, the inter-fragmentary displacement and the presence of an associated lesion (3). There is general agreement that undisplaced or minimally displaced (less than 2 mm) fractures may be treated conservatively with good results, while displaced fractures need to be treated surgically. The most common methods of treatment proposed in the last 20 years are open reduction and internal fixation (ORIF) with tension band wiring or suture, open or percutaneous screw fixation and ORIF with plate and screws. The aim of our systematic review was to identify the best method of surgical treatment in displaced olecranon fractures in children and the role of associated fractures in the prognosis of these lesions.

Materials and methods

Inclusion and exclusion criteria were formulated according to the population, intervention, comparator, outcome (PICO) method and are summarized in **Table 1** (6). Search strategy and sources of information: Authors of this review (PF, FM, GG, DC, AC, and CL) performed a literature search about the topic by querying Medline database, Scopus and Chocrane Library. The search strategy covers PICO and was performed independently by each author in July 2021. Keywords and Medical Subject Headings (MeSH) terms were identified by a preliminary search and selected by discussion. The search was conducted using the following keywords and their synonyms or MeSH Terms assembled in various combinations to obtain most pertinent articles: olecranon, fractures, children. The following is the list of all of the terms used and the Boolean operators used to combine them: ((“olecran*”[Title]) OR ((“olecranon process/injuries”[MeSH Terms] OR “olecranon process/surgery”[MeSH Terms] OR “olecranon process/therapy”[MeSH Terms]))) AND (“fractur”[All Fields] OR “fractural”[All Fields] OR “fracture’s”[All Fields] OR “fractures, bone”[MeSH Terms] OR (“fractures”[All Fields] AND “bone”[All Fields]) OR “bone fractures”[All Fields] OR “fracture”[All Fields] OR “fractured”[All Fields] OR “fractures”[All Fields] OR “fracturing”[All Fields]) AND (“Child”[Mesh] OR “Adolescent”[Mesh] OR “Pediatrics”[Mesh] OR “Child*”[Title] OR “Pediatr*”[Title]).

A publication date filter was applied to select only articles and review articles from the last 20 years (ranging from 2002 to 2022). Language restriction filter was applied to identify only English articles.

TABLE 1 Inclusion and exclusion criteria (PICOT).

	Inclusion criteria	Exclusion criteria
Population	- Children Patients (<18aa) affected by olecranon fractures - Patients affected by associated fractures	- Patients who didn’t underwent surgery. - Patient affected by fracture-dislocation of the proximal ulna. - Patients affected by Osteogenesis Imperfecta
Intervention	- Open or percutaneous fixation of fracture site.	- Non surgical techniques with closed reduction without fixation - Non-surgical treatment
Comparison group	- Studies reporting patients treated with different surgical techniques will be compared.	- Not applicable
Outcome	- Studies reporting clinical and radiographic scores	- Not reporting clinical results
Time	- Studies published from 2002 to 2022	- Studies published prior to 2002
Study type	- Original Articles - Clinical Trials - Cohort Studies - Observational Studies - Randomised Control Trials	- Letters - Case reports - Experimental Studies
Language	- English	- Other languages

The reviewers (PF, FM, GG, DC, AC, and CL) retrieved the data and independently analyzed each selected study; instances of disagreement were resolved by the senior investigator (PF).

The articles were screened for the presence of the following inclusion criteria: pediatric patients affected by olecranon fractures; patients treated with any surgical technique; studies providing an adequate level of evidence, including retrospective studies; availability of full text. The studies were excluded if they provided information regarding: patients affected by Osteogenesis Imperfecta or affected by fracture-dislocation of the proximal ulna; patients treated with non-surgical techniques or with closed reduction without fixation. Letters, Case reports or Experimental Studies and studies not reporting clinical results were also excluded.

Results

The initial search produced 111 studies. After a first screening, by reading title and abstract and evaluation based on inclusion and exclusion criteria, articles were screened and only 10 studies fulfilled the eligibility criteria of our study. The other studies were excluded for the following reasons: 28 were Case Reports; 28 reported fractures not involving olecranon; 26 were about adult patients; 4 didn’t report

TABLE 2 This table presents a list of the included studies, summarizing the number of patients, classification of fracture, associated lesions, age at surgery, surgical technique performed, length of follow-up, results and conclusions.

Authors	Year of pubblication	Title	Study type	Number of cases (surgically treated)	Classification of fracture	Associated fractures	Average age at surgery	Surgical treatment	Length of follow-up	Final results
Caterini et al.	2002	Fractures of the olecranon in children. Long-term follow-up of 39 cases.	Retrospective	5	Caterini: 5 types	NO	7.4 years	ORIF cerclage wiring (4 cases) one screw (1 case)	32 years	Good: 4 cases poor: 1 case (inadequate reduction)
Karlsson et al.	2002	Fractures of the olecranon during growth: a 15–25-year follow-up.	Retrospective	11	Horne and Tanzer: 3 types	NO	11 years	ORIF figure-of-eight wiring (6 cases) tension band wiring (2 cases) Rush pin (1 case) CRIF percutaneous pinning (2 cases)	19 years	Excellent: 9 cases good: 2 cases (occasional symptoms)
Gicquel et al.	2003	Surgical technique and preliminary results of a new fixation concept for olecranon fractures in children.	Retrospective	6	Bracq: 3 types	2 (radial head)	10.2 years	CRIF two threaded pins (percutaneous)	14 months	Excellent: 5 cases good: 1 case (limited ROM—10° flexion + associated radial head fracture)
Gortzak et al.	2006	Pediatric olecranon fractures: open reduction and internal fixation with removable Kirschner wires and absorbable sutures.	Retrospective	6	Intra-articular displaced fractures (no specific classification)	3 (humeral condyle—1, radial head—2)	9.7 years	ORIF removable K wires and figure-of-eight suture	13 months	Excellent: 5 cases good: 1 case (limited ROM—10° extension)
Corradin et al.	2016	Outcome of isolated olecranon fractures in skeletally immature patients: comparison of open reduction and tension band wiring fixation versus closed reduction and percutaneous pinning.	Retrospective	22	AO PCCF classification: 3 types	NO	10.5 years	ORIF tension band wiring (10 cases) CRIF percutaneous 4.5mm cannulated screw (12 cases)	17.9 momths	Quick DASH score: 1.82/3.42 no statistical significant difference between the 2 groups (limited ROM—20° extension—4 patients)
Kim et al.	2017	Early range of motion exercise in pediatric patients with olecranon fractures treated with tension band suture with double loops and double knots.	Retrospective	12	AO PCCF classification: 3 types	2 (radial head)	10.6 years	ORIF K wires and figure-of-eight suture early ROM	12 months	Perfect MEPS: 12 cases

(*continued*)

TABLE 2 Continued

Authors	Year of publication	Title	Study type	Number of cases (surgically treated)	Classification of fracture	Associated fractures	Average age at surgery	Surgical treatment	Length of follow-up	Final results
Perkins	2018	Olecranon fractures in children and adolescents: outcomes based on fracture fixation.	Retrospective	46	Intra-articular displaced fractures (no specific classification)	5 (radial head—4 distal radius—1)	12.3 years	ORIF tension band wiring (17 cases) tension band suture (29 cases)	9.1 months	Revision fixation (TBW: 1 case TBS: 4 cases) children eavier than 50 kg having higher rates of fixation failure with TBS
Li et al.	2022	Short-Term Outcomes of Herbert Screw Fixation for Isolated Olecranon Fractures in Children: A Single-Institution Retrospective Study.	Retrospective	14	Mayo: 3 types	NO	11.3 years	CRIF two 3 mm Herbert screw (percutaneous)	11.9 months	Quick DASH score: 1.58

surgical treatment; 4 reported cases affected by osteogenesis imperfecta; 2 reported less than 5 cases; 2 reported fracture dislocations; 2 reported cases affected by congenital pseudoarthrosis; 2 were experimental studies; 2 reported stress fracture; 1 reported nonunion; 1 didn't report follow-up.

After screening the full text of the remaining 10 articles, we excluded 2 more articles which lacked follow-up measure, clinical outcomes and reported unspecified surgical technique. In conclusion, a total of 8 articles were enrolled in the present review (**Figure 1** shows the flowchart for study selection). All the selected articles were published from 2002 to 2022 and included 122 patients overall. **Table 2** presents a list of the studies, summarizing the number of patients, classification of fracture, associated lesions, age at surgery, surgical technique performed, length of follow-up, results and conclusions.

Discussion

Surgical treatment of displaced olecranon fractures in children is still debated. On the contrary, conservative treatment is usually adopted in non-displaced or minimally displaced fractures with good results. Generally, the majority of authors considered minimally displaced olecranon fractures when the interfragmentary gap is more that 2–3 mm.

In this systematic review, we analyzed the clinical and radiological results obtained in 122 children treated surgically, from eight clinical and radiological studies published in the last 20 years. All these studies were retrospective and the majority of them had a short-term follow-up. The surgical techniques commonly reported are open or closed reduction followed by internal fixation using various devices. Tension band wiring (TBW), tension band suture (TBS) and cerclage techniques are the most common devices used after open reduction while screws or pins are generally applied percutaneously after closed reduction.

Usually, the classification systems are proposed to help guide treatment; however, in regards to olecranon fractures in pediatric patients, several classifications have been reported, without any demonstrating superiority over the others. The adopted classifications in our review are the following: Caterini et al. who proposed five different fracture types (3), on the basis of the anatomic site of the fracture line (7), interfragmentary displacement and presence of an associated lesion (5); Horne and Tanzer, who proposed three types, depending on location of the fracture on the olecranon (8); AO PCCF, based on the morphology of the fracture (9) and Mayo classification (10) in three types, described for adults fractures, based on fracture displacement and elbow stability (11). In two papers no specific classification is reported; the authors had surgically treated all intra-articular displaced olecranon fractures. These data confirm that, there is still no classification commonly adopted for olecranon fractures in children that suggests the best treatment to adopt.

The majority of papers included in the review are short-term follow-up studies. Gicquel et al. reported the preliminary results of a new percutaneous fixation technique to stabilize six olecranon fractures using two threaded pins introduced by a minimal skin incision with a divergent orientation. Only in two cases, the interfragmentary displacement was more than 2 mm. The authors observed excellent result in all patients but one, which was associated with a radial head fracture and mild limited range of motion of the elbow was present. They concluded that their technique can be used routinely because of its effectiveness and simplicity (12). Recently Li et al. reported another short-term follow-up study on 14 cases treated percutaneously using two cannulated Herbert screws with a different direction (13). All the fractures included in the study had a displacement more than 4 mm that were closed reduced, before percutaneous fixation. The authors observed good functional and radiological results in all patients, evaluated with a quickDASH scoring system. The authors strongly recommend the percutaneous technique, to avoid skin complications and hardware irritation causing

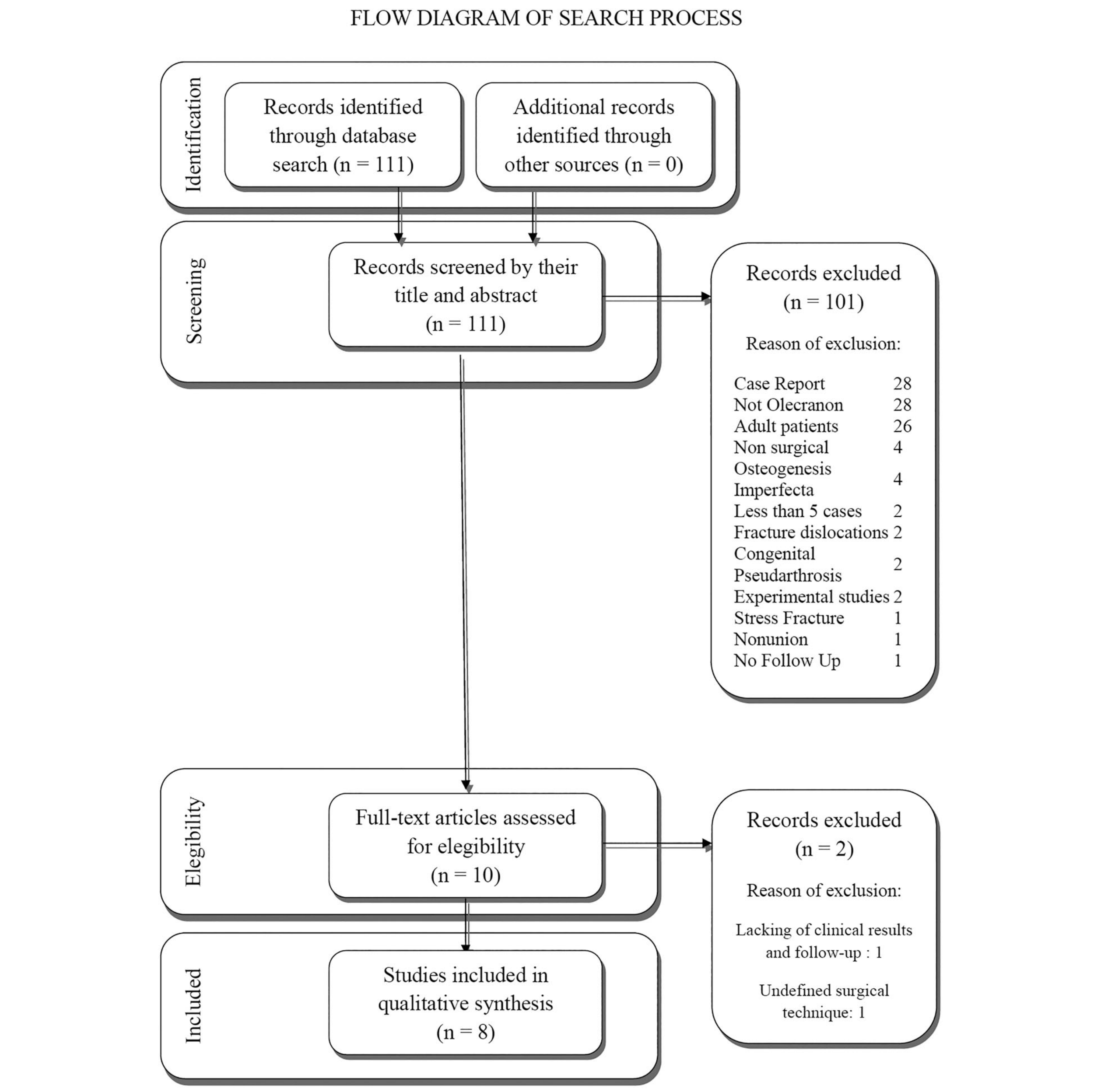

FIGURE 1
Flow diagram of search process.

persistent joint pain, requiring hardware removal. Moreover they underlined the ease of screws removal performed by small incisions. On the contrary, other authors prefer to perform an open reduction; Gortzak et al. in 2006 (14) and more recently Kim et al. in 2017 (15), reported 6 and 12 olecranon fractures respectively, treated by open reduction and internal fixation with two K-wires and figure-of-eight suture. Both papers reported excellent results at an average of 1 year after treatment, except in one case in which the authors observed a limited elbow extension of 10°. Gortzak et al., suggest leaving the two Kirschner wires out of the skin to perform a quick removal of the devices after fracture healing. The authors emphasize their technique that avoid a reoperation for hardware removal. Kim et al., instead emphasize the early range of motion exercise after stabilization fracture performed by tension band suture with double loops and knots (15). Perkins et al. reported 46 olecranon fractures in children and adolescents comparing 17 patients treated by open reduction and tension band wiring and 29 patients treated by open reduction and tension band suture. The authors, who report the largest series of olecranon fractures included in our review, concluded that tension band suture is contraindicated in patients weighting more than 50 kg; in fact, they observed their failures in older and heavier patients (4 cases) (16). Corradin et al. reported a comparison of open reduction and tension band wiring fixation performed in 10 cases versus closed reduction and percutaneous screw fixation performed in 12. The authors, while reporting a difference regarding the quickDASH score at follow-up between the two groups (1.82 in the open series versus 3.42 in the closed series), concluded that no statistically significant differences were present between the two groups, with equally acceptable clinical and radiological final results and similar rate of complications (17).

Only two papers with a long-term follow-up have been published in the last 20 years. Caterini et al. reported only 5 cases of surgically treated patients and concluded that the long-term prognosis of olecranon fractures in children is related to the anatomic site of the fracture line, to the interfragmentary displacement and to the presence of an associated lesion. They observed only one case with poor result related to an inadequate reduction and fixation (3). Karlsson et al. reported 11 olecranon fractures surgically treated and observed that none of their patient developed nonunion or elbow osteoarthritis, therefore they conclude that olecranon fractures during growth have an excellent long-term results (18).

In four studies of our review associated lesions are reported, most of them are radial head fractures that can affect the final result (3, 14).

In conclusion, based on our review, displaced olecranon fractures occurring during skeletal growth surgically treated with various techniques generally have good results, although we are unable to recommend the best surgical treatment to perform. However, we believe that since they are intra-articular fractures in the majority of cases, the overall goal is to get an anatomic reduction that in some cases cannot be obtained using a percutaneous technique. Regarding the devices, tension band suture is preferred but remains contraindicated in adolescence for the high risk of fixation failure. Associated lesions may affect the final result.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Author contributions

FM: data collection, manuscript preparation, data analysis. GG: study conception and design, data collection, manuscript preparation and editing. AC: data analysis, manuscript preparation. CL: data collection, manuscript preparation. DC: data collection, manuscript preparation. PF: study conception and design, manuscript preparation and editing, analysis and interpretation of data. All authors contributed to the article and approved the submitted version.

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Reconstruction of the coronoid process with the olecranon tip for chronic elbow dislocation in children: A rare case report and literature review

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The coronoid process of the ulna, as a key part of the elbow joint, plays an important role in maintaining elbow joint stability. Reconstruction of the coronoid process is necessary in both acute and chronic coronoid defects to restore elbow stability and avoid early joint degeneration. The olecranon tip may be a useful autologous osteochondral graft for reconstructing the same shape of the ulna coronoid process. The purpose of this report was to verify if reconstruction of the coronoid process with the olecranon tip can restore elbow stability and kinematics. Here, we report a 13-year-old boy who had undergone Kirschner-wire fixation for a left supracondylar fracture of the left humerus 9 years previously. After that, the right elbow dislocation and varus deformity gradually appeared. Imaging revealed posterolateral dislocation of the left elbow due to the absence of the coronoid process of the ulna. We reconstructed the ulnar coronoid process by intercepting the ipsilateral olecranon tip. After 22 months of follow-up, the range of motion of the left elbow joint was normal, and the cubitus varus deformity disappeared. The results of this report suggest that olecranon tip autografts are suitable to replace transverse coronoid defects. Given the patient's satisfactory clinical results, this reconstruction technique is safe and effective for the treatment of chronic elbow instability due to coronoid process defects of the ulna.

KEYWORDS

coronoid process, olecranon tip, reconstruction, children, case report

Introduction

The coronoid process of the ulna plays a vital role in the stability of the elbow joint. As the primary osseous structure is related to the stability of the posterior elbow joint, the coronoid process not only resists the stress of the biceps, brachialis, and triceps brachii from the ulna to move backwards during flexion and extension (1–3), but also maintains the axial stability of the elbow joint and the stability of the posteromedial and posterolateral rotation (4, 5). In addition, it can prevent the occurrence of elbow varus and valgus (6, 7). In addition to these important functions related to bone structure, the coronoid process also provides attachment sites for multiple soft tissues (1). Therefore, coronoid defects of the ulna can cause not only acute and chronic joint instability, but also soft tissue instability (8, 9), which leads to posterior or recurrent dislocations of the elbow followed by rapid degeneration to posttraumatic arthritis (5, 10, 11). This shows that the coronoid process of the ulna is the main stabilizer of the elbow, and without proper treatment, it often leads to adverse outcomes (10).

In general, open reduction and internal fixation with the lateral collateral ligament and possible medial collateral ligament repair are recommended for coronoid fracture (12). However, severe comminution coronoid fractures or old coronoid defects are difficult to repair directly, and coronoid reconstruction is required to restore elbow stability (1, 13). Old coronoid process defects cannot be repaired with residual bone tissue due to bone resorption at the fracture site, resulting in elbow dislocation, traumatic arthritis, residual cubital varus deformity, and inability to perform open reduction and internal fixation of the coronoid process (5). Therefore, coronoid reconstruction or replacement is required to restore elbow stability (14).

An ideal reconstruction material should have an articular cartilage surface that matches the elbow and a radius of curvature similar to that of the natural intact coronoid process to achieve a high healing success rate (1). Therefore, we selected the ipsilateral olecranon tip as the reconstruction material. The tip of the olecranon is an intra-articular structure covered by articular cartilage, providing the advantage of an autogenous osteochondral graft that is anatomically similar to the coronoid process (10). Moreover, appropriate removal of the olecranon tip has only a slight effect on joint stability (15). In addition, the olecranon is located adjacent to the surgical site, thus reducing concerns regarding donor site morbidity at different sites (16).

In previous studies, only Moritomo et al. (17) described two adult patients who underwent reconstruction of the coronoid process using the ipsilateral olecranon tip. However, detailed clinical parameters and osteotomy procedures for coronoid and olecranon donors have not been provided. Additionally, there are some biomechanical studies on olecranon reconstruction of coronoid processes *in vitro*, but none have been proven clinically (10, 12, 18, 19). Our case report provides detailed evidence that olecranon tip reconstruction of an ulnar coronoid defect shows good long-term healing results in children.

Case presentation

Chief complaints and physical examinations

A 13-year-old boy had a supracondylar fracture of the left humerus due to trauma 9 years ago, and underwent Kirschner-wire internal fixation in another hospital. As detailed imaging data have been lost, the patient's parents are unable to provide us. After that, the right elbow dislocation and varus deformity gradually appeared. Physical examination revealed a 10 cm longitudinal scar on the left elbow. Obvious osterior dislocation of the left elbow was observed in the extension position, with an obvious varus deformity. Automatic reduction was observed in the flexion position. See **Supplementary Material 1**.

Imaging examinations and final diagnosis

Radiography and three-dimensional computed tomography (CT) revealed partial absence of the coronoid process of the left ulna. The left distal humerus was displaced anteriorly and downward, and there was no bone fracture in the left elbow. The magnetic resonance imaging (MRI) of the left elbow showed posterolateral dislocation of the left elbow and there was no injury in medial collateral ligament and lateral collateral ligament, as shown in **Figure 1**. Combined with the patient's physical and imaging findings, we made a final diagnosis of posterior dislocation and varus deformity of the left elbow.

Treatment

Based on the patient's physical examination and imaging findings, an ipsilateral olecranon osteotomy for reconstruction of the coronoid process of the ulna was performed to treat elbow dislocation. The skin, subcutaneous tissue, and myofascial membrane were sequentially cut by making an anterior s-shaped incision of length 12.0 cm on the left elbow. The median nerve was exposed on the medial side of the biceps tendon and the left elbow joint capsule was opened. After full exposure, the left elbow joint coronoid process cartilage and a part of the bone were found missing. The length of the longitudinal surgical incision at the olecranon at the back of the left elbow was approximately 4 cm to fully expose the olecranon. The left olecranon tip of the left ulna, approximately 1.5 cm × 1 cm in size, was taken. After repair, it was implanted into the coronoid process defect. Two 1.0 g wires were used for temporary fixation, and the bone and cartilage of the ulnar coronoid process were well-reconstructed. Then, a suitable T-shaped plate was placed, and the locking screws were screwed for fixation. C-arm fluoroscopy revealed that the internal fixator was in a good position. Reconstruction of the coronoid process was stable, and the elbow joint was not dislocated. Finally, the two 1.0 g wires were removed. The anterior and posterior surgical incisions of the left elbow were sutured layer-by-layer, and the left elbow was externally fixed with plaster. The total operative time was 3 h. After 6 weeks, the cast was removed, and elbow movement gradually restored.

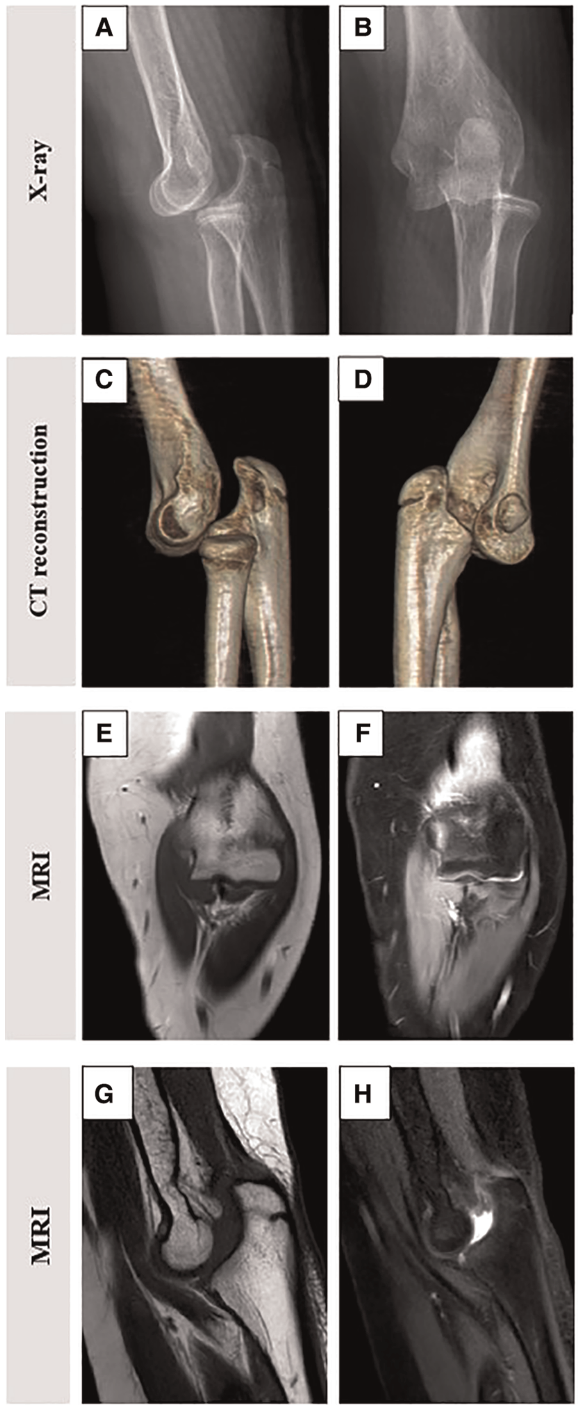

FIGURE 1
Preoperative imaging showing posterolateral dislocation of the left elbow. (A,B) Radiographs show anteriorly inferior slippage of the distal humerus without fracture; (C,D) Three-dimensional computed tomography shows a transverse defect of the coronoid process of the ulna, (E,F) The MRI of left elbow shows no injury of medial collateral ligament and lateral collateral ligament. (G,H) The MRI of left elbow shows posterolateral dislocation.

Outcome and follow-up

The height of the coronoid process of the healthy and affected sides and the osteotomy angle of the olecranon tip were measured postoperatively according to previously used *in vitro* biomechanical analysis methods (10, 12). Measurements showed a preoperative height defect of 12.5% of the coronoid process, and the height of the reconstructed coronoid was 1.2 times that of the unimpaired side (**Figures 2A–C**). We also measured the angle of the olecranon tip, which was 52.1° (**Figures 2D**). At the 10th month follow-up, radiography and three-dimensional CT results of the left elbow showed that the internal fixation device was in a good position without complications, such as displacement and fracture, and there were no manifestations of osteoarthritis changes or graft absorption, as shown in **Figure 3**. After 22 months of follow-up, the patient had a symmetrical range of motion in both elbow joints with no residual dysfunction, as shown in **Figure 4**.

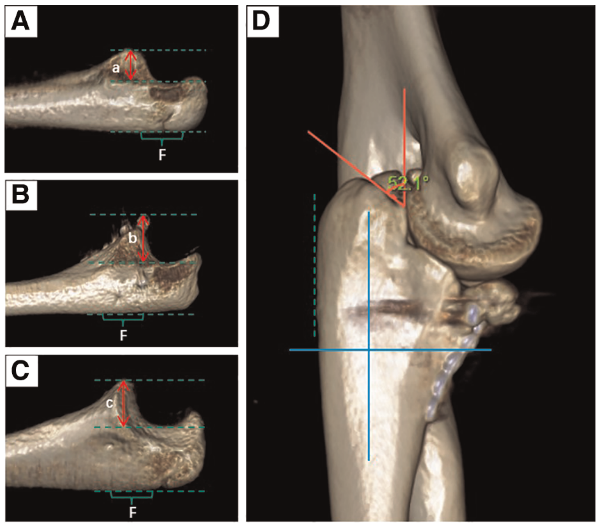

FIGURE 2
Parameters of the coronoid process of the ulna and the tip of the olecranon. (A) represents the height of the coronoid process of the ipsilateral ulna preoperatively; (B) represents the height of the coronoid process of the ipsilateral ulna postoperatively; (C) represents the height of the unaffected coronoid process; (D) shows that the osteotomy angle of the olecranon is about 52.1°. ($a/c = 0.875$, $b/c = 1.2$). *F* is a flat spot in the proximal ulna. The three dashed lines represent the highest point of the coronoid process of the ulna, the lowest point of the sigmoid notch, and the level of the flat spot (green lines). The 0° angle runs parallel to the flat spot of the corresponding olecranon, and is defined by the constructed coordinate system (blue lines).

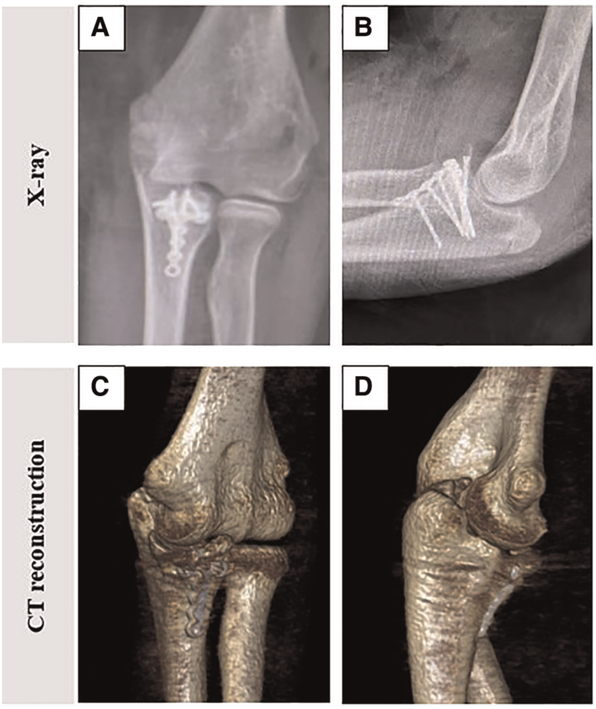

FIGURE 3
Postoperative imaging showed Normal recovery of the left elbow dislocation. (A,B) Radiographs show that the internal fixation device is in good position; (C,D) Three-dimensional computed tomography showed no arthritic or graft absorption of the elbow.

Discussion

The first step in the treatment of elbow instability with coronoid process fracture is to determine whether elbow instability is caused by the injury. If the coronoid process is determined to be the cause, caution should be exercised in the treatment of elbow instability with reconstruction. According to previous literature, the indications for coronoid reconstruction surgery can be summarized as follows (13, 20–23): (1) Regan–Morrey or O'Driscoll type III fresh comminuted fractures, (2) old coronoid fractures, and (3) elbow instability after surgical or non-surgical treatment.

Previous studies have shown that autografts of the radial head, distal clavicle, costal cartilage, iliac crest cortex, and fibula can be used to reconstruct the coronal processes of the ulna. However, different materials have diverse advantages, disadvantages, or limitations (13). For example, complications such as ectopic ossification and unstable elbow joints can easily occur after radial head surgery (24). Poor homogeneity of the iliac crest cortical bone and lack of cartilage on the surface of the iliac crest increases the incidence of postoperative arthritis (25). Autografts of the distal clavicle may not be able to completely reconstruct the anterolateral and anteromedial coronal processes, and are not suitable for the reconstruction of large defects in these specific areas (14). There is also a degree of donor-site morbidity, with unpredictable outcomes. With the development of prosthetic materials and techniques, there has been progress in the application of prostheses for coronoid reconstruction. In 2017, Bellato and O'Driscoll (21) performed coronoid reconstruction in three cases using a non-anatomical metal prosthesis for the first time. After long-term follow-up, the range of motion of the elbow joint improved to varying degrees, and the position of the coronoid prosthesis remained fixed. However, they also acknowledge the disadvantage of using prostheses to reconstruct the coronoid process, as anatomical consistency requires more complex designs and a potentially wider range of size and shape choices. It is important to determine the most important aspects of the coronoid shape to mimic. However, they can be too expensive, making surgery unaffordable for most patients.

To date, the most studied reconstruction material has been the tip of the olecranon. In clinical application, Moritomo et al. first reported two cases using the ipsilateral olecranon tip to reconstruct the coronoid for the treatment of elbow dislocation, but both were applicable to adults, and did not provide detailed measurement parameters of the coronoid and olecranon (17). In an *in vitro* mechanical analysis, Kataoka et al. (12) used *in vitro* biomechanical studies in a cadaveric model to determine whether reconstruction of the coronoid process using the tip of the ipsilateral olecranon would restore the baseline kinematics of the coronoid-deficient elbow. They demonstrated that 40% of transverse coronoid defects caused major changes in the kinematics of the elbow in varus orientation. Simultaneously, a part of the olecranon tip was intercepted for reconstruction, and the distance from the olecranon tip was equal to 40% of the coronoid process height. The results show that this technique can effectively restore the range of motion of the elbow from 20° to 120°, which may be beneficial for patients with elbow instability due to non-reconstructive comminuted coronoid fractures or non-unions. In addition, they demonstrated that resection of no more than 20% to 25% of the olecranon tip did not result in substantial changes in elbow kinematics. Therefore, they believe that the olecranon tip is the most suitable material for coronoid reconstruction. Bell et al. (26) performed a biomechanical study using fresh frozen elbow samples to assess the effect of olecranon on elbow stability. They found that 50% resection of the olecranon had no significant effect on elbow stability, including varus, valgus, and rotation, which was a conclusion consistent with that obtained by An et al. (27).

In 2015, Ramirez et al. (15) used the tip of the olecranon to reconstruct the coronoid process of the ulna. In *in vitro* mechanical analysis, it was found that not only did the olecranon graft provide a continuous osteochondral articular

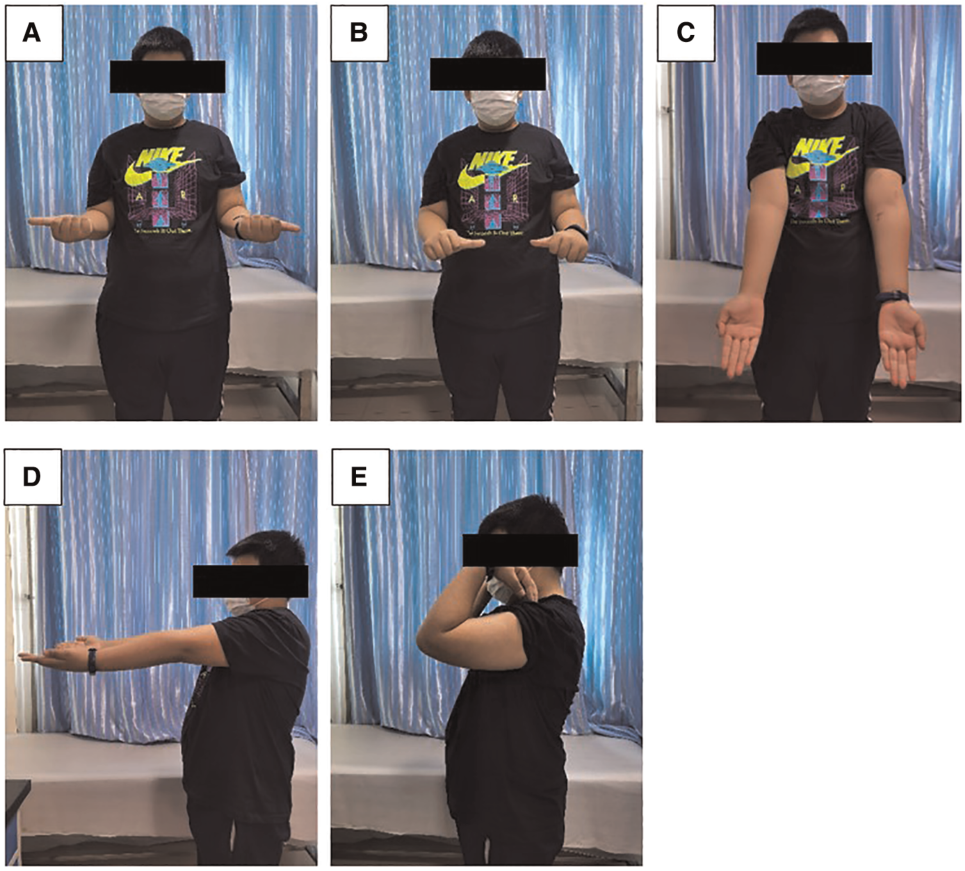

FIGURE 4
After 22 months of follow-up, the functional range of motion of the patient's upper limbs was symmetrical. (A) External rotation; (B) Internal rotation; (C) Extension (front view); (D) Extension (side view); (E) Flexion (side view).

surface in all specimens, but that the bone remodeling prior to loading did not impede the range of motion of the elbow in any specimen. No significant graft displacement or rotation was observed during testing. Statistical analysis before and after reconstruction revealed that at 15°, 45°, 75°, 90°, and 105° elbow flexion, autogenous bone olecranon tip transfer restored the stability of the back of the elbow to a level that was not significantly different from that of the intact elbow. However, they acknowledge that this biomechanical study was based only on an isolated coronoid fracture model, and did not replicate the dreaded triad injury with collateral ligament and radial head injuries. Kataoka (19) analyzed the 3D morphological features of three autologous osteochondral grafts for coronoid reconstruction: the tip of the olecranon, lateral radial head, and proximal radial head. The results showed that the coverage of the olecranon graft was significantly higher than that of the lateral and proximal radial head grafts, probably because the olecranon and coronoid tips are convex in the coronal plane. Olecranon grafts are best suited for coronoid defects, including the tips. In addition, reconstruction of 50% of the coronoid height with an olecranon graft does not use enough ulnar articular surface, nor does it raise concerns about the severe instability of the elbow.

To further determine the shape matching between the ipsilateral and contralateral olecranon tips for graft selection, as well as determine the effect of osteotomy angle on reconstruction, Wegman (10) designed six angles ranging from 10° to 60° in a coronoid process model with a 40% height defect. The results showed that the olecranon tip showed a better shape match to the natural coronoid process when osteotomy was performed at a higher angle (especially at 50°). Simultaneously, the shape match of the contralateral olecranon tip was significantly greater than that of the ipsilateral olecranon tip graft.

Besides, the related ligamentous structures of the elbow joint play an indispensable and important role in its stabilization system. The maintenance of lateral stability of the elbow joint mainly depends on the collateral ligaments, including medial collateral ligament complex (MCLC) and lateral collateral ligament complex (LCLC) (28). The lateral ulnar collateral ligament (LUCL) is considered to be the portion of the lateral collateral ligament playing the most important stabilizing role, can effectively resist the posterolateral rotation of the elbow joint (2). In our case report, none of the imaging findings showed damage to the ligaments or joint capsule, only the defect of the coronoid process of the ulna resulted in the patient's posterolateral dislocation of the elbow.

Despite the positive clinical results in this case report, there are still many limitations. Including the following aspects: (1) more clinical cases are needed to confirm the effectiveness of this procedure; and (2) the patients had chronic ulnar coronoid process defects, which did not involve the medial and lateral collateral ligaments. Therefore, we could not evaluate the therapeutic effects of this method for ligaments. In summary, a multicenter trial with a large sample size should be established.

In conclusion, a method of olecranon tip osteotomy for the reconstruction of the coronoid process of the ulna for chronic dislocation of the elbow joint has been reported. There was no iatrogenic vascular or nerve injury, and the elbow was restored to its normal range of motion. Radiographic results showed good elbow position, no graft dislocation, no osteoarthritic changes, and no radiological evidence of graft absorption. Therefore, this is a safe and effective method for treating chronic dislocation of the elbow caused by a defect in the coronoid process of the ulna in children.

Data availability statement

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

YJ and LQ reviewed the literature and contributed to manuscript drafting. CP, QL and PZ reviewed the figures. YW and DW made critical revisions related to important intellectual content and analyzed and interpreted the imaging findings. All authors approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fped.2022.977866/full#supplementary-material.

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The diagnosis and treatment of a special rare type of Monteggia equivalent fractures in children

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Purpose: To explore the characteristics, mechanism, treatment, and prognosis of head–neck separation type of Monteggia equivalent fractures in children.
Methods: Patients with this injury were reviewed retrospectively. The lesion was characterized by a fracture of the ulnar with radial neck fracture but without dislocation of the radial head. Our classification was based on the direction of displacement and angulation of fractures on radiographs, divided into the extension-valgus type and flexion-varus type. The fractures were treated with reduction and internal fixation, depending on the fracture type. The clinical results were evaluated by using radiology and the Mayo Elbow Performance Score (MEPS).
Results: A total of 12 patients were followed up for an average of 40.5 months. The ulnar fractures were treated with closed reduction (CR) and K-wire fixation in one patient, elastic stable intramedullary nail (ESIN) fixation in four patients, open reduction (OR) and plate fixation in five, with no fixation in two. CR with ESIN fixation was successful in 11 patients with radial neck fractures, but one underwent OR and K-wire fixation. All fractures healed on time, with fewer complications (avascular necrosis in one patient, and bulk formation of metaphysis in another). The therapeutic efficacy was evaluated by using MEPS and was found to be excellent in 10 patients, good in one, and fair in another.
Conclusions: The head–neck separation type of Monteggia equivalent fractures in children is rare. Its characteristics are different from that of Monteggia fracture. The length and anatomic structure of the ulna should be restored and stabilized first, while the radial neck fracture should be treated with CR and ESIN fixation. Satisfactory clinical results can be achieved with fewer complications.

KEYWORDS
Monteggia equivalent, radial neck, fixation, children, diagnosis and treatment

1. Introduction

Monteggia fracture, named after Giovanni Monteggia in 1814, and well-described and classified by Dr. Bado in 1967 (1), involves ulnar fracture and a concomitant dislocation of the radial head. The term "lesion" has gradually superseded those such as "fracture," "fracture–dislocation," or "injury" in the literature, stressing the importance of noticing the radiocapitellar joint and reflecting an increased awareness of the complexity regarding its

Abbreviations
MEPS, Mayo Elbow Performance Score; M, male; F, female; CR, closed reduction; OR, open reduction; ESIN, elastic stable intramedullary nail.

manifestation and mechanism among orthopedists. The groups of “Monteggia equivalent lesion/variant” have considerably expanded after decades of reports of sporadic cases, apart from the established four types proposed by Bado (1). The boundary of that definition has blurred to a great extent. Also, especially in pediatric patients, when immature radiocapitellar epiphysis interferes with judgment and the flexible joint allows more frequent subluxation, a large number of these types tend to be misdiagnosed or neglected because of the occult presentation of the radiocapitellar joint or plastic bowing ulna on radiographs. The Monteggia equivalent fractures proposed by Bado (1) refer to injuries that share similar mechanisms, imaging manifestations, and treatment principles with Monteggia fractures, mainly including Bado type I and type II. However, most of the Monteggia equivalent fractures do not lead to a separation of the proximal radioulnar joint, which is the main difference between Monteggia fractures and Monteggia equivalent fractures. This article aims to describe a special rare type of Monteggia equivalent fractures in children, called head–neck separation type. At present, there are only three case reports on this injury in children (2–4), with no understanding and research on its characteristics or treatment principles. Here, we reviewed 12 patients, the maximum number of such cases at present, diagnosed as a head–neck separation type of Monteggia equivalent fracture in our department from March 2016 to February 2019. By summarizing and analyzing the clinical characteristics, treatment, and prognosis, we hope that our effort will have clinical significance and prevent the risks of misdiagnosis and improper treatment and also enhance the understanding of the concept and clinical classification of Monteggia equivalent fractures in children.

2. Materials and methods

2.1. Ethical consideration

This study was approved by the Ethics Committee of Hong Hui hospital, Xi’an Jiaotong University. All guardians of the minors provided written informed consent prior to participation in the study. All methods were carried out in accordance with relevant guidelines and regulations (Declaration of Helsinki).

2.2. Patient selection

Inclusion criteria: (1) children aged 0–15 years; (2) children with a fracture of the ulnar diaphysis or metaphysis; (3) children with a separated fracture of the radial neck without dislocation of the radial head; and (4) children that could be followed up completely.

Exclusion criteria: (1) older than 15 years; (2) multiple fractures; (3) open fractures; (4) children needing surgical exploration because of neurovascular injuries; and (5) incomplete clinical data.

A total of 12 patients who were examined and treated in our department for head–neck separation type of Monteggia equivalent fractures from March 2016 to February 2019 were identified, and their medical records and radiographs were reviewed retrospectively. There were eight boys and four girls with an average age of 8.3 years (range, 3–14 years). The left, non-dominant limb was involved in nine patients, and the right, dominant extremity was involved in three. The causes of injury were falling from a scooter (six patients), falling from horizontal bars (three), a traffic accident (two), and falling from a cycle (one). All fractures were closed, with a mean time of 9.2 h (range, 2–24 h) from injury to consultation.

The clinical manifestations were significant pain with a deformity of the forearm and significant swelling. Physical examination showed that one of the patients could not bend and stretch the elbow actively, with limited movement due to pain. The skin was intact, and the passive finger-pulling pain was negative, but there was a radial nerve injury in one patient.

By analyzing and summarizing these patient cases, we based our classification on the direction of displacement and angulation of fractures on radiographs. Seven cases belonged to the extension-valgus type with an ulnar fracture with volar ulnar angulation, plus radial neck fracture with a volar ulnar displacement of the distal end (**Figure 1**). Five cases were classified as the flexion-varus type with an ulnar fracture with radial dorsal angulation, plus radial neck fracture with radial dorsal displacement of the distal end (**Figure 2**).

According to the ulnar fracture sites, there were three patients with a metaphysis fracture (one case of the extension-valgus type and two of the flexion-varus type), seven patients with a proximal third ulnar fracture (five cases of the extension-valgus type, and two of the flexion-varus type), and two patients with a middle third ulnar fracture (one case of the extension-valgus type and one of the flexion-varus type). All the ulna metaphysis fractures were greenstick, with little displacement in one patient and obvious displacement and longitudinal splitting in two others. The angulation of the proximal and middle third ulna fractures was obvious, characterized by oblique fractures (six cases of short oblique and three cases of long oblique), with some fractures accompanied by vertical splitting at the proximal end. All the radial neck fractures were located in the metaphysis, without involving the proximal epiphysis and epiphyseal plate, and at the same time, all the proximal radioulnar joints were normal. This was in total contrast to the traditional radial neck fracture and Monteggia fracture.

FIGURE 1
Extension-valgus type, an ulnar fracture with volar ulnar angulation plus a radial neck fracture with a volar ulnar displacement of the distal end.

FIGURE 2
Flexion-varus type, an ulnar fracture with radial dorsal angulation plus a radial neck fracture with a radial dorsal displacement of the distal end.

2.3. Operative technique

All patients were treated with closed reduction (CR) and plaster immobilization in the emergency room. Then, operation was performed on a radiolucent table after the induction of general anesthesia. The length of the ulna should be restored and stabilized according to the treatment principle of Monteggia fracture, and fixation techniques should depend on the location and type of ulna fracture. (1) For metaphysis fractures, patients with little displacement were left untreated or only manual reduction was done, while those with obvious displacement were fixed with smooth K-wires after reduction. (2) For proximal third ulna fractures, if the fracture was a short oblique fracture without longitudinal splitting, fixation was performed using an elastic stable intramedullary nail (ESIN). Generally, the diameter of the nail is approximately two-third of the isthmus diameter of the ulnar bone marrow, and it should be pre-bent into a C shape. (3) For long oblique fractures, open reduction (OR) and plate fixation were performed by using the posterior median approach. (4) For radial neck fractures, CR and retrograde ESIN fixation were performed with minimally invasive technology, and the tip of the nail was made to pass through the epiphyseal growth plate. If CR ended in failure in some instances, OR and smooth K-wire fixation was performed by adopting the anterior elbow Henry approach. After surgery, the arm was fixed in long arm plaster in a neutral position with 90° elbow flexion.

2.4. Assessments

Patients returned for a follow-up examination and radiographic evaluation under a protocol approved by the Ethics Committee. Anteroposterior and lateral radiographs of the entire ulna and radius were obtained to assess bony union, dislocation, ischemic necrosis of the radial head, early closure of the epiphysis, and heterotopic ossification. Clinical examination included an assessment of the rotation function and range of motion. When the x-ray shows a continuous callus passing through the fracture line, the plaster can be removed and functional exercise started under the doctor's guidance. As long as the fracture meets the clinical healing standard, the K-wires can be removed. For the ESIN and plate, the internal fixation can be removed only when an x-ray shows that the fracture line has disappeared completely and the medullary cavity is reopened. The therapeutic efficacy was evaluated at the final follow-up by using the Mayo Elbow Performance Score (MEPS) (5, 6).

3. Results

The 12 patients were followed up for 24–58 months (average, 40.5 months). The ulnar fractures were treated with CR and K-wire fixation in one patient, ESIN in four patients, OR and plate fixation in five, with no fixation in two. CR and ESIN proved successful in 11 patients with radial neck fracture, but one underwent OR and K-wire fixation (details in **Table 1**). All fractures healed on time without delayed union or non-union. Radial nerve injury occurred in one patient, and this patient recovered completely 3 months later. Avascular necrosis occurred in one patient and the bulk form of the proximal metaphysis manifested in another patient. The therapeutic efficacy was evaluated by using the MEPS, and it was found to be excellent in 10 patients, good in one, and fair in another.

4. Discussion

Monteggia fractures are rare injuries in children, accounting for only 5% of elbow fractures, mainly occurring in approximately 4- to 10-year olds (7). The Monteggia equivalent fractures proposed by Bado (1) refer to injuries that share similar mechanisms, imaging manifestations, and treatment principles with Monteggia fractures, mainly including Bado type I and type II, most of which do not lead to a separation of the proximal radioulnar joint, which is the main difference between the two fracture types. Five groups of type I equivalents were described: (Ia) anterior dislocation of the radial head; (Ib) fracture of the ulnar diaphysis with a fracture of the neck of the radius; (Ic) fracture of the neck of the radius; (Id) fracture of the ulnar diaphysis with a fracture of the proximal third of the radius; and (Ie) fracture of the ulnar diaphysis with an anterior dislocation of the radial head and a fracture of the olecranon. Type II equivalents were described: posterior radiocapitellar joint dislocation associated with epiphysis or radial neck fracture. The concept of "equivalent" for the pediatric population continued to evolve as further elucidation came from two study groups separately. Letts et al. (8) stressed the importance of noticing the anterior bend or greenstick of an immature ulnar and the subsequent dislocation or subluxation of the radiocapitellar joint in a pediatric Monteggia lesion. Letts and his colleagues took these occasions into the expanded equivalent lesions. Wiley and Galey (9) raised

TABLE 1 The details of patients and treatment results.

Case	Gender	Age	Type	Location of ulnar fracture	Location of radial neck fracture	Treatment of ulnar fracture	Treatment of radial neck fracture	Total follow-up (months)	Complication	MEPS
1	F	3	Extension-valgus	Proximal third	Metaphysis	CR + ESIN	CR + ESIN	36	No	Excellent
2	F	4	Extension-valgus	Proximal third	Metaphysis	CR + ESIN	CR + ESIN	42	No	Excellent
3	M	12	Extension-valgus	Middle third	Metaphysis	OR + Plate	CR + ESIN	54	No	Excellent
4	M	9	Flexion-varus	Proximal third	Metaphysis	OR + Plate	CR + ESIN	58	No	Excellent
5	F	4	Extension-valgus	Proximal third	Metaphysis	CR + ESIN	CR + ESIN	48	No	Excellent
6	F	5	Flexion-varus	Metaphysis	Metaphysis	No Treatment	CR + ESIN	36	No	Excellent
7	M	6	Extension-valgus	Metaphysis	Metaphysis	CR + K-wires	OR + K-wires	24	Avascular necrosis	Fair
8	F	8	Flexion-varus	Metaphysis	Metaphysis	CR	CR + ESIN	38	Bulk formation of proximal metaphysis	Good
9	M	12	Flexion-varus	Proximal third	Metaphysis	OR + Plate	CR + ESIN	46	No	Excellent
10	M	6	Extension-valgus	Middle third	Metaphysis	CR + ESIN	CR + ESIN	24	No	Excellent
11	M	7	Extension-valgus	Proximal third	Metaphysis	OR + Plate	CR + ESIN	50	No	Excellent
12	M	10	Flexion-varus	Proximal third	Metaphysis	OR + Plate	CR + ESIN	30	No	Excellent

CR, closed reduction; OR, open reduction; ESIN, elastic stable intramedullary nail.

specific concerns on the olecranon and proximal ulnar fracture–related radiocapitellar joint issues. The authors suggested including the three scenarios in type I–III pediatric Monteggia equivalent lesions, respectively. Olney and Menelaus (10) and Čepelík et al. (11) proposed a classification based on the status of the radiocapitellar joint, as follows: group I: anterior ulnar plastic deformity combined with radial neck fracture and anterior radiocapitellar joint dislocation, group II: ulnar fracture associated with posterior radial neck fracture and posterior radiocapitellar joint dislocation, and group III: ulnar shaft fracture associated with a radial neck fracture. However, there are still disputes about the above classifications. Of course, with the increasing number of reported cases, some authors attempt to redefine or revise the concept and clinical classification of Monteggia equivalent fracture.

In our patients in this study, this special type of Monteggia equivalent fracture was characterized by an ulna fracture, located in the middle and above (metaphysis, proximal third, middle third), most of which had obvious angulation. The accompanying radial neck fractures were located in the metaphysis, without involving the epiphysis and epiphyseal plate. This was in total contrast to the traditional radial neck fracture. In addition, the lesion was characterized by a separated fracture of the radial neck with no dislocation of the radial head. A line appeared through the longitudinal axis of the radius off the center of the capitellum, but with an intact annular ligament and normal radiocapitellar line, which was different from the Monteggia fracture. This type of injury is very rare, perhaps caused by a relative relaxation of the annular ligament in children, so we called it "head-neck separation type." The relevant literature is very rare, and all are case reports, so we reported a total of 12 cases, the largest number to date.

Our classification was based on the direction of displacement and angulation of fractures on radiographs, including the extension-valgus type and flexion-varus type. We concluded that the characteristic of the extension-valgus type was an ulnar fracture with volar ulnar angulation plus a radial neck fracture with a volar ulnar displacement of the distal end, which was similar to the mechanism of type I Monteggia fracture. When falling is supported by the palm, the forearm is in the extension supination position, and the stress is transmitted upward along the forearm. The radial neck fracture is first caused by the vertical and valgus stress. The strong contraction of the biceps muscle caused by elbow hyperextension makes the distal end of the radial fracture at the attachment point shift to the proximal and volar side, resulting in a complete separation of the head and neck. The stress of hyperextension and valgus continues to transmit, resulting in an ulna fracture with volar ulnar angulation. However, the flexion-varus type is opposite to the former, with angulation and displacement direction of the fracture point to the radial dorsal side. The injury mechanism is similar to type II Monteggia fracture. When falling is supported by the palm, the elbow is in a semiflexion position and pronation position, resulting in an ulnar fracture under the combined action of axial and varus stresses. At the same time, the proximal radius strikes the capitulum of the humerus, resulting in a radial neck fracture, while the proximal end of the radial neck fracture is located in the joint capsule, and the distal end of the fracture point is on the radial dorsal side. In our report, seven cases belonged to the extension-valgus type, and five cases were classified as the flexion-varus type. Compared with the three cases reported in the previous literature, all of them were of the extension-valgus type.

The majority of fresh Monteggia fractures in children can yield satisfactory results by performing CR and plaster immobilization. In contrast, most Monteggia equivalent fractures in children require surgical treatment; otherwise, the prognosis is considered poor (12, 13). Anatomic reduction of the proximal radius is essential for its function. However, if the reduction is unsatisfactory or redisplaced, the prognosis would be affected, and therefore, surgical treatment is recommended (12, 13). In our patients in this study, if CR and plaster immobilization are performed for extension-valgus-type fractures, the forearm needs to be fixed in the position of supination with extreme elbow flexion (100–110°). The greater the flexion angle is, the more stable the reduction will be, but this will increase the risk of forearm osteofascial compartment syndrome. For flexion-varus-type fractures, elbow extension with plaster fixation is required, which obviously limits daily life activities combined with the inconveniences resulting from nursing. At the same time, the fracture may be displaced again. Therefore, all patients were treated surgically in our department.

The treatment principle is similar to that for Monteggia fracture. First, restore and stabilize the length of the ulna and then deal with the radial neck fracture. In this report, one patient with ulna metaphysis fracture with little displacement did not require treatment, one patient with greenstick fracture underwent manual reduction (**Figure 3**), and the rest underwent CR and K-wire fixation. For the proximal and middle third ulna fractures, ESIN is minimally invasive and does not require cutting of the fracture end; also there is no loss of blood supply and there are relatively few complications (14). It is suitable for short oblique fractures of the ulna, but the rate of stability is poor for long oblique fractures. In patients with proximal third ulna fractures, if the proximal end of the fracture has a longitudinal splitting and the proximal ulna has a relatively wide medullary cavity, the insertion point of the nail will be closer to the fracture line, which makes it difficult to achieve a three-point fixation and is not conducive to reduction and stability. In such patients, plate fixation may be more ideal. Therefore, in our seven patients with proximal third ulna fractures, four were treated with plate fixation and three with ESIN fixation. In two patients with middle third ulna fractures, one (short oblique type) was treated with CR and ESIN, and the other (long oblique type) was treated with OR and plate fixation (**Figure 4**).

Although the treatment of radial neck fractures remains controversial, most authors still prefer minimally invasive treatment. OR can lead to complications such as early closure of the proximal radius epiphysis, a long radial head, ischemic necrosis of the radial head epiphysis, and elbow dysfunction (15). According to a retrospective analysis by Basmajian et al. (16), the success rate of percutaneous minimally invasive treatment of radial neck fractures is 73%, while that of OR is only 35%. According to an analysis by Yilmaz, the MEPS in the Métaizeau technique group was 95.2, with excellent results in 15 patients (68%), good results in seven (31%), and fair or poor results in none of the patients, but the mean MEPS in the open reduction/K-wire group was 88, with excellent, good, fair, and poor results in nine (36%), 12 (48%), four (16%), and none of the patients, respectively (17). In our patients, after satisfactory reduction and fixation of the ulna fracture, we attempted to perform CR and a

FIGURE 3
A 5-year-old girl with a head–neck separation type of Monteggia equivalent fractures (flexion-varus type) (A–C). No treatment for ulna greenstick fracture, closed reduction with elastic intramedullary nail for radial neck fracture (D,E). The last follow-up was 3 years after surgery (F,G).

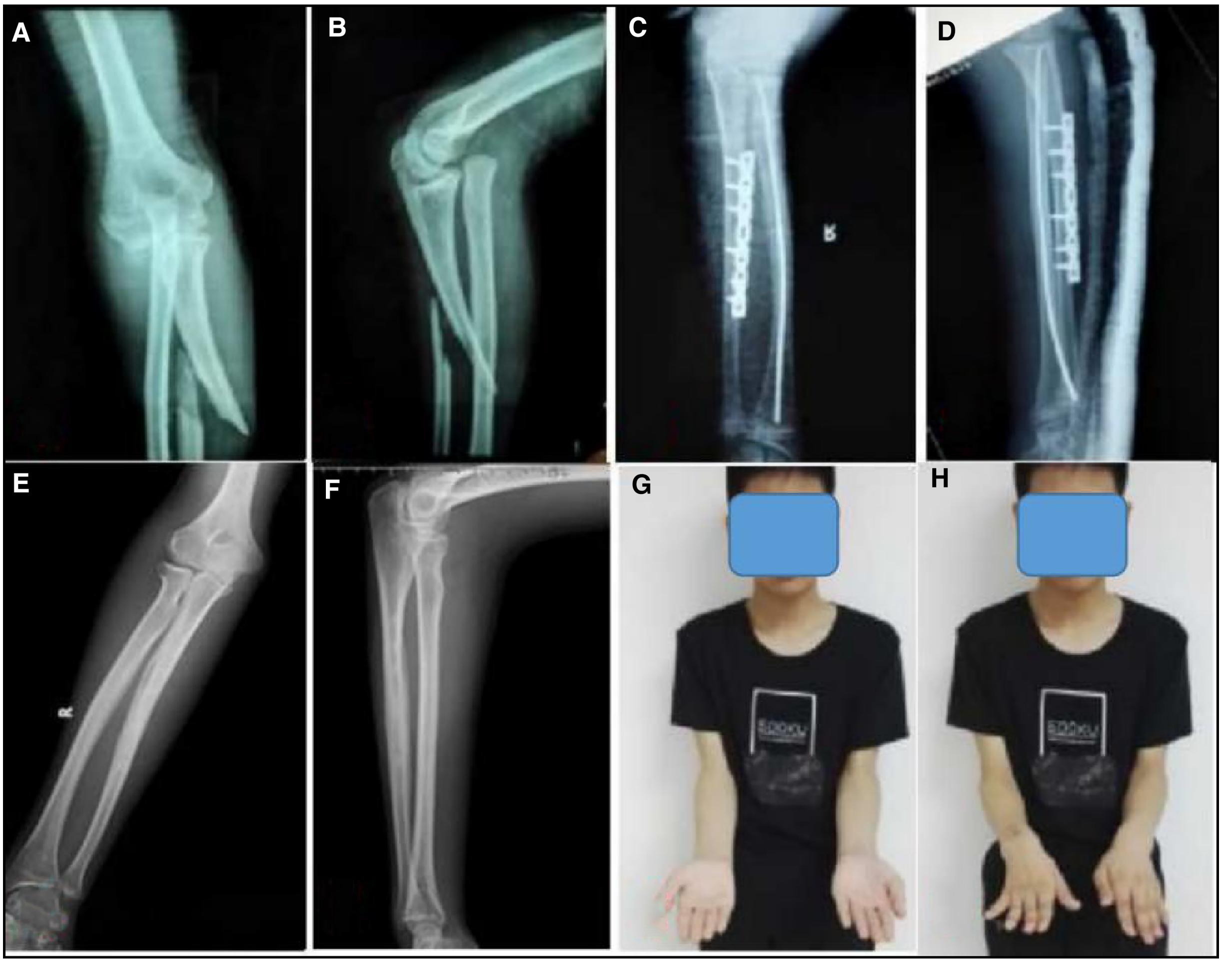

FIGURE 4
A 12-year-old boy with a head–neck separation type of Monteggia equivalent fractures (extension-valgus type) (**A,B**). OR and internal fixation with a bone plate for an ulna fracture and CR with ESIN for a radial neck fracture (**C,D**). The last follow-up was 4.5 years after surgery, which showed normal elbow movement and an excellent MEPS (**E–H**).

retrograde ESIN for radial neck fracture, and we succeeded in 11 patients. In order to avoid re-displacement, the tip of the nail was passed through the epiphyseal plate to increase stability. One patient underwent OR and K-wire fixation because of the failure of CR. During the operation, the fracture line was found to be located outside the joint capsule, with a separation of the head and neck and obvious displacement, but the proximal position of the fracture and proximal radioulnar joint were normal and the annular ligament was intact, which also confirmed our previous inference and injury mechanism. The therapeutic efficacy was evaluated at the final follow-up by using the MEPS and it was found to be excellent in 10 patients, good in one, and fair in another.

5. Limitations

There are several limitations in our study. First, this is a retrospective analysis, and the number of cases is small, and therefore, we were not able to carry out a statistical comparative analysis. In addition, the follow-up time of some patients was short, and as a consequence, whether there would be later development of complications is difficult to predict.

6. Conclusion

The head–neck separation type of Monteggia equivalent fractures in children is rare. Its clinical characteristics are different from those of Monteggia fracture and radial neck fracture. According to the location and type of ulna fracture, the length and anatomic position of the ulna should be restored and stabilized first, while the radial neck fracture should be treated with CR and ESIN fixation. Through such standard treatment and early functional exercise, satisfactory clinical results can be achieved.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of Hong Hui hospital, Xi'an Jiaotong University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s) and minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

Author contributions

QJ and BW designed the study, and modified and approved the final version of the manuscript. FS, ML, YM, YY, and YD wrote the first draft of the manuscript. XH, HJ, QL, CL, SY, and HW collected, analyzed, and interpreted the data. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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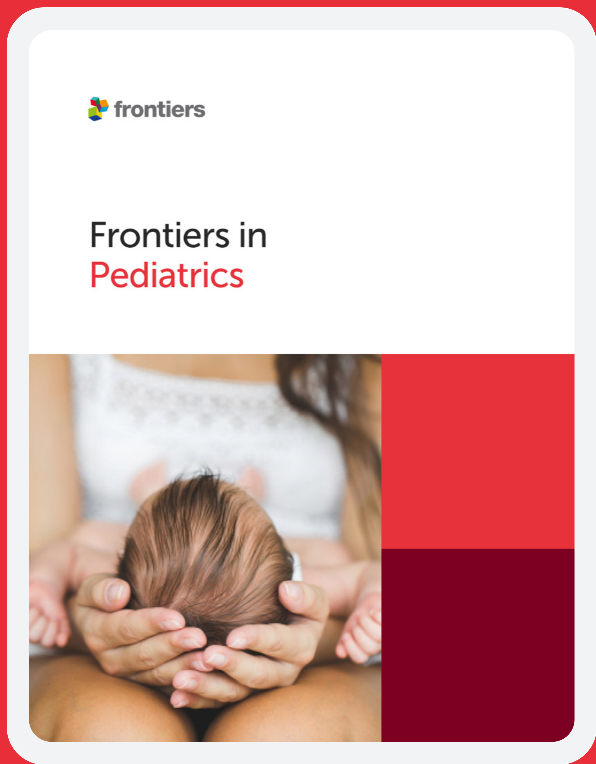

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