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Original Article

Efficacy of minimally invasive small-incision-assisted reduction with percutaneous Kirschner wire fixation in pediatric supracondylar humerus fractures

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Abstract: Objectives: To retrospectively evaluate whether minimally invasive small-incision-assisted reduction with percutaneous Kirschner wire fixation (MIAR-PKWF) provides superior clinical outcomes compared to conventional closed reduction with Kirschner wire fixation (CR-KWF) in pediatric supracondylar humerus fractures (SCHFs), focusing on surgical outcomes, postoperative recovery, and elbow joint function. Methods: A total of 100 pediatric SCHF cases were included and divided into either an observation group (MIAR-PKWF, n=55) or a control group (standard CR-KWF, n=45) based on their treatment approach. Outcome measures included operative time, recovery indicators, radiographic and serological parameters, elbow joint function, elbow range of motion, complications, and post-reduction swelling. Results: In comparison with the control group, the observation group exhibited significantly improved surgical outcomes, accelerated rehabilitation, and better elbow joint function and mobility, radiographic indices, and serological markers. Additionally, the observation group experienced fewer complications and milder post-reduction swelling. Conclusion: MIAR-PKWF is more effective in optimizing surgical outcomes, expediting postoperative rehabilitation, and improving elbow function in pediatric SCHF patients.

Keywords: Supracondylar humerus fractures in children, minimally invasive small incision-assisted reduction, percutaneous Kirschner wire fixation, surgical outcomes, elbow joint functionality

Introduction

Among pediatric elbow injuries, supracondylar humerus fractures (SHFs) are most frequently encountered, particularly in children aged 5-10 years [1, 2]. Accounting for approximately 15% of all pediatric fractures, these injuries predominantly result from falls onto an outstretched, hyperextended arm, causing posteromedial displacement of distal fracture fragments [3, 4]. Clinically, SHFs present with pain, swelling, restricted range of motion, and visible deformity. Inadequate or delayed management may result in severe complications like compartment syndrome and cubitus varus deformity [5]. Notably, surgical delays exceeding 12 hours are associated with increased open reduction rates, as exacerbated elbow swelling can complicate closed reduction [6]. Gartland classification system remains the standard for guiding treatment strategies. Type I-II SHFs are generally managed conservatively, whereas type III and IV fractures typically require surgical stabilization due to a higher risk of neurovascular injury, including damage to the anterior interosseous nerve and brachial artery [7, 8]. While favorable outcomes are commonly observed in most type I-II SHFs, type IV fractures, though rare, are clinically challenging owing to their inherent instability and complicated injury mechanisms. Moreover, optimal treatment of Gartland type III fractures remains a topic of ongoing debate among orthopedic specialists [9, 10]. This study aims to compare the clinical effectiveness of different surgical approaches for Gartland type III SHFs, with the goal of informing more effective clinical solutions.

Closed reduction with Kirschner wire (K-wire) fixation (CR-KWF) has become a mainstream

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Table 1. Comparison of baseline characteristics between the two groups

Indicators	Control group (n=45)	Observation group (n=55)	χ^2/t	P
Gender			0.201	0.654
Male	25 (55.56)	33 (60.00)		
Female	20 (44.44)	22 (40.00)		
Age (years)	6.51±2.20	6.33±2.15	0.412	0.681
Time from injury to surgery (h)	13.71±4.15	13.96±3.85	0.312	0.756
Body weight (kg)	25.91±7.88	27.05±6.56	0.790	0.432
Fracture type			0.117	0.732
Extension-ulnar deviation	22 (48.89)	25 (45.45)		
Extension-radial deviation	23 (51.11)	30 (54.55)		
Preoperative comorbidities			0.155	0.926
Nerve injury	12 (26.67)	15 (27.27)		
Median nerve injury	13 (28.89)	14 (25.45)		
Ulnar nerve injury	20 (44.44)	26 (47.27)		
Mechanism of injury			1.686	0.430
Fall from height	13 (28.89)	12 (21.82)		
Sports injury	25 (55.56)	29 (52.73)		
Traffic accident	7 (15.56)	14 (25.45)		

surgical approach for managing Bennett's fractures, osteoporotic Colles fractures, and SHFs, owing to its accurate fracture alignment, procedural efficiency, and reliable clinical outcomes. Studies have shown that CR-KWF facilitates effective bone healing and precise joint realignment in Bennett's fractures, while reducing pain and discomfort during movement [11-13]. In osteoporotic Colles fractures, CR-KWF has demonstrated clinical superiority over plate fixation, by reducing operative time and hospitalization durations as well as reducing intraoperative hemorrhage and costs [12]. Furthermore, in pediatric SHFs with median nerve impairment, CR-KWF has been reported to improve both life quality and neurological recovery [13].

In contrast, minimally invasive small-incision-assisted reduction with percutaneous Kirschner wire fixation (MIAR-PKWF) streamlines fracture management through a small incision, allowing direct visualization and real-time palpation to achieve optimal alignment and confirm reduction quality [14]. Nevertheless, as this approach involves skin and soft tissue incision, it inevitably causes some degree of tissue trauma [15].

This study comparatively analyzed MIAR-PKWF versus conventional CR-KWF in pediatric SHF management, with a particular focus on surgical outcomes, postoperative recovery, and elbow joint function. Given the limited clinical research in this area, our investigation seeks to bridge the existing knowledge gap and contribute to the development of an optimized surgical protocol for managing pediatric SHFs. For clarity, **Table 1** provides all abbreviations used throughout this manuscript.

Materials and methods

Research participants

This retrospective study was approved by the Ethics Committee of the Affiliated Children's Hospital of Jiangnan University (Wuxi Children's Hospital) and included 100 pediatric patients with SHF between December 2022 and December 2024. The control group (n=45) underwent conventional CR-KWF, while the observation group (n=55) received MIAR-PKWF. Baseline demographic and clinical characteristics were comparable between the two groups (P>0.05).

Eligibility criteria

Inclusion criteria: Age between 3 and 12 years; Radiographically confirmed Gartland type III SHFs [16]; Closed fractures; No prior treatment for the current fracture; Eligible for surgical intervention with no contraindications; No history of medications potentially affecting fracture healing within the preceding 3 months; Complete and accessible medical records; Sufficient cognitive and communication abilities; Compliance with the treatment protocols and follow-up.

Exclusion criteria: Concurrent fractures of the ulna, radius, or humeral shaft; Open fractures; Chronic or neglected SHFs; Epiphyseal fractures; Pathological fractures (e.g., due to tuberculosis, neoplasms, or metabolic bone disease such as osteoporosis); Concurrent infections.

Methods

The control group underwent CR-KWF. The detailed procedure was performed as follows: After achieving adequate traction and countertraction to correct bone overlap and rotational malalignment, manual fracture reduction was conducted. With the elbow joint in maximal flexion and satisfactory fracture alignment confirmed, the reduced position was carefully maintained. A standard 2.0 mm diameter K-wire was then inserted through the lateral humeral epicondyle at a 40°-45° angle relative to the longitudinal axis, penetrating the medial cortex of the proximal fracture segment. A second K-wire of the same specification was introduced from the medial epicondyle, crossing the fracture site proximal to the fracture line and penetrating the contralateral cortex. Upon confirmation of stable fracture fixation, the protruding wire ends were trimmed, bent, and secured with a sterile dressing. The elbow was immobilized at 90° flexion with the forearm in a neutral position using a plaster splint.

The observation group received MIAR-PKWF. The procedure was performed as follows: A lateral elbow approach was used, with a 2-3 cm incision centered over the fracture site. After hematoma evacuation and removal of interposed soft tissue at the fracture ends, manual traction reduction was performed. A 2.0 mm K-wire was then inserted from the lateral epicondyle, directed obliquely upward at a 45° angle to the humeral shaft to stabilize the distal fracture end. Once satisfactory axial alignment was confirmed, a second 2.0 mm K-wire was introduced from the lateral aspect of the proximal fracture end, angled obliquely downward to engage the contralateral medial cortex of the humerus. Finally, external fixation was completed using a plaster splint.

Postoperative care included close monitoring of distal limb perfusion and skin color, along with strict maintenance of pin-site hygiene through regular disinfection. Upon the child's recovery from anesthesia, caregivers were guided in assisting with metacarpophalangeal joint mobilization exercises on the affected side. In the observation group, sutures were removed two weeks postoperatively. In both groups, the plaster splint was removed at approximately four weeks postoperatively, at which functional rehabilitation of the affected limb was initiated. K-wires were removed between 4 and 6 weeks postoperatively, depending on the individual healing progress. Caregivers were advised to guide children in performing gentle, progressive, and non-forceful active range-of-motion exercises during recovery. All patients were followed up for six months.

Evaluation criteria

(1) Surgical outcomes: Operative time, length of hospital stay, and intraoperative first-attempt reduction success rate were documented for both groups.

(2) Postoperative recovery: Primary endpoints included clinical and fracture healing time. Clinical healing was defined as the absence of localized tenderness, longitudinal percussion pain, and abnormal mobility, with radiographic evidence of bridging callus the fracture line blurring. Fracture healing was defined as meeting clinical union criteria along with radiographic confirmation of callus crossing the fracture line and near-complete or complete fracture line obliteration.

(3) Elbow joint function: Functional recovery of the elbow was graded using Flynn's criteria [17]: Excellent: 0°-5° loss in both flexion-extension arc and carrying angle (CA); Good: 6°-10° loss in both parameters; Fair: 11°-15° loss in both parameters; Poor: >15° loss in either parameter.

(4) Elbow joint mobility: Postoperative elbow range of motion (extension and flexion degrees) was compared at 3-month follow-up.

(5) Radiographic parameters: Baumann's angle (BA), CA, and tilt angle (TA) were measured on standardized anteroposterior/lateral elbow radiographs at 3 months postoperatively.

(6) Serological analysis: Serum levels of osteocalcin (BGP), bone-specific alkaline phosphatase (BALP), insulin-like growth factor-1 (IGF-1), and neuropeptide Y (NPY) were quantitatively assessed in both groups using commercial enzyme-linked immunosorbent assay (ELISA; Wuhan Bairuide Biotechnology Co., Ltd., A-QEK01904-96 wells, A-QEK01862-96 wells, BGT-KET-14443; AmyJet Scientific Inc., GBS-IT1626) kits at baseline (preoperative) and 3 weeks postoperatively.

On the morning of sampling, 4 mL of fasting peripheral venous blood was collected from the subject. Samples were centrifuged at 3,500 r/min for 10 minutes to isolate the serum, which was then frozen at -80°C. Prior to analysis, frozen serum samples were thawed at room temperature for 20 minutes. Meanwhile, the test kits were equilibrated for 4 hours to room temperature after being removed from the -4°C refrigerator. Assays were conducted according to the manufacturer's instructions. Blank, standard, and sample wells were prepared accordingly. Standards was reconstituted as specified, and serum samples were diluted 5-fold. The prepared samples and standards were then added to their respective wells and incubated in a 37°C for 30 minutes. After discarding the liquid, plates were washed five times. Enzyme conjugate reagent was then introduced to each well, followed by another 30-minute incubation at 37°C and a second round of five washes. Chromogenic substrates A and B were added sequentially, and the reaction was allowed to proceed for 10 minutes at 37°C. The reaction was terminated by adding stop solution.

Optical density (OD) was measured within 15 minutes of reaction termination using a microplate reader calibrated against the blank well. Absorbance was recorded at 450 nm. Measured concentration of the samples was determined based on the standard curve and subsequently adjusted by the dilution factor (5×) to determine the final serum concentrations.

(7) Adverse Events: The incidence of cubitus varus, transient ulnar nerve injury, pin track infections, and K-wire migration/loosening was calculated and compared between groups.

(8) Post-reduction swelling: Limb swelling severity was classified as mild (slight swelling compared to normal skin with preserved skin folds), moderate (pronounced swelling with effacement of skin folds but no blistering), or severe (tense swelling with cutaneous tightness and blister formation).

Statistical methods

All statistical analyses were performed using SPSS 20.0 (IBM Corp.). Continuous variables were reported as mean ± standard deviation ($\bar{x}\pm s$) and compared between groups using Student's t-tests. Categorical data were presented as frequencies (percentages) and analyzed using the chi-square (χ^2) test. Statistical significance was set at $P<0.05$.

To determine the required sample size for this study, a power calculation was performed. The initial estimation suggested a minimum of around 40 participants per group. To account for a potential 10% dropout rate, the sample size was adjusted to approximately 44 per group. Ultimately, the study included 45 subjects in the control group and 55 in the observation group, both exceeding the calculated minimum requirement. The sample size was calculated using the following formula:

$$n = \frac{(Z_{1-\alpha/2} + Z_{1-\beta})^2 \times (p_1(1-p_1) + p_2(1-p_2))}{(p_1 - p_2)^2}.$$

Results

Baseline characteristics

No significant differences were observed between the two groups regarding gender distribution, age, time from injury to surgery, body weight, fracture type, preoperative comorbidities, or mechanism of injury (all $P>0.05$) (**Table 1**).

Surgical outcomes

The observation group demonstrated significantly superior surgical outcomes compared to the control group, with significantly reduced operative time ($P<0.01$) and length of hospital stay ($P<0.01$). Notably, the first-attempt reduction success rate was markedly higher in the observation group (94.55% vs. 71.11%; $P<0.01$). These findings are illustrated in **Figure 1**.

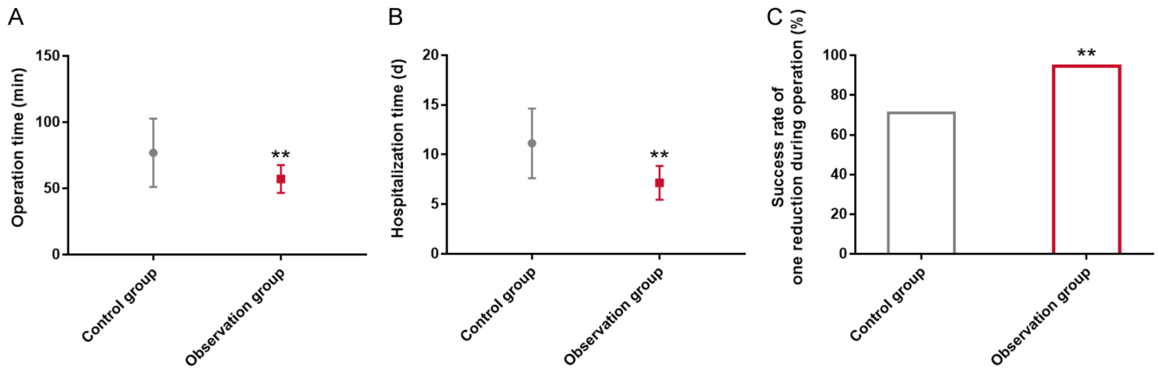

Figure 1. Comparison of surgical outcomes between the two groups. A. Comparison of operation time between the observation (n=55) and control (n=45) groups. B. Comparison of hospitalization time between the observation (n=55) and control (n=45) groups. C. Comparison of the first-attempt reduction success rate between the observation (n=55) and control (n=45) groups. Note: **P<0.01 versus control group.

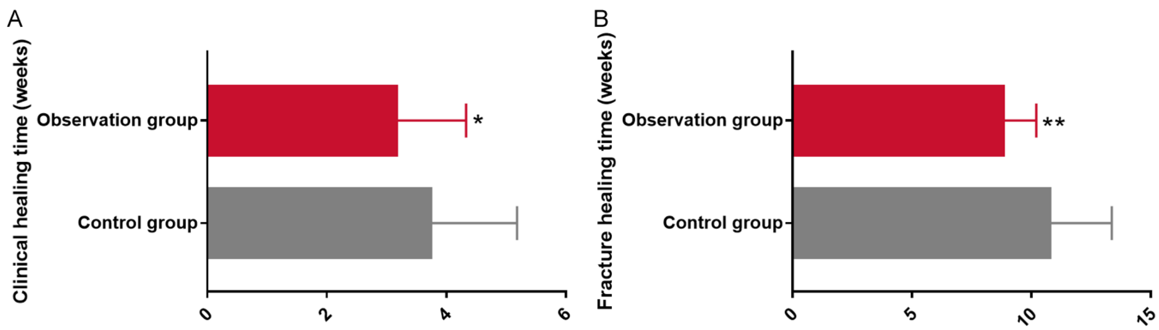

Figure 2. Comparison of postoperative recovery parameters between the two groups. A. Comparison of clinical healing time between the observation (n=55) and control (n=45) groups. B. Comparison of fracture healing time between the observation (n=55) and control (n=45) groups. Note: *P<0.05, **P<0.01 versus control group.

Table 2. Comparison of elbow joint function outcomes between the two groups

Assessment	Control group (n=45)	Observation group (n=55)	χ^2	P
Excellent	25 (55.56)	30 (54.55)		
Good	8 (17.78)	20 (36.36)		
Fair	10 (22.22)	5 (9.09)		
Poor	2 (4.44)	0 (0.00)		
Excellent/good	33 (73.33)	50 (90.91)	5.418	0.020

Postoperative recovery

Patients in the observation group achieved significantly faster clinical healing (P<0.05) and fracture healing (P<0.01) compared to those in the control group (**Figure 2**).

Elbow joint functional recovery

Elbow joint function assessment (Flynn's criteria) revealed a significantly higher proportion of excellent/good outcomes in the observation group (90.91%) compared to controls (**Table 2**).

Elbow joint mobility

The observation group exhibited significantly greater elbow mobility, with improved extension (P<0.05) and flexion (P<0.05) ranges compared to the control group (**Figure 3**).

Radiographic evaluation

Radiographic parameters, including BA, CA, and TA, demonstrated significantly superior improvement in the observation group compared to the control group (P<0.05) (**Figure 4**).

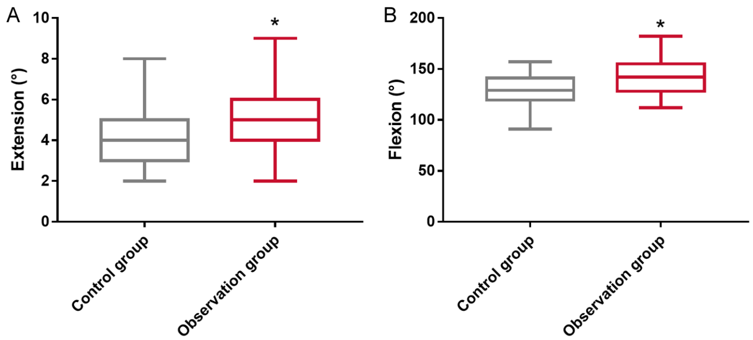

Figure 3. Comparison of elbow joint mobility between the two groups. A. Comparison of extension degree between the observation (n=55) and control (n=45) groups. B. Comparison of flexion degree between the observation (n=55) and control (n=45) groups. Note: *P<0.05 versus control group.

Serological biomarkers

Serum levels of bone metabolism markers (BGP, BALP) and growth-related factors (IGF-1, NPY) were quantitatively assessed by ELISA in both groups. Baseline levels of all biomarkers were comparable between groups (P>0.05). Post-intervention analysis revealed a significant elevation in all measured parameters in both groups, with markedly higher concentrations of BGP, BALP, IGF-1, and NPY in the observation group compared to the control group (P<0.05), as shown in **Figure 5**.

Complication rates

The incidence of complications - including cubitus varus, transient ulnar nerve injury, pin tract infections, and K-wire migration/loosening - was documented in both groups. The observation group exhibited a significantly lower overall complication rate compared to the control group (10.91% vs. 31.11%, P<0.05) (**Table 3**).

Post-reduction swelling severity

A significantly higher proportion of patients in the observation group exhibited mild or no swelling after reduction, whereas moderate to severe swelling was more frequently observed in the control group (P<0.001) (**Table 4**).

Discussion

Current evidence indicates that CR-KWF demonstrates satisfactory outcomes for Gartland type I and II SCHFs, while its effectiveness in more severe Gartland type III fractures remains to be thoroughly evaluated [18]. In contrast, the MIAR-PKWF technique - under C-arm fluoroscopic guidance - enables direct visualization and real-time adjustments of pin insertion angle and force, thereby maximizing the precision of fracture reduction and fixation [19].

Our findings indicate that MIAR-PKWF offers distinct advantages over conventional CR-KWF in surgical outcomes, postoperative recovery. Specifically, MIAR-PKWF significantly reduced operative time and hospital stay while achieving a higher first-attempt reduction success rate (94.55% vs. 71.11%). These findings indicate that MIAR-PKWF not only enhances surgical and recovery efficiency but also provides superior management of complex fracture displacement. Closed reduction for pediatric Gartland type III SCHFs presents considerable procedural complexities, requiring prolonged traction, and multiple fluoroscopic evaluations due to soft tissue interposition, making optimal alignment difficult to achieve [20]. MIAR-PKWF addresses these limitations by providing limited but effective fracture site exposure, facilitating direct assessment and correction of fracture alignment. Besides, this approach enables intraoperative evaluation of reduction quality, consequently increasing single-attempt reduction success rates. Additionally, MIAR-PKWF reduces the need for excessive elbow joint flexion or rigid immobilization postoperatively, minimizing venous congestion in the injured limb while accelerating healing processes, ultimately leading to favorable rehabilitation outcomes [21].

In pediatric SCHFs, MIAR-PKWF offers distinct benefits in promoting clinical recovery, fracture healing, and elbow joint function restoration. This approach significantly improves elbow range of motion, including extension and flexion, while achieving more favorable radiographic measurements (BA, CA, TA). These outcomes highlight MIAR-PKWF's clinical superiority in functional rehabilitation acceleration and its ability to achieve more precise anatomical reduction. Conventional CR-KWF, however, is associated with suboptimal BA and CA due to

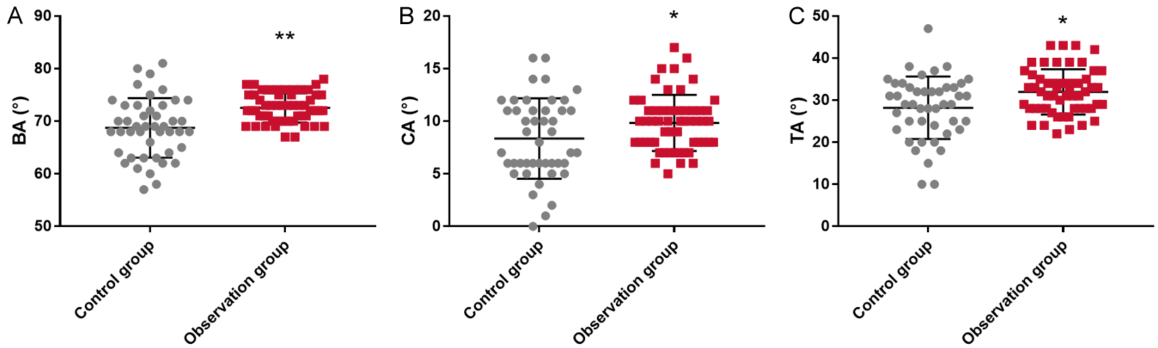

Figure 4. Comparison of radiographic parameters between the two groups. A. BA measurements in two groups. B. CA measurements in two groups. C. TA measurements in two groups. Note: BA, Baumann's angle; CA, carrying angle; TA, tilt angle. *P<0.05, **P<0.01, versus control group.

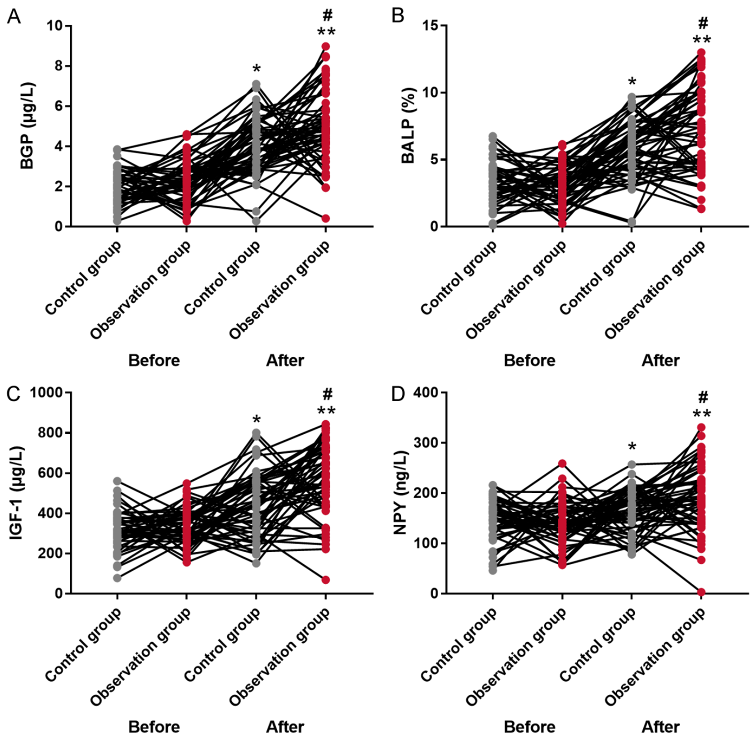

Figure 5. Comparison of serum biomarkers between the two groups before and after treatment. A. BGP. B. BALP. C. IGF-1. D. NPY. Note: BGP, osteocalcin; BALP, bone-specific alkaline phosphatase; IGF-1, insulin-like growth factor-1; NPY, neuropeptide Y. *P<0.05, **P<0.01, versus baseline levels within group; #P<0.05, versus control group.

inadequate anatomical alignment. Its relatively lower fixation stability often necessitates extended cast immobilization, which can impede joint mobility recovery [22]. Unlike it, MIAR-PKWF provides direct visualization, which ensures precise three-dimensional fracture realignment, thereby normalizing BA, CA, and TA. Combined with stable percutaneous K-wire fixation, this technique permits early initiation of supervised motion exercises, typically within 7-14 days postoperatively, effectively minimizing joint stiffness and enhancing flexion/extension outcomes [23].

Additionally, our serological findings support the biological benefits of MIAR-PKWF. Patients in the observation group exhibited significantly greater elevations in bone formation markers (BGP, BALP) and growth-related factors (IGF-1, NPY) compared to those receiving CR-KWF. BGP and BALP, well-established indicators of osteogenic activity, play a crucial role in bone formation and mineralization [24, 25]. Their upregulation suggests enhanced osteoblast function and accelerated bone matrix deposition. IGF-1, a critical mediator of endochondral ossification, promotes angiogenesis and callus formation at the fracture site. NPY, a key neuropeptide regulating both neuroendocrine function and local microcirculation, is also implicated in bone metabolism. The observed elevation in these biomarkers highlights the therapeutic advantage of MIAR-PKWF, likely through optimizing the growth factor milieu and improving neuroendocrine-mediated bone remodeling [26, 27].

Table 3. Comparison of complication rates between the two groups

Indicator	Control group (n=45)	Observation group (n=55)	χ^2	P
Cubitus varus	5 (11.11)	1 (1.82)		
Transient ulnar nerve injury	2 (4.44)	1 (1.82)		
Pin tract infections	3 (6.67)	2 (3.64)		
Kirschner wire migration/loosening	4 (8.89)	2 (3.64)		
Total	14 (31.11)	6 (10.91)	6.313	0.012

Table 4. Comparison of post-reduction swelling severity between the two groups

Indicator	Control group (n=45)	Observation group (n=55)	χ^2	P
Normal	8 (17.78)	18 (32.73)		
Mild	22 (48.89)	35 (63.64)		
Moderate	15 (33.33)	2 (3.64)		
Severe	0 (0.00)	0 (0.00)	21.475	<0.001

Regarding safety, pediatric SCHF patients treated with MIAR-PKWF demonstrated a significantly lower overall complication rate, including cubitus varus, transient ulnar nerve injury, pin tract infections, K-wire loosening or displacement and postoperative limb swelling. In traditional K-wire fixation, inadequate visualization during reduction can lead to coronal plane malalignment, increasing the BA and predisposing patients to cubitus varus deformity. Furthermore, blind medial K-wire insertion also increases the risk of iatrogenic ulnar nerve injury, while repeated reduction attempts prolong operative time, aggravate tissue trauma, and elevate the risk of pin tract infections or wire instability [28]. In contrast, MIAR-PKWF enables direct intraoperative visualization, safeguarding the ulnar nerve, minimizing mechanical stress on K-wires, and facilitating active correction of medial column collapse. Together, these advantages reduce postoperative complications and alleviate swelling, enhancing recovery [29].

Extensive research has been conducted on the clinical application of minimally invasive techniques for pediatric SCHFs. For example, Liu S et al. [30] reported excellent outcomes in delayed (>14 days) fractures treated with minimally invasive closed reduction and external fixation, achieving satisfactory fracture healing and functional elbow recovery - findings consistent with our results. Similarly, Li Y et al. [31] reported successful outcomes using percutaneous poking reduction and K-wire fixation for irreducible flexion-type SCHFs in older children, highlighting its advantages of minimal invasiveness, stable fixation, and favorable long-term joint function. Zhu C et al. [32] further supported the clinical utility of minimally invasive surgery, showing that combined external fixation for pediatric flexion-type SCHFs provided comparable outcomes to conventional closed reduction while significantly reducing operative time.

This study has several limitations that warrant consideration. (1) The relatively short follow-up period precluded evaluation of long-term treatment efficacy. Prolonged follow-ups would be valuable for assessing the durability of therapeutic effects and long-term functional prognosis of both interventions. (2) The evaluation framework did not include measures of psychological well-being or life quality metrics. Future studies should incorporate these assessments to enable a more thorough demonstration of MIAR-PKWF's clinical utility. (3) This study did not systematically examine key variables potentially influencing elbow joint function and post-reduction swelling severity. A more comprehensive exploration of these elements could advance precision medicine applications and aid in identifying optimal candidate populations for the procedure.

In conclusion, MIAR-PKWF demonstrates superior clinical outcomes compared to conventional CR-KWF in the treatment of pediatric SCHFs. This optimized approach offers multiple benefits including enhanced surgical efficacy, accelerated postoperative recovery, improved elbow joint function, greater range of motion, and reduced complication rates, making it a valuable technique for widespread clinical adoption. These findings are expected to offer novel perspectives and valuable references for managing SCHFs in pediatric patients, thereby contributing to evidence-based clinical decision-making in future practice.

Disclosure of conflict of interest

None.

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