Clinical Trial/Experimental Study

Medicine

OPEN

Bone cemented K-wire fixation versus elastic stable intramedullary nailing fixation of paediatric proximal humerus fractures

A prospective cohort study

Shibo Liu, MD[a,b], Yanlong Zhang, MD[a], Jinchao Cao, MD[a], Shijie Fu, MD[b], Aqin Peng, MD[a,*]

Abstract

Background: The objective of this study is to compare the treatments of pediatric displaced proximal humerus fractures with external-fixation technique using the combination of K-wires and bone-cement versus close reduction and internal fixation technique using elastic stable intramedullary nail.

Methods: From April 2016 to March 2020, 72 children with proximal humeral fractures were allocated to group A and 44 children with proximal humeral fractures were allocated to group B. Patients in group A were treated with bone-cemented K-wire fixation, and patients in group B were treated with elastic stable intramedullary nailing. The function of the upper limb was assessed using the Shortened Version of the Disabilities of the Arm, Shoulder and Hand questionnaire and Neer score. Patient satisfaction was assessed using the 10-cm visual analogue scale.

Results: Bone healing was achieved in group A and B after a mean time of 6.1 ± 1.2 and 6.4 ± 1.1 weeks, respectively. The mean surgical time of groups was 33 ± 9 and 54 ± 12 minutes, respectively. The mean Quick Disabilities of the Arm, Shoulder and Hand questionnaire score of groups were 0.5 ± 1.4 and 0.7 ± 1.5, respectively. Based on Neer score, we obtained 69 excellent and 3 good results in group A, and 41 excellent and 3 good results in group B. There were significant differences regarding duration of operation, cost of treatment, and postoperative angle at bone healing ($P < .05$).

Conclusions: The external cemented K-wire fixation is a useful and reliable alternative technique for the treatment of severely displaced proximal humerus fractures in children. The technique is a minimally invasive procedure with minimal complications.

Abbreviations: ESIN = elastic stabilized intramedullary nail, K-wires = Kirschner wires, PP = percutaneous pinning, PPHFs = pediatric proximal humerus fractures.

Keywords: cemented K-wire fixation, fracture, paediatrics, proximal humerus

1. Introduction

Paediatric proximal humerus fractures (PPHFs) account for 2% of all fractures in children aged between 11 and 15 years.[1–3] According to the proximal growth plate of the humerus is responsible for 80% of the bone's longitudinal growth and has a high remodeling potential, most of PPHFs without or with slight displacement are treated with non-operative.[4–6] The mainstay of nonsurgical treatment was immobilization which included hanging arm casts, slings, slings and swathes, and even Velpeau bandages. All these methods had obtained a highly satisfactory results.[7–12] However, the treatment of severely displaced PPHFs remains controversial. Severely displaced PPHFs may require a surgical treatment when the displacement exceeds the remodeling potential or the potential of correction was much less.[3,7,13] Currently, the surgical techniques vary widely.

Based on the amount of displacement, PPHFs are classified as Neer-Horowitz type 1 (<5 mm), type 2 (<1/3 shaft width), type 3 (>1/3 and <2/3 shaft width), and type 4 (>2/3 shaft width) fractures.[5] Types 1 and 2 PPHFs are usually treated nonsurgically because minimal displacement can be remodeled with

Written informed consent was obtained from each patient to authorize the publication of their data.

The authors have no funding and conflicts of interest to disclose.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

This study was performed in line with the principles of the Declaration of Helsinki. This study was approved by the ethics committee of The Third Hospital of Hebei Medical University. Informed consent was obtained from all parents of patients. Informed consent was obtained from the patient for publication of this case report details.

[a] Department of Orthopedics Surgery, Third Hospital of Hebei Medical University, Shijiazhuang, China, [b] Department of Hand and Foot Surgery, Affiliated Hospital of Chengde Medical University, Chengde, China.

*Correspondence: Aqin Peng, Department of Orthopedics Surgery, Third Hospital of Hebei Medical University, Shijiazhuang, Hebei 050051, China (e-mail: pengaqinssy@sina.com).

How to cite this article: Liu S, Zhang Y, Cao J, Fu S, Peng A. Bone cemented K-wire fixation versus elastic stable intramedullary nailing fixation of paediatric proximal humerus fractures: A prospective cohort study. Medicine 2023;102:6(e32959).

Received: 25 November 2022 / Received in final form: 23 January 2023 / Accepted: 24 January 2023

http://dx.doi.org/10.1097/MD.0000000000032959

growth. Many surgeons suggest that types 3 and 4 PPHFs should be treated surgically because remodeled may not achieve with time, resulting in functional morbidity.[7,14] Bahrs et al[15] recommended surgical treatments in patients aged > 10 years with angulation >30° and in patients aged ≤ 10 years with angulation >60°. Binder et al[16] suggested that an angulated neck >30° is indicated. Dobbs et al[17] suggested surgical treatments in patients aged < 7 years with angulation >75°, 8 to 11 years with angulation >60°, and >12 years with angulation >45°.

A myriad of fixation methods for PPHFs can be utilized, the managements are mainly performed by Kirschner wires (K-wires), Elastic Stabilized Intramedullary Nail (ESIN), or screws and plate.[13,18–21] Open reduction and internal fixation using a plate and screws system was rarely used in PPHFs because iatrogenic injuries to the proximal humerus were the major concern.[22] The intramedullary nailing is a commonly fixation method and always used for the shaft fractures.[23] In the last decades years, ESIN was used to treat PPHFs and achieved good results.[24,25] However, ESIN required more experience and more operative time, and the technique was not suitable for very proximal PPHFs, especially the fractures that through the humeral head; This technique required a larger incision which was associated with more blood loss and needed a second procedure to remove the hardware under anesthesia.[3,13,21,26–28] Nevertheless, the intramedullary nailing still is a very important and commonly fixation method. Percutaneous fixation using K-wires is another simple and commonly technique, but some important disadvantages such as unstable osteosynthesis and the need for postoperative immobilization, and postoperative wire migration that may occur due to poor quality of pediatric bone.[12,13,22,26]

Based on above reasons, we hoped to find an external device that can enhance the strength of K-wires fixation and avoid wire migration. We paid attention to the role of external fixator in the treatment of PHFs, while there were few literatures reported on the treatment of PPHFs with external fixator.[29] However, in the biomechanical study, some authors found the external fixator seemed to be superior to plate fixation in load bearing and resistance to torsional stress in the treatment of PHFs.[29–31] In literature on the bone-cemented biomechanical study, they found that bone cement was strong enough in compressive strength, bending modulus, and its elastic modulus was 1 to 4 GPa compared to 10 to 2000 MPa and 10 to 20 GPa for cancellous and cortical bone, respectively.[32,33] Therefore, we developed a combination of K-wires and cement to create a simple external fixator which can utilize the advantage of external fixator and avoid the drawback of percutaneous fixation using K-wires. The technique can be used in severely displaced proximal humerus fractures, acquired a rigid fixation, and avoided the pins migration. The cemented K-wires was much cheaper than an external fixator. The technique can be used in various patterns of proximal humerus fractures.

This study was used to test the hypothesis that bone-cemented K-wire fixation was a stable and reliable fixation like an external fixator for the treatment of PPHFs. The objective of this report was to introduce a novel surgical technique for the treatment of severely PPHFs using external bone-cemented K-wire fixation. We also reported efficiency with the use of the alternative technique.

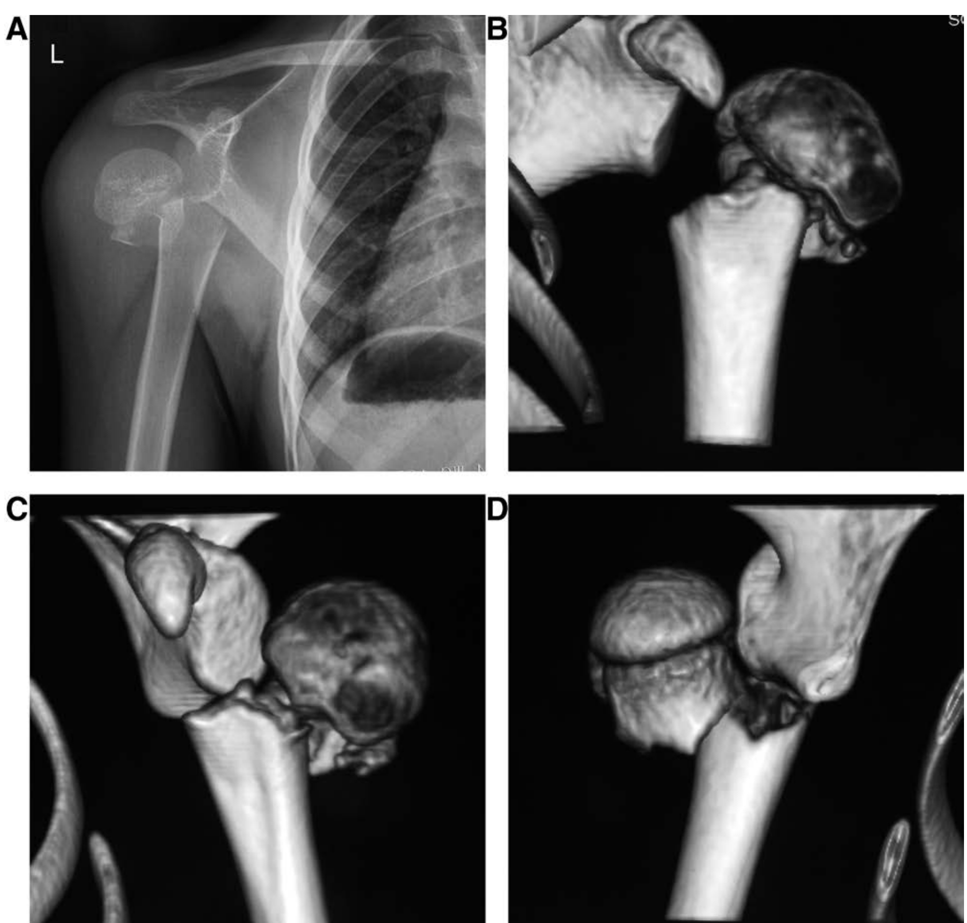

Figure 1. A 10-year-old female patient suffered an extra-articular proximal humerus fracture of her left upper limb. (A) AP X-ray. (B) Anterior CT image. (C) Anterolateral CT image. (D) Posterior CT image. AP = anteroposterior, CT = computed tomography.

2. Patients and methods

This research has been approved by the IRB of the authors' affiliated institutions. Informed consent was obtained from the parents of each child.

From April 2016 to March 2020, 121 consecutive patients with PPHFs were selected in our hospital. Our eligibility criteria were Neer-Horowitz types 3 and 4 PPHFs; a failed trial of nonsurgical treatments; skeletal immaturity as determined by the presence of open epiphysis; acute fractures within 14 days; closed injuries; and patients aged < 7 years with angulation > 75°, 8 to 11 years with angulation >60°, and >12 years with angulation >45°.[17]

Our exclusion criteria were patients older than 18 years; involvement of articular surface; pathologic fractures, neuromuscular disorders; skeletal dysplasia, and other disease affecting bony structures; and patients who declined to participate.

Each patient chose his or her preferred method after we explained the potential advantage and disadvantage of both methods. 75 consecutive patients (75 upper limbs) with PPHFs were treated with bone-cemented K-wire fixation and allocated to group A (Fig. 1A– D); and 46 patients (46 upper limbs) with PPHFs who underwent ESIN were allocated to group B. Finally, 3 patients lost to follow-up in group A and 2 patients in group B, respectively. Preoperative radiographs were obtained in all patients. Computed tomography scan was performed as needed to better understand of the fractures. The same senior surgeon performed all operations with the same surgical techniques.

2.1. Surgical technique

2.1.1. Group A (bone-cement K-wire fixation) The operation was carried out under general anesthesia. The patient was positioned in the supine position. We first attempt to perform closed reduction using traction and rotation maneuver (Fig. 2A). If closed reduction failed, we reduced the fracture with the aid of a percutaneous pin. We temporarily introduced a 2.0-mm percutaneous K-wire to maintain the reduction, from the humeral head to the shaft. Acceptable reduction was confirmed on anteroposterior and lateral X-rays (Fig. 2B and C). We percutaneously introduced two 1.5- to 2.0-mm K-wires from the lateral aspect of the distal humerus. The fracture was stabilized with the 2 cross K-wires. More K-wires were added as needed to reinforce the fixation depending on the fracture pattern (Fig. 2D–F). Care was taken not to injury the neurovascular structures or extrude the pins out the articular surface. Desired wire position was confirmed with an image intensifier. The temporary K-wire was removed. The K-wires were bent at a level about 2 cm distal to the skin, toward the fracture site (Fig. 3A–C). We mixed Monomer (liquid) and polymer (powder) of bone cement (Single dose 40 g, US$170: PALACOS1, Hanau, Germany). When the bone cement viscosity changed over time from a runny liquid into a dough-like state, we applied it to the external bent wire ends outside the bone and then waited it hardened into solid material (Fig. 3D).

2.1.2. Group B (elastic stable intramedullary nailing) The operation was carried out under general anesthesia. The patient was positioned in the supine position. As described by Fernandez et al,[28] a skin incision of 2 cm in length was made above the lateral epicondyle of the humerus. Posteriorly to the crista supraepicondylaris the intramedullary cavity was opened with an awl. When the entrance to the bone was opened enough, the first nail was inserted and brought up to the fracture site. The closed reduction was performed using traction and rotation maneuver. The nail is then passed over the fracture line into the proximal fragment. The tip of the nail must perforate the growth plate. Subsequently the second nail was inserted into

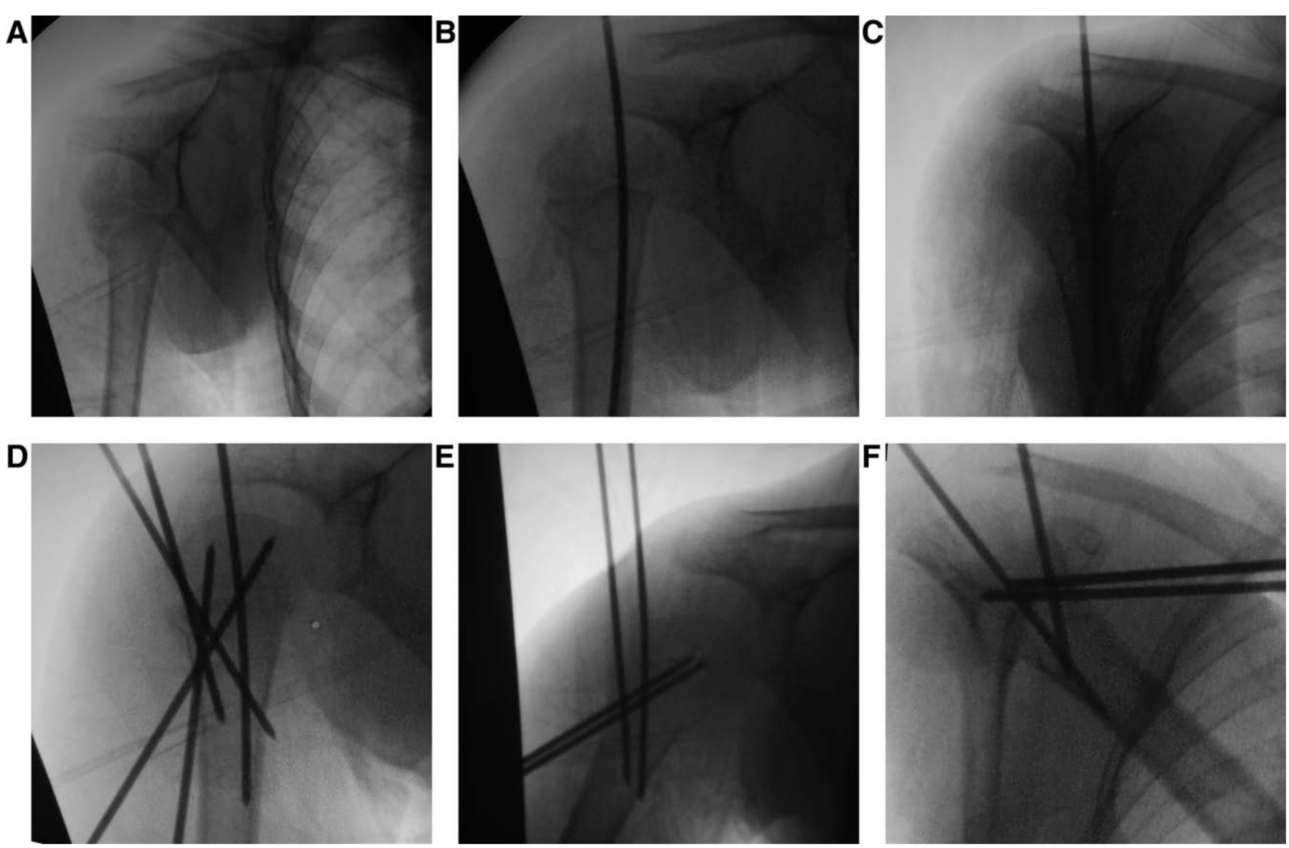

Figure 2. (A) Close reduction is achieved on AP view. (B) An axial K-wire is provisionally introduced to maintain the reduction. AP view. (C) Lateral view. (D) The cross K-wires are introduced to stabilize the facture. (E) The provisional K-wire is removed. AP view. (F) Lateral view of the humerus. AP = anteroposterior.

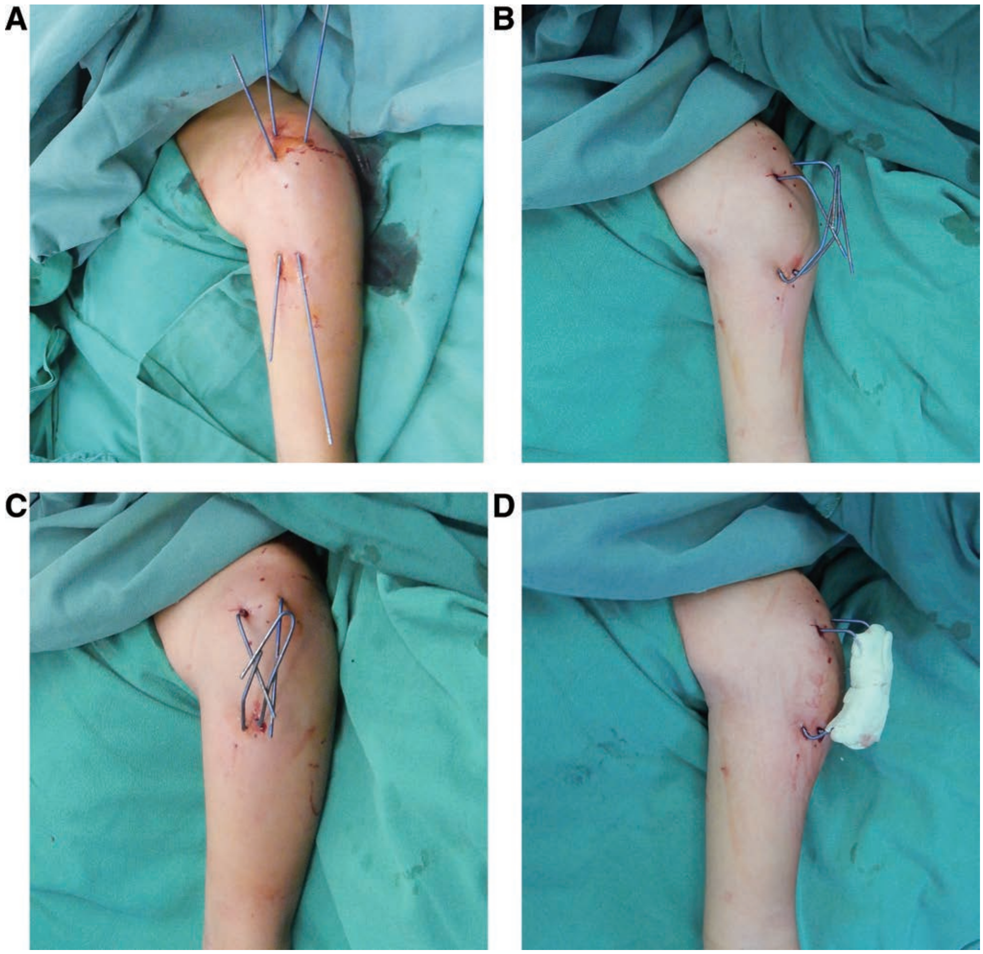

Figure 3. (A) The K-wires are introduced into the distal fragment. (B) The wire ends are bent. AP view. (C) Lateral view. (D) Cement has been applied to the wire ends. AP = anteroposterior.

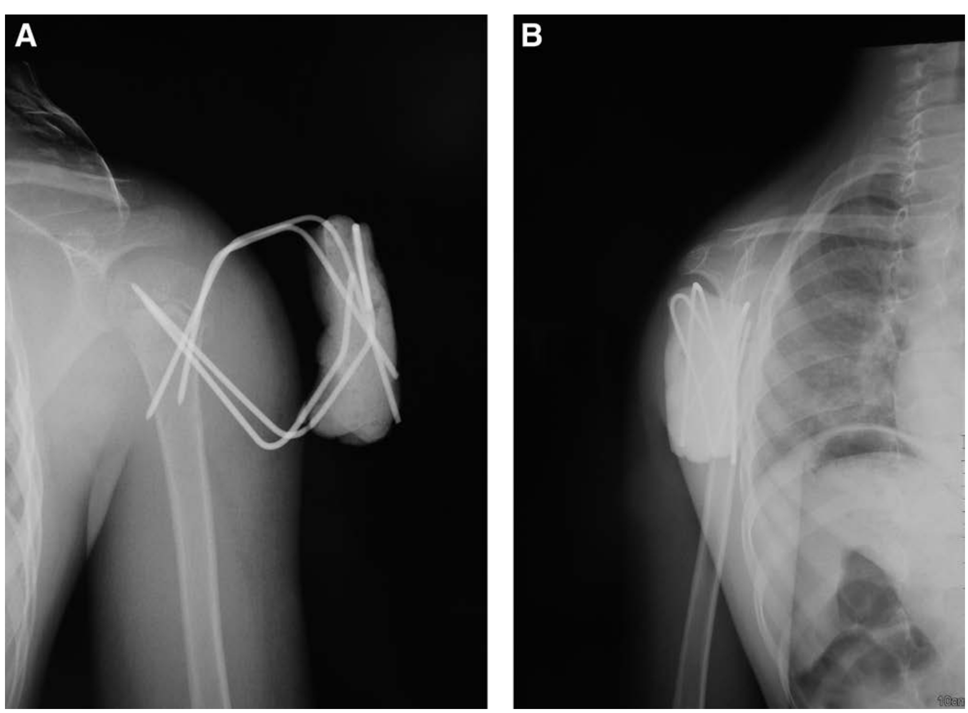

Figure 4. (A) AP view showing bone healing after 4 weeks. (B) Lateral view. AP = anteroposterior.

the humerus using the same entrance point. When using the "single nail technique," the size of the nail was bigger. Finally, the nail was kept over the lateral cortex by 1.5 to 2 cm for easier removal.

2.2. Postoperative managements

Postoperatively, the upper limb was protected with an arm sling for 3 weeks. Range of motion exercises were allowed 2 and 14 days after surgery in group A and group B, respectively. X-rays were taken at the end of the fourth week and every 2 weeks thereafter until initial callus formation was visible (Fig. 4A and B). The K-wires were then cut off and removed in group A. In group B, removal of metal was usually performed 5 to 10 months after the surgery.

2.3. Outcome evaluation

All assessments were performed by a senior orthopedic surgeon who did not involve the treatments. The angle between the axes of the proximal and the distal fragments was measured on anteroposterior X-rays taken before surgery, immediately after surgery, and at the time of bone healing. Bone healing was confirmed when the initial callus formation appeared on radiographs. Nonunion was defined if the evidence of bone healing was not observed 3 months after surgery. At the final follow-up, active range of motion of the shoulder was measured with a goniometer. Arm length was the distance from the tip of the acromion to the elbow flexion crease.[34] Limb function was assessed using the 11-item Disabilities of the Arm, Shoulder and Hand (QuickDASH) score questionnaire and Neer score. Patients reported on shoulder pain and satisfaction using the 10-cm visual analogue scale.

2.4. Statistical analysis

Quantitative variables were described as mean and standard deviation for symmetric distribution or median and interquartile range for asymmetric distribution. A $P < .05$ was considered statistical significance. The collected data were analyzed with t-test and Mann–Whitney U test to symmetric and asymmetric distribution. A $P < .05$ was considered statistical significance. The collected data were analyzed with the Statistical Package for Social Sciences 19.0 (SPSS, Inc., Chicago, IL).

3. Results

Patient demographic and surgical characteristics are shown in Table 1. The mean age of group A and B were 10 years (range, 6–16 years) and 10 years (rang, 8–16 years), respectively. There were Neer-Horowitz types 3 (n = 43) and 4 (n = 29) PPHFs in group A. Neither wire loosening nor migration was observed. Bone healing was achieved in group A and B after a mean time of 6.1 ± 1.2 and 6.4 ± 1.1 weeks, respectively. In group A, a mild pin tract infection occurred in 3 patients, which was cured with oral antibiotics and pin care. In group B, loss correction occurred in 2 cases, 1 child was revised, the other child was within the acceptance range. In 2 cases the metal removal was difficult.

Follow-ups of groups lasted for 27.2 ± 3.6 and 27.5 ± 3.5 months, respectively. In group A, active ROM of the glenohumeral joint of the injury side reached 170 ± 10° (flexion), 175 ± 7° (abduction), respectively (Fig. 5). There were no significant differences regarding active ROM of flexion and abduction between the 2 shoulder joints (P = .08 and .27, respectively). In group B, active ROM of the glenohumeral joint of the injury side reached 172 ± 10° (flexion), 175 ± 6° (abduction), respectively. There were no significant differences regarding active ROM of flexion and abduction between the 2 shoulder joints (P = .432 and .104, respectively). The mean Quick Disabilities of the Arm, Shoulder and Hand questionnaire score of groups were 0.5 ± 1.4 and 0.7 ± 1.5, respectively. Based on Neer score, we obtained 69 excellent and 3 good results in group A, and 41 excellent and 3 good results in group B. No patient presented a clinically significant limb-length discrepancy (see Table 2).

4. Discussion

We find that percutaneous K-wire fixation with adding cement to the bent part of K-wires outside the bone is a reliable technique for the treatment of PPHFs, especially for the severely PPHFs. The technique is a minimally invasive procedure with minimal complications and achieves similar results to ESIN.

Table 1

Baseline demographic and surgical characteristics between group A and group B.

	Group A (bone-cement K-wire fixation)	Group B (intramedullary nailing)	*P* valuable
Age (mean; range; yr)	10 (6–16)	10 (8–16)	.916
Gender (M:F)	43:29	24:20	.361
Side affected (L:R)	32:40	24:20	.194
Injury (open:closed)	0:72	0:44	
Injury mechanism (n)			
Fall	42	25	.984
Traffic accident	13	8	
Sport	17	11	
Preoperative angle (°)	63.8 ± 11.9	64.9 ± 11.3	.612
Time from injury to operation (d)	3.9 ± 1.3	3.9 ± 1.3	.959
Duration of operation (min)	32.5 ± 8.5	54.2 ± 12.0	<.001
Number of internal hardware	3.1 ± 0.7	2.0 ± 0.4	
Complication			
Loss correction	0	2	.245
Difficult to remove	0	2	
Pin tract infection (n)	3	0	
Discrepancy	0	0	
Cost (US$)	2349 ± 356	2942 ± 399	<.001
Bone healing (wk)	6.1 ± 1.2	6.4 ± 1.1	.148
Follow-up time (mo)	27.2 ± 3.6	27.5 ± 3.5	.698

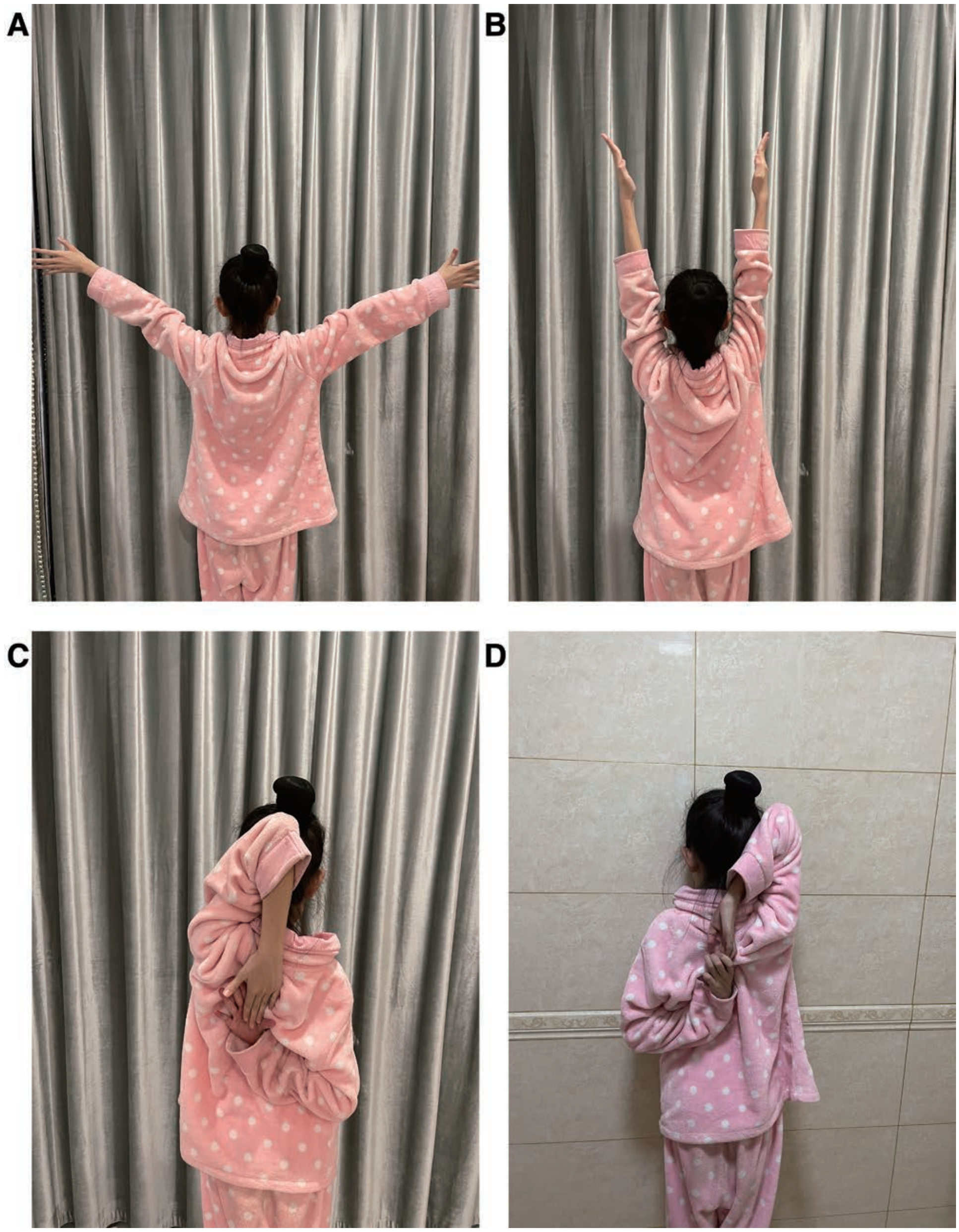

Figure 5. Range of motion of the left shoulder after 3 yr. (A) Abduction. (B) Flexion. (C) Apley Scratch test (the hand touching the opposite scapula) to show abduction and external rotation. (D) Testing abduction and internal rotation.

Several fixation techniques are available for the treatment of severely displaced PPHFs, including K-wires, screws, ESIN, external fixator, or screws and plate. Percutaneous pinning techniques (PP) and ESIN techniques are the most common methods.[13,18–21] Binder et al[10] treated 40 children (40 PPHFs) using percutaneous pinning. They obtained 36 excellent, 2 average, and 2 poor results based on the Constant-Murley Score. Though the technique was simple and effective, it also had certain disadvantages such as unstable osteosynthesis and the need for postoperative immobilization, and postoperative wire migration. Hutchinson et al[13] reported complications in 11 of 27 patients (41%) treated with PP, including pin migration and infection. Fernandez et al[28] treated 35 children (35 PPHFs) using 1 or 2 elastic stable intramedullary nails. Two years after surgery, they achieved an average of 99 points based on the Constant-Murley score. However, severe injuries to the humeral head with loss of reduction occurred in 2 children. Nail misplacement occurred in 1 child. Revision due to hematoma occurred in 1 child. Difficult removal of the nail occurred in 2 children. Hutchinson et al[13] treated 27 children with pins and 23 children with intramedullary nails. They found intramedullary nailing was associated with a lower incidence of angulation deformity than PP (9° vs 16°). Intramedullary nailing was also associated with a lower complication rate (4% vs 41%). In the children treated with pins, pin migration occurred in 5 children. Pin tract infection occurred in 5 children, which healed after removal of the pin. However, ESIN needed more operative time than PP (121 minutes vs 63 minutes), and more average estimated blood loss (173 mL vs 45 mL), and some other authors had the similar results as the study by Hutchinson et al.[24–27,35] In our study, there was a significant difference in the duration of operation of the 2 groups ($P < .05$), the time were 32.5 and 54.2 minutes, respectively. Additionally, compared to the study by Hutchinson et al,[13] there was no pin migration occurred, the complication rate in our study was lower. The technique with adding cement to the bent part of K-wires outside the bone achieved similar results to ESIN, the complication rate between 2 groups was no significant ($P > .05$).

Table 2

Clinical outcome between group A and group B.

	Group A (bone-cement K-wire fixation)	Group B (intramedullary nailing)	*P* valuable
Postoperative angle			
Immediately after surgery (°)	6.4 ± 5.6	6.8 ± 6.8	.699
At bone healing (°)	6.5 ± 5.7	9.9 ± 11.3	.032
P value	.06	.002	
Range of motion			
Abduction of injury side (°)	175 ± 7	175 ± 6	.978
Abduction of opposite side (°)	176 ± 7	173 ± 7	.081
P value	.27	.104	
Flexion of injury side (°)	170 ± 10	172 ± 10	.202
Flexion of opposite side (°)	170 ± 9	171 ± 10	.511
P value	.08	.432	
Quick DASH	0.5 ± 1.4	0.7 ± 1.5	.47
Pain (VAS)	1.1 ± 1.3	1.3 ± 1.0	.569
Satisfaction (VAS)	9.8 ± 0.4	9.7 ± 0.3	.255
Neer score*	95.6 ± 4.0	95.8 ± 4.2	.933
Excellent (n)	69	41	.532
Good (n)	3	3	
Arm length			
Injury side	23.8 ± 2.4	23.9 ± 2.5	.847
Opposite	23.9 ± 2.4	23.9 ± 2.5	.941
P value	0.106	0.878	

DASH = Disabilities of the Arm, Shoulder and Hand questionnaire, VAS = 10-cm visual analogue scale.
*Excellent (90–100), good (80–89), fair (71–79), and poor (0–70).

Physeal injury of the proximal humerus is the major concern, and the number of K-wire used is controversial.[20,36,37] Bahrs et al[15] treated 33 physeal fractures of the proximal humerus with 2 to 4 K-wires, and physeal arrest was not observed after 3 years. Binder et al[16] treated 15 physeal fractures with the similar technique, and physeal injuries did not occur in this series. In reviewing the literature, no data was found on the association between physeal arrest and the number of K-wire, those authors believed the incidence of physeal arrest was extremely low if only anatomical reduction was achieved. In the biomechanical study, Durigan et al[38] suggested the use of 2 ascending K-wires and 2 descending parallel intersecting K-wires to achieve a rigid fixation. However, in our study, we initially introduce 2 K-wires across the physis. One or 2 K-wires are added depending on wire position and fracture pattern. In few cases, we add more K-wires to the distal fragment (not across the physis) to reinforce the stability by securing the wire onto the bone cement. Currently, the incidence of physeal arrest is not reported, but we believe less K-wires used and avoiding repeated wire introduction decrease the risk of physeal injuries. In our study, both groups had no clinically significant limb-length discrepancy.

In biomechanical study of bone cement, Struemph et al[32] found the compressive strength, bending modulus, and bending strength of bone cement are above 70 MPa, 1800 MPa, and 50 MPa, respectively. The cement could provide strength which was between cancellous bone and cortical bone in compressive strength, bending modulus, and bending strength.[33] In biomechanical study of external fixator, Huang[31] found that the external fixator seemed to be superior to plate fixation in load bearing and resistance to torsional stress, the ultimate bearing capacity and load bearing were higher in the external fixator group (145.16 ± 17.42 N and 140 N, respectively) than plate group (120.21 ± 13.15 N and 69.63 ± 25.16–90.78 ± 17.18 N, respectively), and in the resistance to torsional stress, the external fixator's torque fluctuated (within 1 Nm) more evenly distributed than plate's torque (1–5 Nm), and external fixation provided the better rigidity. Li et al[30] also found that linking together the ends of fixation wires with external fixator could provide enough stability and could enhance the rotational stiffness of the construct. Lollino et al[29] reported that external fixator can achieve a rigid fixation in the treatment of PPHFs. In our study, the cemented K-wire system was similar to an external fixator and could provide strong rigidity in bending, compression, and torque. Compared to the study by Hutchinson et al,[13] we acquire a good result in the postoperative angle, and there was no significant difference in the postoperative angle between the immediately after surgery and bone healing ($P > .05$). The cement frame combined with K-wires would be strong enough for fixation, which allows early joint motion exercise.

The percutaneous technique is a minimally invasive procedure with fewer complications. We secure all ends of wires together using cement, which prevents re-displacement and wire migration. Bending the wires over felt or using Jurgan pin balls can prevent K-wire migration, but the K-wire may still move back and forth because the wire ends are not secured together. The wire ends can also be secured with an external fixator, but the device is expensive, and manipulation may be difficult. It is associated with a low rate of pin tract infection because we prevent wire movement at the pin site. The above-mentioned issues also show the advantages of our technique. In addition, the cemented frame can be removed in the office and is cheaper than the conventional external fixators. Disadvantages include the risks of iatrogenic injuries to the axillary nerve and vessels and inconvenience to patient's daily life due to the external fixator.

Indications of our technique include severely displacement or angulation PPHFs (such as Neer-Horowitz types 3 and 4 PPHFs), a failed trial of closed reduction, or an acceptable alignment that is difficult to maintain. Intraarticular fractures may require open reduction to achieve complete restoration of articular surface. Contraindications are mild displacement (such as Neer-Horowitz types 1 and 2 PPHFs) and acceptable alignment that can be achieved by closed reduction.

Our study has limitations. The kinematics of bone-cemented K-wire fixation needs further studies. Surgeons' preferences, experience, and ability may influence wire configuration and position. A reliable conclusion about treatment outcomes for these injuries requires follow-up of patients until completion of growth. The functional assessments are based on adult patients, and a specifical scoring system is better to assess the adolescent population. To get a more comprehensive conclusion, conservatively treated patients who do not undergo surgery should be accessed in future studies. Future studies should be prospective, randomized, and blinded, and a longer follow-up period would be required to ascertain the long-term viability of this technique better.

5. Conclusions

The external cemented K-wire fixation is a feasible and alternative option for the treatment of PPHFs with minimal complications, especially for the severely PPHFs which cannot use the ESIN. The percutaneous technique achieves a relatively rigid fixation, which allows early joint motion exercise, resulting in good function of shoulder.

Author contributions

Formal analysis: Yanlong Zhang, Jinchao Cao.
Methodology: Shijie Fu.
Project administration: Aqin Peng.
Writing – original draft: Shibo Liu.
Writing – review & editing: Shibo Liu.

References

[1] Larsen CF, Kiaer T, Lindequist S. Fractures of the proximal humerus in children. Nine-year follow-up of 64 unoperated on cases. Acta Orthop Scand. 1990;61:255–7.
[2] Shore BJ, Hedequist DJ, Miller PE, et al. Surgical management for displaced pediatric proximal humeral fractures: a cost analysis. J Child Orthop. 2015;9:55–64.
[3] Hannonen J, Hyvönen H, Korhonen L, et al. The incidence and treatment trends of pediatric proximal humerus fractures. BMC Musculoskelet Disord. 2019;20:571.
[4] Pahlavan S, Baldwin KD, Pandya NK, et al. Proximal humerus fractures in the pediatric population: a systematic review. J Child Orthop. 2011;5:187–94.
[5] Neer CS, Horwitz BS. Fractures of the proximal humeral epiphysial plate. Clin Orthop Relat Res. 1965;41:24–31.
[6] Hohloch L, Eberbach H, Wagner FC, et al. Age- and severity-adjusted treatment of proximal humerus fractures in children and adolescents – a systematical review and meta-analysis. PLoS One. 2017;12:e0183157.
[7] King ECB, Ihnow SB. Which proximal humerus fractures should be pinned? Treatment in skeletally immature patients. J Pediatr Orthop. 2016;36(Suppl 1):S44–48.
[8] Shahriar R, Hosseinzadeh P. Proximal humerus fractures: what alignment is acceptable in children 10 and up? J Pediatr Orthop. 2021;41(Suppl 1):S20–3.
[9] Gladstein AZ, Schade AT, Howard AW, et al. Reducing resource utilization during non-operative treatment of pediatric proximal humerus fractures. Orthop Traumatol Surg Res. 2017;103:115–8.
[10] Binder H, Tiefenboeck TM, Payr S, et al. Treatment of proximal humerus fractures in children and young adolescents. Wien Klin Wochenschr. 2016;128:120–4.
[11] Popkin CA, Levine WN, Ahmad CS. Evaluation and management of pediatric proximal humerus fractures. J Am Acad Orthop Surg. 2015;23:77–86.
[12] Lefèvre Y, Journeau P, Angelliaume A, et al. Proximal humerus fractures in children and adolescents. Orthop Traumatol Surg Res. 2014;100(1 Suppl):S149–56.
[13] Hutchinson PH, Bae DS, Waters PM. Intramedullary nailing versus percutaneous pin fixation of pediatric proximal humerus fractures: a comparison of complications and early radiographic results. J Pediatr Orthop. 2011;31:617–22.
[14] Giebel G, Suren EG. [Injuries of the proximal humeral epiphysis. Indications for surgical therapy and results]. Chirurg. 1983;54:406–10.
[15] Bahrs C, Zipplies S, Ochs BG, et al. Proximal humeral fractures in children and adolescents. J Pediatr Orthop. 2009;29:238–42.
[16] Binder H, Schurz M, Aldrian S, et al. Physeal injuries of the proximal humerus: long-term results in seventy two patients. Int Orthop. 2011;35:1497–502.
[17] Dobbs MB, Luhmann SL, Gordon JE, et al. Severely displaced proximal humeral epiphyseal fractures. J Pediatr Orthop. 2003;23:208–15.
[18] Al-Omari AA, Alrawashdeh M, Obeidat O, et al. Entrapped long head of biceps tendon in pediatric proximal humerus fracture dislocation: a case report and review of the literature. Ann Med Surg (Lond). 2021;67:102510.
[19] Freislederer F, Bensler S, Specht T, et al. Plate fixation for irreducible proximal humeral fractures in children and adolescents – a single-center case series of six patients. Children (Basel). 2021;8:635.
[20] Swarup I, Hughes MS, Bram JT, et al. Percutaneous pinning of pediatric proximal humeral fractures. JBJS Essent Surg Tech. 2019;9:e33.1–6.
[21] Kelly DM. Flexible intramedullary nailing of pediatric humeral fractures: indications, techniques, and tips. J Pediatr Orthop. 2016;36(Suppl 1):S49–55.
[22] Pandya NK, Behrends D, Hosalkar HS. Open reduction of proximal humerus fractures in the adolescent population. J Child Orthop. 2012;6:111–8.
[23] Ligier JN, Metaizeau JP, Prévot J. [Closed flexible medullary nailing in pediatric traumatology]. Chir Pediatr. 1983;24:383–5.
[24] Chee Y, Agorastides I, Garg N, et al. Treatment of severely displaced proximal humeral fractures in children with elastic stable intramedullary nailing. J Pediatr Orthop B. 2006;15:45–50.
[25] Rajan RA, Hawkins KJ, Metcalfe J, et al. Elastic stable intramedullary nailing for displaced proximal humeral fractures in older children. J Child Orthop. 2008;2:15–9.
[26] Kraus T, Hoermann S, Ploder G, et al. Elastic stable intramedullary nailing versus Kirschner wire pinning: outcome of severely displaced proximal humeral fractures in juvenile patients. J Shoulder Elbow Surg. 2014;23:1462–7.
[27] Samara E, Tschopp B, Kwiatkowski B, et al. A single retrograde intramedullary nail technique for treatment of displaced proximal humeral fractures in children: case series and review of the literature. JB JS Open Access. 2021;6:e20.00119.
[28] Fernandez FF, Eberhardt O, Langendörfer M, et al. Treatment of severely displaced proximal humeral fractures in children with retrograde elastic stable intramedullary nailing. Injury. 2008;39:1453–9.
[29] Lollino N, Assom M, Fumero S, et al. Salter-Harris type II proximal humerus injuries: our experience with a new external fixator. Tech Hand Up Extrem Surg. 2013;17:176–8.
[30] Li WC, Meng QX, Xu RJ, et al. Biomechanical analysis between Orthofix® external fixator and different K-wire configurations for pediatric supracondylar humerus fractures. J Orthop Surg Res. 2018;13:188.
[31] Huang H. Treatment of the surgical neck fracture of the humerus with a novel external fixator in the elderly with osteoporosis: biomechanical analysis. BMC Musculoskelet Disord. 2019;20:218.
[32] Struemph JM, Chong AC, Wooley PH. Evaluation of different experience levels of orthopaedic residents effect on Polymethylmethacrylate (PMMA) bone cement mechanical properties. Iowa Orthop J. 2015;35:193–8.
[33] Duffy RK, Shafritz AB. Bone cement. J Hand Surg Am. 2011;36:1086–8.
[34] Edmond T, Laps A, Case AL, et al. Normal ranges of upper extremity length, circumference, and rate of growth in the pediatric population. Hand (N Y). 2020;15:713–21.
[35] Khan A, Athlani L, Rousset M, et al. Functional results of displaced proximal humerus fractures in children treated by elastic stable intramedullary nail. Eur J Orthop Surg Traumatol. 2014;24:165–72.
[36] Burgos-Flores J, Gonzalez-Herranz P, Lopez-Mondejar JA, et al. Fractures of the proximal humeral epiphysis. Int Orthop. 1993;17:16–9.
[37] Kim AE, Chi H, Swarup I. Proximal humerus fractures in the pediatric population. Curr Rev Musculoskelet Med. 2021;14:413–20.
[38] Durigan A, Barbieri CH, Mazzer N, et al. Two-part surgical neck fractures of the humerus: mechanical analysis of the fixation with four Shanz-type threaded pins in four different assemblies. J Shoulder Elbow Surg. 2005;14:96–102.