



# Hinge positioning method of Ilizarov apparatus in correcting radial head luxation caused by multiple hereditary exostoses

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Multiple hereditary exostoses (MHE) is featured with disordered cartilage growth in metaphysis and accompanied by defect in bone remodeling and retardation of bone lengthening.<sup>[1,2]</sup> The most common deformities of forearm MHE were reported as shortened ulna or radius, bowing forearm appearance, ulnar deviation of carpus and hand, and dislocation of radial head due to a “tether effect”.<sup>[3-6]</sup> Exostoses excision, osteotomy, and immediate lengthening of the ulna were recommended by several studies, while severe displacement of the radial head still challenges after adequate length of the forearm is obtained.

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## ABSTRACT

**Objectives:** In this study, we present a specified hinge positioning method to achieve satisfying and steerable lengthening and angulation to correct forearm multiple hereditary exostoses (MHE) combined with severe radiocapitellar joint dislocation using Ilizarov ring fixators.

**Patients and methods:** Between January 2014 and December 2018, a total of 30 forearms of 23 patients (11 males, 12 females; mean age: 18.3±6.8 years; range, 8 to 35 years) who suffered from type IIa (n=2) or IIb (n=28) MHE with severe radiocapitellar joint luxation were retrospectively analyzed. All patients were treated with Ilizarov external fixators with our specified hinge positioning method. Range of motion of the elbow, forearm and wrist and Visual Analog Scale (VAS), as well as Disabilities of Arm, Shoulder, and Hand (DASH) score, and radiological parameters, including radial articular angle (RAA), ulnar variance (UV) and carpi slip (CS), were recorded preoperatively and at final follow-up and were compared.

**Results:** Clinical and radiological outcomes were evaluated. Range of motion of the elbow, forearm and wrist, VAS, DASH and radiological features, including RAA, CS, and UV were significantly improved, except for range of motion of the forearm supination. Temporary nail track infection was seen in two of the forearms and was controlled with oral antibiotics. None of the patients developed radial head dislocation again.

**Conclusion:** Clinical and radiological outcomes of this novel hinge positioning method are satisfactory in treating MHE with severe radial head dislocation, and this method can be an alternative treatment for MHE by setting a milestone for accurate radiocapitellar joint reduction.

**Keywords:** Dislocation; hinge positioning; Ilizarov fixator; multiple hereditary exostoses; radial head; ulnar osteotomy.

Forearm MHE combined with radiocapitellar joint dislocation has been reported to be treated by osteotomy, gradual lengthening, and angulation of the ulna with the Modified Ilizarov ring fixators, a distraction osteogenesis technique introduced

by Ilizarov.<sup>[7-10]</sup> However, ulnar elongation may not promise a properly reduced radiocapitellar joint, since the intensity and direction of the force, which was transduced through interosseous membrane during lengthening, remained difficult to control.<sup>[8,11-16]</sup> Hinges are fundamental components of Ilizarov apparatus to correct angulating and rotational deformities. To the best of our knowledge, no study has reported where exactly these hinges should be installed to angulate the ulna and reduce the radial head. In the present study, we, therefore, aimed to introduce and evaluate our specified hinge positioning while treating forearm MHE with gradual lengthening of the ulna with Ilizarov ring fixators.

## PATIENTS AND METHODS

This single-center, retrospective study was conducted at Department of Orthopedics of Shanghai Sixth People's Hospital between January 2014 and December 2018. A total of 30 forearms of 23 patients (11 males, 12 females; mean age: 18.3±6.8 years; range, 8 to 35 years) whose forearm deformities were due to MHE were retrospectively analyzed. A written informed consent was obtained from each patient and/or their parents and guardians. The study protocol was approved by the Shanghai Jiao Tong University Affiliated Sixth People's Hospital Human Research Committee (Date: 2020-08-25, No: 2020-107). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Forearm deformities were morphologically assessed according to Masada classification.<sup>[5]</sup> Two of the forearms were evaluated as Masada type IIa, while the rest 28 were considered Masada type IIb. Shortened ulna/radius and dislocated radial head existed in all these forearms preoperatively.

### Surgical procedures and postoperative care

The patients received a surgical intervention due to one or more of the following indications: (i) painful and/or malfunctioned forearm movements, (ii) disturbed daily activities, (iii) forearm cosmetic problem, and (iv) progressive deformities. Two main types of operations were performed: (i) simple osteotomy and gradual lengthening of the ulna, and (ii) excision of exostoses. The exostoses were resected, if the lesions were prominent, painful and, most importantly, limited motion of the forearm.

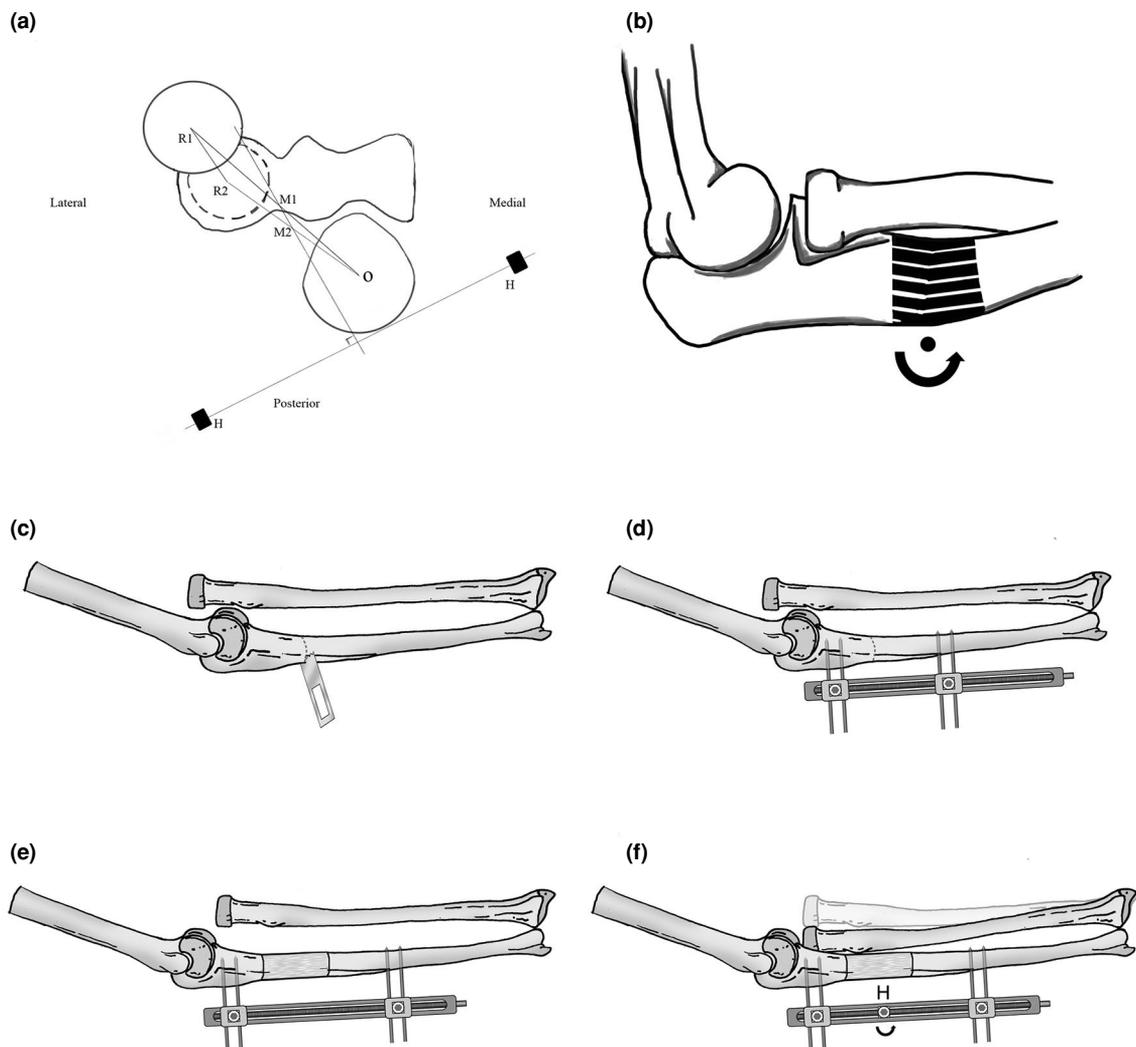
Surgery was operated under brachial plexus nerve block anesthesia in adult patients and under general anesthesia in adolescents and children. The exostoses lesions were firstly cut out, if they blocked joint movements or hindered the application of the pins and

external fixators. The Ilizarov apparatus was prepared according to the relative position of the hypothesized pins which would, then, be penetrated into forearm bones. Three rings, which suit the size of the upper extremity, were selected to establish the plastic frame. The rings would be placed around the olecranon, middle of the forearm and the distal radioulnar joint (DRUJ). Two rotational hinges were fixed and were installed between the proximal and middle rings with axial elongation rods. The distal two rings were, then, stabilized with other 3 or 4 rods. After adjusting the frame to suit the forearm, a Kirschner wire (Φ2.0 mm) was transversely penetrated to fix the DRUJ. Two half pins (Φ4.5 mm) were, then, placed into the one third part of the distal ulna and another two into the one third part of the distal radius. A full pin and a half pin were applied to the proximal ulna. Ilizarov apparatus were applied over half pins for fixation at proximal, middle and distal forearm. Ulnar osteotomy was performed between the proximal and middle rings at one-fourth of the ulna through adequate drill holes to preserve the periosteum.

*To illustrate, specified positions of rotational hinges are as follows:*

- a. Multiple planar computed tomography (CT) scan of the ipsilateral forearm and elbow is obtained. Three-dimension reconstruction of the ipsilateral forearm and elbow is, then, performed.
- b. The midpoints (M1 and M2) of the segment that connects the dislocated radial head (R1) and olecranon (O), as well as the segment that connects the hypothesized reduced radial head (R2) and olecranon (O), are then connected.
- c. A line perpendicular to the line connecting the two midpoints is then drawn, which is posterior to the ipsilateral forearm. The two axial hinges (H) should be installed on this line.
- d. For the rotating hinge, we prefer to install it on line M1M2 to provide equal supportive force on both sides of the paired axial hinges, which is of vital importance to ensure accurate correction (Figure 1).

Gradual distraction started at a rate of 1 mm/d after a latency of 10 d. During the elongation period, the co-fixed radius was pulled distally through both the distal Ilizarov frame and forearm interosseous membrane. For patients who were skeletally immature, an over-lengthening of 5 mm was applied in case of recurrence of ulnar shortening. All patients stuck to the follow-up schedule before reduction which ordered clinical visit every two weeks after



**FIGURE 1.** Schematic diagram of the novel hinge positioning and main procedures of the technique. (a) How the two axial hinges are located. (b) Callus is modified for radial head reduction by hinge rotation, seen from lateral-medial view. (c) The osteotomy is performed at just distal to the radial notch of the ulna. (d) Gradual elongation of the ulna. (e) After adequate lengthening, the radial head reaches the estimated plane for reduction. (f) Manual angulation of the ulna callus results in the reduction of the radial head, as it is sent back to the radial notch.

distraction and a last specific visit date, if the radial head would be reduced within two weeks.

The patients were encouraged to use their wrists, forearms, and elbows postoperatively. The reduction of the dislocated radial head was performed in outpatient after the ulna gained adequate length in previous lengthening period. We consider that a radial head 5 mm distal to the capitellum on lateral film during 90-degree elbow flexion, which guarantees suitable radiocapitellar joint space after reduction, an adequate elongation. By unlocking the fixed rotational hinges and dismantling the elongation rods, the frame between the proximal and

middle rings as well as tissues within this segment, including the callus which formed during distraction osteogenesis, became mobilizable. Brachial plexus anesthesia was performed and the ulnar callus was rotated along the line travelling through the two hinges manually. The bony process (the dislocated radial head) gradually faded away during this procedure and once a snapping was felt, the radial head was reduced. The hinges were, then, fixed and additional rods were applied to the proximal frame for safe mineralization.

Radiological examinations were applied to ensure the reduction. Additional radial osteotomy and

elongation were performed, if there still remained a pathologically negative ulnar variance (UV). The UV is measured, as the distance from the lip of the ulnar metaphysis to that of the radial metaphysis. Negative numbers are representative of a shortened ulna. All patients were advised for follow-up visit every month after reduction. After the consolidation period, the Ilizarov external fixator was completely removed. The criteria to decide removing the apparatus included radiologically confirmed bone union at each osteotomy site and no recurrence of the dislocation of the radial head three months after reduction.

### Clinical outcome evaluation

Three experienced surgeons, who participated in none of these surgical procedures above, were appointed to review the clinical outcomes of these patients. We evaluated the level of pain using Visual Analog Scale (VAS) and range of motion (ROM) of the wrist, forearm and elbow preoperatively and at time of final interview, and also measured the amount of ulnar lengthening (UL) gained, external fixator time (EFT), duration of distraction (DD), external fixator index (EFI) and distraction index (DI). The UL refers to the radiological difference between the preoperative length of the ulnar and its length measured at the final follow-up. The EFI and DI were calculated using the formulae below:

$$\text{EFI} = \text{EFT} / \text{UL}$$

$$\text{DI} = \text{DD} / \text{UL}$$

The VAS was subjectively described by the patient before and after the whole procedure.

The ROM of the wrist, forearm, and elbow was measured before and after the procedure. Satisfaction comparison was measured using the Disabilities of Arm, Shoulder, and Hand (DASH) score system pre- and postoperatively.<sup>[17]</sup>

Complications were recorded and treated, if observed.

### Radiological outcome evaluation

X-ray test, as a routine examination, against the ipsilateral wrist, forearm and elbow was applied before and after the operation, and at each time point of follow-up.

The Masada classification was performed based on the location of exostoses and the radial head luxation. The locations of the exostoses were first recognized. To identify a dislocated radial head, Storen line was applied.<sup>[18]</sup> Masada type IIa is characterized by a dislocated radial head and radial exostoses lesion, with or without ulnar exostoses lesion while Masada

type IIb by a dislocated radial head with only ulnar exostoses lesion.

Radial articular angle (RAA), carpi slip (CS), and UV are the main radiological parameters to evaluate the deformity and therapeutic effect.<sup>[19]</sup> The RAA is measured by first drawing a line perpendicular to the line which connects the center of the radial head to the radial aspect of the radial epiphysis; another line parallel to the distal radial joint surface is, then, drawn. The RAA is defined as the angle alpha ( $\alpha$ ) between the joint surface and the perpendicular line. Normally, this angle ranges from 15° to 30°. The CS is assessed by a line drawn from the tip of the olecranon to the ulnar border of the radial physis. A positive CS is defined, when less than 50% of the lunate is radial to this line.

### Statistical analysis

Statistical analysis was performed using the Graphpad Prism version 8.0 software (Graphpad Software, San Diego, USA). Descriptive data were expressed in mean  $\pm$  standard deviation (SD), median (min-max) or number and frequency. The Paired two-group t-test was applied to compare ROM and radiological parameters before and after the treatment. The Mann-Whitney U-test was applied to evaluate the level of pain and CS before and after the treatment. A *p* value of <0.05 was considered statistically significant.

## RESULTS

Except for eight of the patients who were skeletally mature (34.8%), the rest 15 were skeletally immature (65.2%). The mean follow-up was 55.8 $\pm$ 7.4 (range, 41.4 to 72) months. Demographic characteristics and the amount of UL gained, EFT, DD, EFI, and DI of the patients are presented in Table I.

Radial head dislocation existed in all of these deformed forearms. The mean EFT, EFI and DI were 167.1 $\pm$ 13.7 d, 16.0 $\pm$ 1.64 d/cm and 9.9 $\pm$ 1.1 d/cm, respectively. The mean amount of extra ulnar length was 105.2 $\pm$ 12.5 mm. All of the exostoses were removed simultaneously.

The clinical outcomes at the final follow-up and statistical analysis of clinical and radiological parameters are presented in Table II. Patients described pain in 80% (VAS  $\geq$ 2) of the deformed forearms, with a mean VAS of 2.7 $\pm$ 1.9, either of which was durable (66.7%, 2 $\leq$  VAS  $\leq$ 4) or undurable (13.3%, VAS >4). All clinical parameters, but ROM of the forearm supination, were significantly improved. Preoperatively, the mean wrist flexion was 48.3 $\pm$ 6.2°, mean wrist extension was 60.5 $\pm$ 5.5°, mean radial deviation was 20.2 $\pm$ 3.1°, and mean ulnar deviation was

**TABLE I**  
The demographic characteristics and the amount of UL gained, EFT, DD, EFI and DI of the patients

Case	Sex	Age (year)	FU (m)	Side	Masada type	Ex	UL (mm)	EFT (d)	EFI (d/cm)	DI (d/cm)
1	F	14	41.4	R	IIb	Y	108.9	159	14.6	8.72
2	F	13	44.64	R	IIb	Y	99.3	147	14.8	8.76
3	F	18	42.36	R	IIb	Y	114.4	183	16.6	10.75
4	F	16	48.12	L	IIb	Y	106.2	166	15.63	9.42
5	F	21	45.84	L	IIb	Y	98.2	165	16.8	10.18
6	F	27	45	R	IIb	Y	103.4	167	16.15	9.67
7	F	35	58.92	R	IIb	Y	132.8	210	15.81	10.61
8	F	10	64.44	L	IIb	Y	87.1	185	21.24	13.78
9	F	8	56.88	R	IIa	Y	82.7	174	21.04	13.3
10	M	12	54.6	R	IIb	Y	95.3	152	15.95	9.65
11	M	12	55.32	L	IIb	Y	93.4	149	15.95	9.63
12	M	11	54.72	R	IIb	Y	92.5	158	17.08	10.59
13	M	15	54.24	R	IIb	Y	101.5	155	15.27	9.36
14	M	14	54.96	L	IIb	Y	117.4	166	14.16	9.37
15	M	17	55.56	R	IIb	Y	97.6	151	15.47	9.32
16	M	25	57.72	L	IIb	Y	124.7	177	14.19	8.82
17	F	19	72	L	IIb	Y	121.5	183	15.06	9.3
18	F	16	61.8	R	IIa	Y	104.6	165	15.77	10.04
19	F	23	57.72	L	IIb	Y	117.5	172	14.64	8.94
20	M	26	59.16	R	IIb	Y	97.3	171	17.57	10.79
21	M	30	58.2	L	IIb	Y	128.5	183	14.24	9.26
22	M	11	58.56	R	IIb	Y	110.6	167	15.1	9.31
23	M	17	44.76	L	IIb	Y	97.1	153	15.76	9.06
				R	IIb	Y	108.2	171	15.8	9.7

UL: Ulnar lengthening; EFT: External fixator time; DD: Duration of distraction; EFI: External fixator index; DI: Distraction index; FU: Follow-up time; Ex: Excision of exostoses; d: Day; Y: Yes.

17.1±3.5°. The mean forearm pronation was 65.5±7.0° and mean forearm supination was 76.1±4.8°. The mean elbow flexion was 117.9±10.3° and mean elbow extension was 1.2±2.3°. The mean preoperative DASH score was 41.8±10.7.

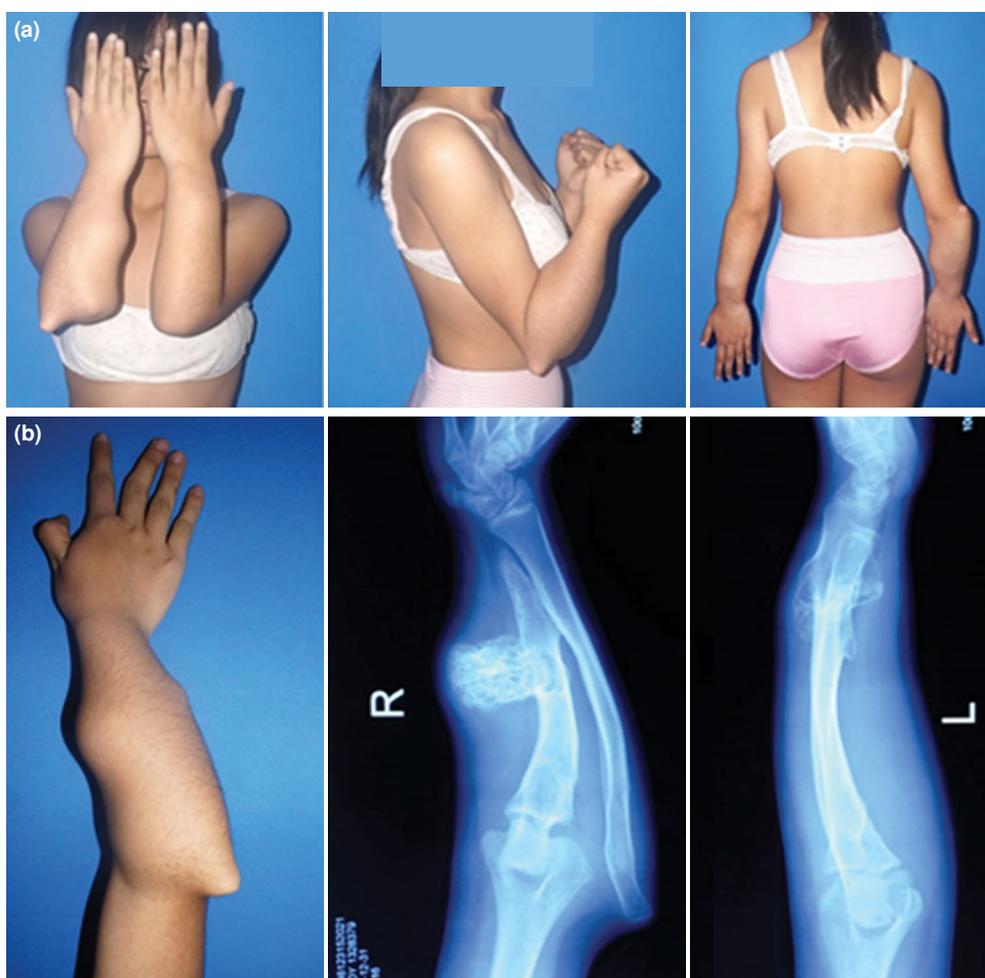
At time of the final interview, only seven of 30 deformed forearms remained slight pain, which could mostly be tolerated (mean VAS 0.5±0.8). The mean wrist flexion was 63.3±5.2°, mean wrist extension was 66.0±4.1°, mean radial deviation was 22.7±3.1°, and

men ulnar deviation was 19.8±3.0°. The mean forearm pronation was 76.5±6.2° and mean forearm supination was 76.5±5.7°. The mean elbow flexion was 136.1±9.5° and mean elbow extension was 2.6±1.3°. The mean postoperative DASH score was 9.7±4.4.

The mean ROM of the limbs at the point of final follow-up was significantly improved compared to the preoperative range of elbow flexion and extension, forearm pronation, and wrist flexion, extension, radial and ulnar deviation. However,

TABLE II Statistical analysis of clinical and radiological parameters								
Parameters	Preoperative			Last follow-up			t value	p
	n	%	Mean±SD	n	%	Mean±SD		
<b>Clinical</b>								
Elbow flexion (°)			117.9±10.3			136.1±9.5	13.23	<0.0001*
Elbow extension (°)			1.2±2.3			2.6±1.3	4.052	0.0003*
Forearm pronation (°)			65.5±7.0			76.5±6.2	8.957	<0.0001*
Forearm supination (°)			76.1±4.8			76.5±5.7	0.3243	0.7480
Wrist flexion (°)			48.3±6.2			63.3±5.2	15.31	<0.0001*
Wrist extension (°)			60.5±5.5			66.0±4.1	7.799	<0.0001*
Wrist ulnar deviation (°)			17.1±3.5			19.8±3.0	7.130	<0.0001*
Wrist radial deviation (°)			20.2±3.1			22.7±3.1	6.074	<0.0001*
VAS score			2.7±1.9			0.5±0.8	6.000	<0.0001*
DASH score			41.8±10.7			9.7±4.4	18.58	<0.0001*
<b>Radiological</b>								
Radial articular angle (°)			44.6±9.5			31.7±9.9	11.25	<0.0001*
Ulnar variance (mm)			-31.3±13.5			1.3±1.2	12.74	<0.0001*
Carpi slip	18/30	60		0/30	0			

SD: Standard deviation; \* Significant difference.



**FIGURE 2.** Preoperative appearance, (a) range of motion and (b) radiological details of the typical case were recorded physiologically and radiographically.

no significant improvement was observed in the forearm supination.

The mean preoperative RAA and UV were  $44.6 \pm 9.5^\circ$  and  $-31.3 \pm 13.5$  mm, respectively. Eighteen of 30 forearms presented positive CS, suggesting an appearance of ulnar deviation. At the time of the final appointment, the mean RAA was  $31.7 \pm 9.9^\circ$  and mean UV was  $1.3 \pm 1.2$  mm. Carpi slips were all corrected and no radial head dislocation recurred.

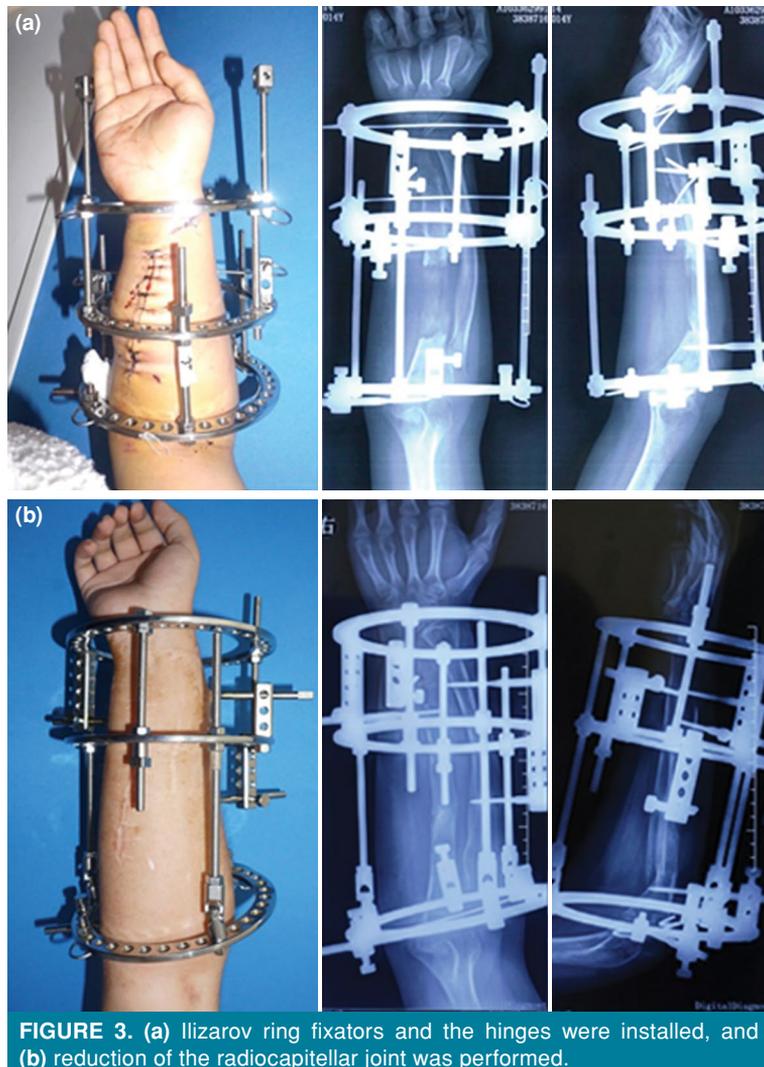
All patients were satisfied with the clinical outcomes and the cosmetic improvements, as the DASH score significantly improved.

Temporary nail track infection was seen in two of the forearms and was controlled with oral antibiotics. None of the patients suffered from nonunion, nerve palsy, compartment syndrome, or ankylosis of the ipsilateral elbow or the wrist.

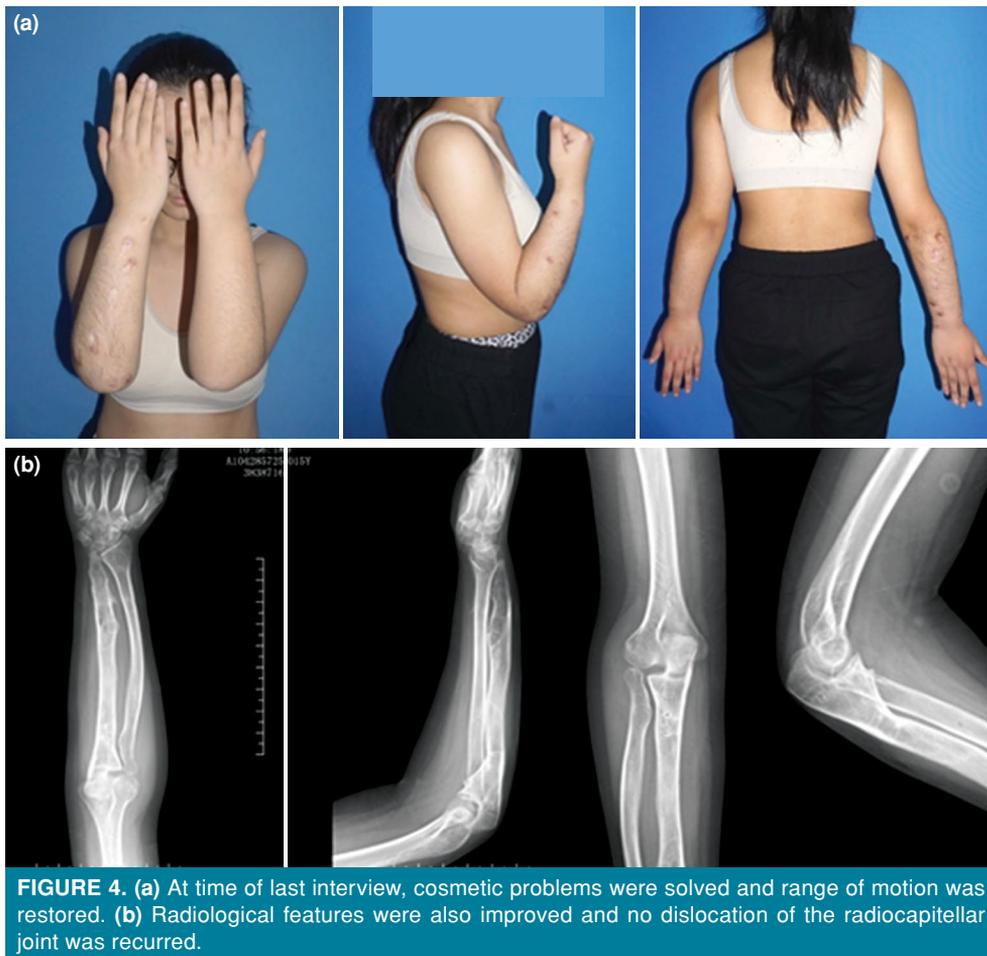
### Typical case

A 14-year-old girl suffered from Masada IIb type MHE. Her right forearm was in poor appearance, ulnar deviation, shortening and elbow prominence, in particular. Although the motion of her right elbow was not limited, the radiocapitellar joint remained dislocated and the whole forearm instability was obvious. Ipsilateral elbow flexion and extension, forearm pronation and supination, and wrist flexion, extension, ulnar deviation and radial deviation were  $130^\circ$ ,  $4^\circ$ ,  $71^\circ$ ,  $79^\circ$ ,  $54^\circ$ ,  $67^\circ$ ,  $18^\circ$  and  $22^\circ$ , respectively. For radiological properties, RAA of her right wrist was  $35.5^\circ$ , and UV was  $-12.9$  mm with a positive CS (Figure 2).

Apart from the excision of the exostoses, the patient received osteotomy and lengthening of the right ulna at first. The Ilizarov ring fixators were,



**FIGURE 3.** (a) Ilizarov ring fixators and the hinges were installed, and (b) reduction of the radiocapitellar joint was performed.



then, installed (Figure 3a). The radial head was reduced later in outpatient.

For the first step, an experienced surgeon performed the osteotomy under general anesthesia. After external fixator installation, the ROM of the elbow joint was well checked. Ipsilateral elbow flexion and extension were 118° and 6°, slightly reduced due to the intervention of the external fixators. After the lengthening of the ulna started, the patient received forearm X-ray examination monthly, until the proximal part of the dislocated radial head just reached the distal part of the capitellum. Additional elongation was applied for five days. The patient, then, came to the outpatient clinic.

The angulation of the ulna was corrected under moderate pressure and the dislocated radial head was reduced due to the distraction of forearm interosseous membrane and muscles. Radiography was applied to ensure the reduction of the radiocapitellar joint.

The patient acclimatized herself to the external fixator shortly after surgery. At the time of her final

visit (at 41.4 months), the ipsilateral elbow flexion and extension, forearm pronation and supination, and wrist flexion, extension, ulnar deviation and radial deviation were 150°, 4°, 80°, 80°, 66°, 70°, 20° and 25°, respectively. Stability of the elbow was eventually reconstructed and the ROM of elbow. Cosmetic problems were solved, and radiological results were also satisfying.

## DISCUSSION

In this study, all patients received excellent clinical and radiological outcomes after the whole procedure, since all the clinical and radiological parameters of ROM of the forearm supination were significantly improved and none of the patients developed recurrent radial head dislocation.<sup>[20]</sup> Besides, cosmetic problems of the forearm were perfectly solved, which enhanced self-confidence of the patients, a potential wealth for both the patient and the society. Thus, we found this novel hinge positioning method quite effective in treating MHE with severe radial head dislocation.

Multiple hereditary exostoses is a monogenetic autosomal dominant abnormality. Mutated and disabled gene exostosin-1 (EST-1) and/or exostosin-2 (EST-2) are the main cause in almost 90% of cases, whilst no new EST gene loci has been identified in the rest 10%.<sup>[1,21]</sup> It is believed that mutated gene EXT-1 and/or EXT-2 may impair cell-surface heparan sulfate proteoglycans (HSPG) synthesis, which consequently interferes with several signaling pathways, including fibroblast growth factor (FGF) pathway, and leads to abnormal proliferation of the chondrocytes during exostoses formation.<sup>[22-24]</sup> Recent studies have shown that the exostoses contain excessive extracellular heparanase which can paradoxically reduce HS level and exacerbate pathogenesis, but by cleaving mis-synthesized HSPG the excessive heparanase may produce abnormal HSPG fragments, recruit aberrant growth factors and progenitors, and play roles in MHE severity.<sup>[25]</sup>

Radial head dislocation occurs in Masada type II cases due to either proximal radial or distal ulnar exostoses, causes pain and instability, and limits elbow and forearm motions, in addition to shortened and bowing of the forearm.<sup>[4]</sup> It is believed that MHE combined with severe radial head dislocation is quite a difficulty while performing ulnar elongation alone to correct the deformity. Yan and Nan<sup>[8]</sup> treated eight pediatric Masada IIB MHE patients with Orthofix external fixators or Ilizarov annular fixators by proximal ulnar osteotomy and elongation. Although radiological (RAA) and functional (ROM of elbow, forearm and wrist) outcomes significantly improved, they did not receive reduction of the radial head in each patient. Chomiak et al.<sup>[15]</sup> reported three out of 28 MHE patients with radial head dislocation who were treated with UL, but none of the radial heads became reduced. The same failure of which dislocated radial head did not achieve concentric reduction was seen in seven forearms using ulnar osteotomy and monolateral external fixator gradual lengthening, reported by Li et al.<sup>[14]</sup>

Dislocated radial head in MHE can be reduced through gradual UL with Ilizarov frame with a certain intervention to the radius.<sup>[11-13,26]</sup> It is considered earlier that the traction force to pull down the radial head may come from either the forearm interosseous membrane or a transfixation wire through DRUJ.<sup>[11]</sup> However, given that Litzelmann et al.<sup>[27]</sup> failed to reduce the radial head in two of five MHE patients with unilateral external fixator and without radioulnar transfixation, transfixation of both radius and ulna may be more essential than expected previously. Interestingly, Ahmed<sup>[13]</sup> confirmed that

radioulnar transfixation is of great importance to achieve spontaneous radial head reduction with the Ilizarov fixators in their retrospective study. Besides, Cho and Jung<sup>[12]</sup> treated four MHE patients with dislocated radial head with osteochondromas excision, temporary radial head reduction pin and gradual lengthening of the ulna with Ilizarov frame and all four patients were satisfied with the cosmetic and functional outcomes. Other methods for radial head reduction include concomitant radial shortening osteotomy.<sup>[16]</sup> Despite the fact that optimistic outcomes have been achieved in treating radial head dislocation with Ilizarov ring fixators and radial reconstruction, detailed surgical maneuvers have never been reported in these attempts. Therefore, the installation of the Ilizarov frame is often empirical and may sometimes result in poor outcomes.

We also previously noticed that ulnar elongation alone could not perfectly reduce the severely dislocated radial head or could develop re-dislocation. In those cases, additional hinges are applied after adequate ulnar elongation to correct ulnar angulation and reduce the dislocated radial head at the same time through the tension of the interosseous membrane and forearm muscles. Therefore, we currently establish our positioning of the hinges, which is based on the relative location among the ulna, the displaced radius and a hypothesized normal radius, as well as on the therapeutic goal of lengthening and angulation of the ulna. If necessary, CT scan of multiple transverse sections of the distraction callus should be obtained initially. Center of the dislocated radial head (R1) and that of a hypothesized reduced radial head (R2) are connected to center of the ulnar (O) separately in a selected plane. The optimal plane we select is at the middle of the distraction callus, where shows active osteogenesis effect. At this plane, angulation of the ulna for radial head reduction is the most flexible to perform. Midpoints of these two connections (M1 & M2) were then marked, connected and prolonged. This line is the perpendicular bisector of the paired axial hinges (H). The segment connecting the two axial hinges should travel through the CORA or be on the convex side of the CORA. The axis of the rotating hinge and the connecting line of the two midpoints intersects and its axis is perpendicular to the selected plane (Figure 1).

The most important innovation of this type of hinge positioning is that no matter where the dislocated radial head lies, it would always be reduced to the right place during gradual correction of the ulnar curvature, as the motion trail of the radial head is always parallel to the line which

connects the two midpoints and is perpendicular to the connection between the two hinges. As the axial hinges extend, the midpoint (M1) of the center of the dislocated radius and the center of the ulna moves toward the midpoint (M2) of the center of the hypothesized radius and the center of the ulna. Eventually, M1 and M2 get reclosed, and the center of the dislocated radius and that of the hypothesized radius get reclosed at the same time; in other words, the displaced radial head is reduced. Successful concentric reduction of all radial heads in our patients was a milestone in treating Masada type IIb MHE compared with previous studies which achieved only functional and cosmetic improvements, but left the radiocapitellar joint luxated or brought too much intervention to the radius for a radiological reduction. We did not attempt to restore the annular ligament due to atrophy after chronic dislocation of the radial head, while scar or fiber tissues might form ligament-like structures which prevented re-dislocation after reduction.

The indications to treat forearm MHE patients with this minimally invasive technique are as follows: (i) with severe radial head dislocation, (ii) limited ROM of elbow, forearm and wrist, and (iii) painful exostoses lesions with forearm curvature deformity. We, then, consider the followings: (i) previous resection of radial head, (ii) ulna absence or an ulna that is too short to install the Ilizarov frame and to perform osteotomy, and (iii) any other circumstances under which the patient cannot tolerate surgery, as the contraindication of this technique.

External fixators seem to be the current tendency in orthopedics, which indicates an optimistic application in forearm deformities.<sup>[8,11-16,27]</sup> The device enables gradual, progressive, and controlled reduction of the forearm, as well as the elbow joint, and avoids excessive soft tissue interruption as well as widespread scarring. Besides, our novel hinge positioning, which is based on the expectant length and angulation of the ulna, provides adequate and balanced traction through the ring fixators and averts limiting the motion of the elbow. Thus, early mobilisation and partial weight-bearing of the proximal arm are allowed in postoperative rehabilitation. This technique can be also a potential option for all types of radial head luxation and not just neglected Monteggia fracture or MHE, particularly.

This study has certain limitations. The number of samples of this study is rather small and follow-up time should be much longer and more frequent. This

distraction osteogenesis technique shares the same major disadvantages with any other external fixator surgeries: e.g., tract infection, discomfort, tightness of the tendons, nerve palsies, and nonunion.<sup>[13,26-29]</sup> Furthermore, recurrence of ulnar shortening and bending was observed in younger patients with MHE, as reported by Fogel et al.<sup>[19]</sup> We also failed to restore the morphological structure of the styloid process of the ulna. Besides, long-term follow-up for adolescent patients is expected, as we still do not know whether the radial head would re-dislocate or not as the patient grows up. Therefore, further cohort investigations should be carried out to confirm whether our novel hinge positioning is more effective in treating radial head dislocation surgically.

In conclusion, the severely displaced radial head caused by MHE can be reduced with Ilizarov ring fixators through lengthening and angulating of the ulna. We propose a specified hinge positioning method which depends on the locations of the olecranon, the displaced radial head, and the hypothesized normal radial head in the transverse section of the preoperative three-dimensional reconstruction of the elbow, as well as on the expected postoperative length and angulation of the ulna. Outcomes of this method are satisfactory, and this method could be an alternative treatment for MHE.

#### Declaration of conflicting interests

The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

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