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CLINICAL RESEARCH

Distal Radius Osteotomy with Volar Locking Plates Based on Computer Simulation

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Abstract

Background Corrective osteotomy using dorsal plates and structural bone graft usually has been used for treating symptomatic distal radius malunions. However, the procedure is technically demanding and requires an extensive dorsal approach. Residual deformity is a relatively frequent complication of this technique.

Questions/purposes We evaluated the clinical applicability of a three-dimensional osteotomy using computer-aided design and manufacturing techniques with volar locking plates for distal radius malunions.

Patients and Methods Ten patients with metaphyseal radius malunions were treated. Corrective osteotomy was simulated with the help of three-dimensional bone surface models created using CT data. We simulated the most appropriate screw holes in the deformed radius using computer-aided design data of a locking plate. During surgery, using a custom-made surgical template, we predrilled the screw holes as simulated. After osteotomy, plate fixation using predrilled screw holes enabled automatic reduction of the distal radial fragment. Autogenous iliac cancellous bone was grafted after plate fixation.

Results The median volar tilt, radial inclination, and ulnar variance improved from −20°, 13°, and 6 mm, respectively, before surgery to 12°, 24°, and 1 mm, respectively, after surgery. The median wrist flexion improved from 33° before surgery to 60° after surgery. The median wrist extension was 70° before surgery and 65° after surgery. All patients experienced wrist pain before surgery, which disappeared or decreased after surgery.

Conclusions Surgeons can operate precisely and easily using this advanced technique. It is a new treatment option for malunion of distal radius fractures.

Level of Evidence Level IV, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles for research, and that informed consent for participation in the study was obtained.
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Introduction

Malunion is a common complication occurring in distal radius fractures treated by closed reduction and cast immobilization [4, 7]. A considerable number of patients with malunions complain of wrist pain, restricted ROM in the wrist, reduced grip strength, unsightly appearance, and/or late neuropathy [6, 10, 14, 25]. Corrective osteotomy that restores anatomic configuration can improve these complaints in the majority of patients, and there have been numerous reports of osteotomy using structural bone grafting and nonlocking plates, usually dorsal, to stabilize the osteotomy [1, 6, 9–11, 14, 25, 27]. However, the procedure requires an extensive dorsal approach and causes tendon problems because dorsal plates sometimes result in tendon irritation after osteotomy [9, 11, 25, 27]. Furthermore, the osteotomy is usually a complex, demanding procedure, and previous studies revealed the rate of residual deformity ranged from 38% to 60% even after operations performed by experienced surgeons [9, 25, 27]. These findings may be attributed to the fact that malunion of distal radius fractures usually has a three-dimensional (3-D) deformity that sometimes is complex and extensive [1, 12]. Two-dimensional evaluation using plain radiographs does not always provide accurate information [1, 12, 18].

We developed a computer simulation system that allows surgeons to precisely evaluate a deformity and simulate a 3-D osteotomy using computer models reconstructed with CT data. We also developed an intraoperative guiding system using a custom-made surgical template that makes it possible to perform a 3-D osteotomy as simulated for the treatment of malunited forearm fractures, cubitus varus deformity, and malunited distal radius fractures [17, 18, 20, 22].

Volar locking plates with an anatomic contour have been introduced for treatment of distal radius fractures to provide rigid fixation and perhaps relieve tendon irritation [19, 23]. Corrective osteotomy using volar locking plates also has been reported [16, 24]. However, Malone et al. [16] reported dorsal tilt still remained in three of four patients they evaluated after performing this procedure. Using the computer-aided design (CAD) data of a locking plate in the above-mentioned simulation system, we may be able to perform a more accurate operation in a more systematic manner than was possible before.

We present our experience with this technique in our first 10 patients and evaluate clinical applicability. Our specific aims were to investigate (1) radiographic outcome and (2) clinical outcome as compared with the preoperative condition and (3) describe complications.

Patients and Methods

We retrospectively reviewed 10 consecutive patients with symptomatic distal radius malunions. Between February 2008 and November 2009, these 10 patients (all women) were treated with 3-D corrective osteotomy with volar locking plates using a custom-made surgical guide based on computer simulation (Table 1). Minimum followup was 7 months (median, 16 months; range, 7–28 months). The median age was 60 years (range, 27–79 years). Eight patients had extraarticular fractures (AO/ASIF classification, A3), and two had minimally displaced intraarticular fractures (AO/ASIF classification, C2). All showed metaphyseal, dorsally displaced malunions without intraarticular malunion. Initially, all patients were treated with closed reduction and cast immobilization. After bony union was achieved, they visited our institution complaining of wrist pain, deformity, and/or numbness in the median nerve region. The median interval between injury and surgery was 10 months (range, 2–360 months). Each patient provided informed consent, and approval was obtained from our research ethics board for this study.

To plan corrective osteotomy, we attempted to simulate a 3-D correction of the deformity using a computer model of the bone. The technique has been described in detail previously [17, 18, 20, 22]. The affected and contralateral forearms of all patients were scanned using a CT scanner

Table 1. Clinical data

Patient	Age (years)	Gender	Side	Fracture type	Delay until fracture osteotomy (months)	Additional procedure	Complications
1	79	Female	Right	A3	8	Ulnar shortening	Screw loosening* (ulnar plate)
2	59	Female	Right	C2	12	Carpal tunnel release	
3	27	Female	Left	A3	28	TFCC repair	
4	32	Female	Left	C2	2		
5	60	Female	Right	A3	18	Ulnar shortening	Screw loosening* (radial plate)
6	58	Female	Right	A3	5		
7	47	Female	Left	A3	7		Tendon problem[†] (EPL)
8	60	Female	Right	A3	360		
9	61	Female	Right	A3	4	Tendon repair (FPL)	
10	77	Female	Left	A3	33	Ulnar shortening	
Average	56				48		

* Revision surgery using a longer plate was required; [†]hardware removal was required; TFCC = triangular fibrocartilage complex; FPL = flexor pollicis longus; EPL = extensor pollicis longus.

(LightSpeed Ultra 16; GE Medical Systems, Waukesha, WI, USA) with a low-radiation dose technique (scan time, 0.5 seconds; scan pitch, 0.562:1; tube current, 10–30 mA; tube voltage, 120 kV) [1]. Scans were performed with the patient in a prone position with the shoulder at full elevation, elbow at full extension, forearm neutral, and both limbs overhead to reduce radiation exposure to the head and eyes. The DICOM data were sent to a workstation (Dell Precision™ Workstation 390; Dell Inc, Round Rock, TX, USA). 3-D bone surface models of the entire bilateral radius and ulna were created from the 1.25-mm slice digital data using an original computer program based on the Visualization Toolkit (Kitware, Clifton Park, NY, USA). First, the proximal part of the model of the affected radius was semiautomatically superimposed on the corresponding part of the mirror image of the contralateral normal radius, which was considered the goal model. Second, the same procedure was applied to the distal part. Thereafter, the degree of deformity was evaluated as the distance between the mirror image of the normal radius and the image of the affected radius superimposed proximally to distally. On the basis of the evaluation, corrective osteotomy was simulated on the computer (Fig. 1) [17, 18]. The distal fragment usually had dorsal angulation, shortening, and pronation deformities, and approximately 50% of the cases showed a radial tilt on 3-D evaluation. An opening-wedge osteotomy was considered appropriate for all patients.

Using a CAD model of a volar locking plate (Alliance® plate system; Newclip Techniques SAS, La Haye-Fouassiere, France), the most appropriate location for a volar locking plate and screws was simulated by an operator to fit the volar surface of the reduced bone model and to achieve subchondral support (Fig. 2A). Thereafter, the location and direction of the screw holes in a deformed radius model were calculated by the computer to automatically correct the deformity after osteotomy-osteosynthesis using a volar locking plate (Fig. 2B). During the simulated operation, the plate was fixed to the distal radius fragment first (Fig. 2C), and plate fixation of the radial shaft using the predrilled screw holes enabled automatic reduction (Fig. 2D).

To reproduce the preoperative simulation during the actual surgery, a custom-made osteotomy template with drilling guide holes and an osteotomy slit were designed on the basis of the preoperative 3-D computer simulation to exactly fit onto the volar surface of the distal radius using commercially available software (Magics RP; Materialise, Leuven, Belgium) (Fig. 2A). On the computer,

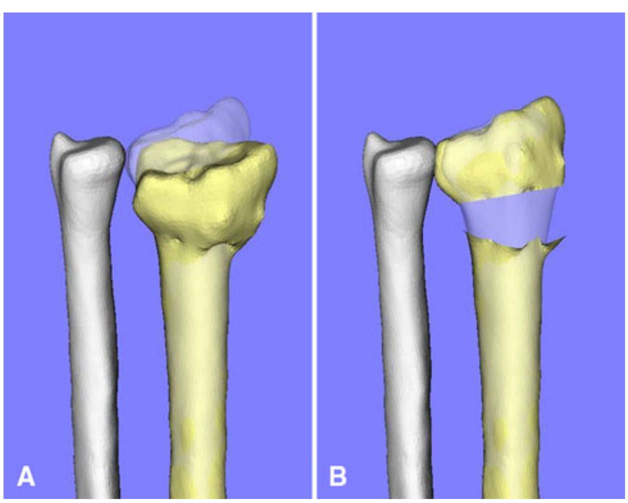

Fig. 1A–B (**A**) On the computer, the proximal part of the affected radius model was superimposed on the corresponding part of the mirror image of the contralateral normal radius. (**B**) Corrective osteotomy was simulated by considering the mirror image as the goal model.

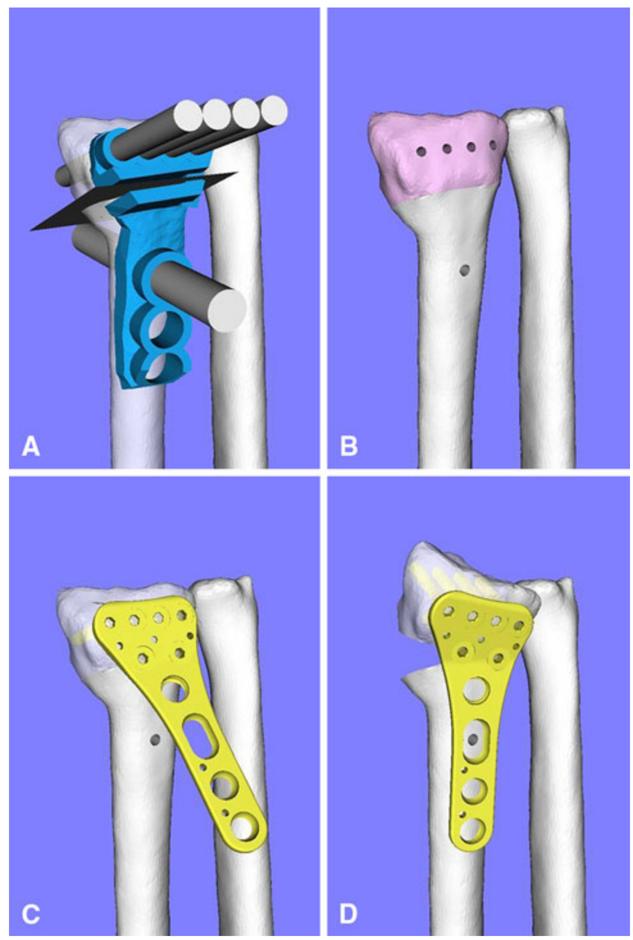

Fig. 2A–D A 3-D computer simulation of a corrective osteotomy is shown. (**A**) On the computer, a custom-made osteotomy template with drilling holes and an osteotomy slit was designed on the basis of the preoperative 3-D computer simulation. (**B**) The location and direction of the screw holes in the deformed radius model were calculated to spontaneously reduce the deformity after osteosynthesis. (**C**) During the operation, the plate was fixed to the distal radius fragment first. (**D**) During the operation, plate fixation of the radial shaft using predrilled screw holes enabled automatic reduction.

an appropriately sized block was placed on the volar surface of the distal radius that was to be exposed during surgery. The osteotomy plane, multiple cylinders of drilling guide, and the bone were subtracted from the block. The computer design of the custom-made template was completed by shaping it [18]. The surgical guide was embodied as a plastic model through rapid prototyping technology that automatically constructs physical objects from computer data (Eden250; Objet Geometries, Rehovot, Israel) with medical-grade resin (Fig. 3).

Fig. 3 The osteotomy template was embodied as a real plastic model.

To start surgery, the volar surface of the distal radius was exposed through a volar approach between the flexor carpi radialis and the flexor pollicis longus muscles. The pronator quadratus was detached from the radius, and the osteotomy template was closely fit onto the volar surface of the distal radius (Fig. 4A). Then, through the guiding holes on the template, we predrilled into the subchondral bone of the distal radius and into the shaft of the radius. The periosteum was detached around the bone and an elevator was inserted between the bone and periosteum dorsally to protect the extensors. We then osteotomized the volar half of the bone with a bone saw through the cutting slit and used an osteotome to complete the osteotomy (Fig. 4B). After the osteotomy was completed, the distal fragment was mobilized by release of the periosteum and the brachioradialis muscle. The plate was fixed to the distal radius fragment first by inserting the distal locking screws into the predrilled screw holes (Fig. 4C). Thereafter, the proximal part of the plate was pushed against the stem of the radius followed by screw fixation into the predrilled screw hole on the radius and the sliding hole on the plate (Fig. 4D). This manipulation brought about automatic angular correction of the distal radial fragment. Under a fluoroscope, radial length then was adjusted by spreading the osteotomy space using a laminar spreader inserted into the osteotomy site. Finally, the other proximal screw fixations were completed. (Video 1 shows the 3-D corrective osteotomy. Supplemental video is available with the online version of CORR). Autogenous iliac cancellous bone was grafted into the opening site of the osteotomy (Fig. 5). Three patients showing residual tightness of the distal radius fragment and

Fig. 4A–D (**A**) The osteotomy template was fixed on the volar surface of the radius. (**B**) After osteotomy through the cutting slit in the template, (**C**) the plate was fixed to the distal radius fragment first using predrilled screw holes. (**D**) Plate fixation of the radial shaft enabled automatic reduction.

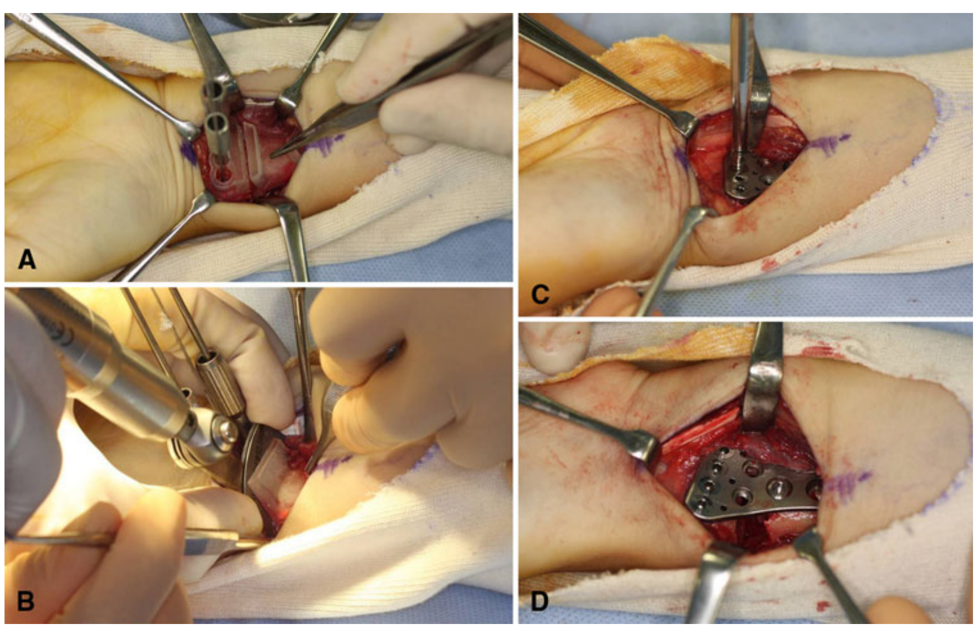

Fig. 5 A postoperative radiograph of the wrist shows good anatomic correction.

difficulty in preserving enough radial length even after release of the periosteum and the brachioradialis muscle underwent ulnar shortening osteotomy combined with the radial osteotomy (Patients 1, 5, 10). One patient with carpal tunnel syndrome underwent release of the carpal tunnel (Patient 2), one patient with instability of the distal radioulnar joint underwent repair of the triangular fibrocartilage complex (Patient 3), and one patient with rupture of the flexor pollicis longus tendon underwent tendon repair (Patient 9) at the time of corrective osteotomy. Cast immobilization was applied for 3 weeks postoperatively in all patients. After removal of the plaster, the patients were encouraged to actively exercise the wrist and forearm under supervision of a physiotherapist.

Radiographic and clinical evaluations were conducted for all patients before surgery and at the most recent followup. Union was considered complete when the osteotomy line had disappeared and osseous trabecular continuity was confirmed. Volar tilt, radial inclination, and ulnar variance were evaluated from radiographs [8]. The values used for our study were the averages from two independent observers.

For clinical evaluation, wrist flexion-extension was measured with the goniometer placed along the axis of rotation and with the forearm in a neutral position [3]. Forearm rotation was measured using a goniometer with the humerus in a vertical position and the elbow in 90° flexion [26]. Grip strength was measured using a hand dynamometer (Matsumiya Medical Instruments, Tokyo, Japan) and was recorded as a percentage of that of the contralateral, normal side. Pain was graded as none (no pain), mild (occasional pain with excessive use of the hand), moderate (persistent, but endurable pain), or severe (pain necessitating analgesic control). The patient graded the level of satisfaction as very satisfied, satisfied, neither satisfied nor dissatisfied, dissatisfied, or very dissatisfied [15].

The differences between the preoperative and postoperative radiographic values, ROM, and grip strength were determined by the Wilcoxon signed-rank sum test; preoperative and postoperative scores for pain were compared using the Wilcoxon signed-rank test. Significance was established at $p < 0.05$.

Results

All osteotomy sites united at a median of 4 months (range, 2–5 months) after surgery. The median volar tilt, radial inclination, and ulnar variance improved from −20°, 13°, and 6 mm, respectively, before surgery to 12°, 24°, and 1 mm, respectively, after surgery ($p = 0.007$, $p = 0.007$, and $p = 0.01$, respectively) (Table 2).

All patients experienced clinical improvement in range of wrist flexion, grip strength, and pain after the procedure ($p = 0.01$, $p = 0.006$, and $p = 0.007$, respectively). The median wrist flexion improved from 33° before surgery to 60° after surgery. The median wrist extension was 70° before surgery and 65° after surgery ($p = 0.18$). The median range of forearm pronation was 80° before surgery and 85° after surgery ($p = 0.06$). The median range of forearm supination was 80° before surgery and 90° after surgery ($p = 0.29$). The median grip strength improved from 37% to 80% of that of the normal side. All patients experienced wrist pain before surgery, which disappeared or decreased after surgery. Seven patients were very satisfied and three were satisfied with the operation (Table 3).

Early postoperative screw loosening occurred in two patients with osteoporosis. One patient (Patient 5) experienced loosening of the diaphyseal screws of the radial plate and the other patient (Patient 1) had loosening of screws of the ulnar plate. These two patients required revision surgery using longer plates. One patient experienced irritation of the extensor pollicis longus tendon necessitating hardware removal (Patient 7). No other major complications, including nonunion, neurovascular compromise, and infection, were observed.

Discussion

To treat limb deformities, we developed a computer simulation system and an intraoperative guiding system using

Table 2. Radiographic results

Patient	Time to bone union (months)	Volar tilt (degrees)			Radial inclination (degrees)			Ulnar variance (mm)		
		Preoperative	Last followup	Unaffected side	Preoperative	Last followup	Unaffected side	Preoperative	Last followup	Unaffected side
1	3	−18	16	14	11	21	25	5	3	1
2	4	−30	14	16	10	28	26	6	2	2
3	2	−20	11	12	22	23	27	0	0	0
4	2	−17	21	26	15	22	25	6	2	2
5	5	0	10	26	6	27	24	7	3	0
6	5	−40	0	10	8	25	30	10	0	0
7	3	−55	19	20	20	24	29	2	−1	−1
8	4	−12	12	15	17	23	25	3	0	0
9	3	−17	11	15	2	20	24	8	3	3
10	4	−47	11	16	15	25	23	8	0	0
Average	4	−27	13	17	13	24	26	6	1	1

Table 3. Functional results

Patient	Wrist ROM (flexion/extension) (degrees)			Forearm ROM (pronation/supination) (degrees)			Grip strength (% of normal side)		Pain		Level of satisfaction
	Preoperative	Last followup	Normal side	Preoperative	Last followup	Normal side	Preoperative	Last followup	Preoperative	Last followup	
1	50/30	50/50	80/70	60/80	70/45	80/80	17	100	Moderate	Mild	Satisfied
2	35/80	70/80	75/80	90/90	90/90	90/90	66	100	Moderate	None	Very satisfied
3	60/80	90/90	90/90	80/90	90/80	90/90	69	77	Moderate	None	Very satisfied
4	40/60	80/70	80/80	70/70	90/90	90/90	62	86	Moderate	None	Very satisfied
5	80/70	60/60	80/80	80/80	80/80	80/90	45	105	Moderate	None	Very satisfied
6	−20/20	45/40	80/80	0/40	50/90	80/90	0	59	Moderate	Mild	Satisfied
7	20/70	60/60	70/80	80/50	90/90	90/90	16	70	Moderate	None	Satisfied
8	30/90	60/90	80/90	90/90	90/90	90/90	64	83	Mild	None	Very satisfied
9	30/45	50/55	80/80	90/90	80/90	90/90	21	69	Moderate	None	Very satisfied
10	0/80	60/70	85/85	70/80	80/90	80/90	29	68	Moderate	None	Very satisfied
Average	33/63	63/67	80/80	71/76	81/84	86/89	39	82			

a custom-made surgical template that makes it possible to perform a 3-D osteotomy as simulated [17, 18, 20, 22]. The purpose of the current study was to present our first experience with distal radial osteotomy performed in 10 patients for distal radius malunions performed using volar locking plates using a custom-made surgical guide based on computer simulation and to evaluate its clinical applicability. Our specific aims were to investigate radiographic outcome and clinical outcome as compared with the preoperative condition and describe complications. In this series, good radiographic and functional results were achieved. Early postoperative screw loosening occurred in two patients with osteoporosis and one patient experienced irritation of the extensor pollicis longus tendon.

The current study was based on a preliminary series, therefore it had several limitations, which included a relatively small number of patients, the absence of a control group, and combined procedures such as release of the carpal tunnel, repair of the triangular fibrocartilage complex, and tendon repair. There may be additional criticism that the preoperative deformities and ROM deficits in this series were relatively mild compared with those reported in previous studies [1, 6, 16].

Residual deformity is a relatively frequent complication of corrective osteotomy using plates even if it has been performed by an experienced surgeon [6, 9, 16, 25, 27]. Fernandez [6] reported dorsal tilt remained in six of 20 patients after performing the procedure using dorsal plates and a structural bone graft. Malone et al. [16] also reported an unresolved dorsal tilt in three of four patients when using volar locking plates. Conversely, Athwal et al. [1] reported good radiographic results after the procedure using a 3-D planning and intraoperative navigation system with an optic sensor. Good radiographic results also were achieved in this series with no remaining dorsal tilt. We considered 3-D evaluation and planning to be key to greater anatomic reduction because malunion of distal radius fractures usually has a 3-D deformity that can be complex and extensive [1, 12].

Good functional results also were achieved in this series. We consider anatomic correction to lead to favorable functional results. The median ranges in wrist flexion and extension were 60° and 65°, respectively, at the time of final followup. These results were slightly better than the results obtained with the procedure using dorsal plates [1, 6] but were similar to the results obtained with the procedure using volar locking plates [16, 24]. Although the preoperative deformities and ROM deficits in the studies using volar locking plates were less than those in studies using dorsal plates, we believed the procedure with volar locking plates to have the potential to provide better ROM postoperatively because of rigid fixation and less invasiveness for the extensors.

One of the benefits of this technique using a custom-made surgical guide is that the intraoperative procedure is simple and undemanding to accomplish. The conventional technique usually requires several steps. After osteotomy, a structural bone graft is shaped to fit the opening site of the osteotomy to restore the physiologic volar tilt and radial inclination, a structural bone graft is inserted into the space, and the distal fragment then is fixed with a plate to maintain the reduction [6, 14, 24]. Malone et al. [16] reported rigid fixation using volar locking plates with fixed-angle screws allows the use of a cancellous bone graft, not a structural bone graft that needs extra effort to shape it. In their technique, determining the position and direction of the distal locking screws for anatomic correction was essential. However, it may be demanding, particularly in cases with complex deformities. In our technique that uses a computer simulation and an intraoperative guiding system, we were able to perform surgery in a simplified fashion because plate fixation using predrilled screw holes achieves automatically precise reduction of the distal radial fragment.

Early postoperative screw loosening occurred in two patients with osteoporosis necessitating revision surgery using longer plates. In the computer system, we simulated the operation without considering the resistance of soft tissue or the bone quality. Therefore, the successful outcomes partly depend on the experience of the surgeon, even using these advanced techniques. To avoid these complications, we now suggest careful evaluation of the bone quality of the patient before surgery, and for patients with osteoporosis, we suggest surgeons try to avoid excessive lengthening of the radius or shortening of the ulna during the computer simulation.

When dorsal plates are used, a high incidence of plate removal has been reported because of painful hardware, tendon rupture, and/or irritation [9, 10, 27]. In this series, one patient also experienced irritation of the extensor pollicis longus tendon caused by longer screws of the third extensor compartment. This complication is thought to be avoidable. When volar locking plates are used, properly locating the plates and an adequate screw length are important to avoid tendon problems [2, 5, 13]. In the computer system, we can simulate the best location for the plates and calculate the best screw length. For these cases, however, the length of screws was not calculated in the preoperative simulation.

Other disadvantages of the technique include radiation exposure during CT scanning, the need for specialized computer programs available only at our hospital at this point, the time and effort required for computer simulation, and the cost of the custom-made template. However, regarding radiation exposure, our simulation system can produce 3-D bone models with low-dose radiation that is $\frac{1}{30}$ of the normal radiation dose for the forearm [21]. We also plan to distribute our simulation system as commercial software in a few years. Computer simulation takes 2 to 3 hours for a trained operator, and the cost of manufacturing the template is approximately $50 (US dollars). Therefore, these shortcomings have been reduced with the advance of technology.

This was the first study providing evidence for the feasibility of clinical application of 3-D corrective osteotomy using a custom-made surgical guide manufactured based on computer simulation in combination with volar locking plates for the treatment of distal radius malunions. Using this advanced technique, surgeons can operate precisely and easily. We thus believe the technique reported herein can be considered a new treatment option for malunion of distal radius fractures.

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