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A Comparison of Radiographic Outcomes between 3D Preoperative Planning and Conventional Planning in the Osteosynthesis of Distal Radius Fractures

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Background: To assess the usefulness of three-dimensional (3D) digital pre-operative planning, we compared the radiographic parameters of the distal radius from 3D planning and conventional planning after osteosynthesis of distal radius fractures. We hypothesized that the use of 3D digital planning may improve radiographic outcomes for reduction and decrease the risk of correction loss.

Methods: Sixty wrists of 60 distal radius fracture patients were randomly divided into two groups according to the order of hospital visits. Thirty wrists were treated with 3D preoperative planning as the plan group. Another thirty wrists were treated with conventional preoperative planning as the control group. Both groups were treated with volar locking plates. In the plan group, 3D digital preoperative planning and a surgical simulation were performed in order to determine the reduction and placement of the implants in addition to the plate/screw size prior to surgery. In the control group, conventional preoperative planning was performed. Ulnar variance, volar tilt, and radial inclination were measured at one week, three and six months after surgery. Difference of the measurement of radiographic parameters between operated and healthy side wrists were compared between plan and control groups at one week after surgery. Loss of corrections for radiographic parameters were compared between plan and control groups.

Results: The differences between the operated and healthy side wrists were significantly smaller in the plan group compared to the control group for the volar tilt and radial inclination ($p < 0.05$).The loss of corrections for ulnar variance and volar tilt were significantly smaller in the plan group compared to the control group at six months after surgery ($p < 0.05$).

Conclusions: 3D preoperative planning offers better reduction accuracy and reduces correction loss in the osteosynthesis of distal radius fractures.

Keywords: *Three-dimensional, Distal radius fracture, Osteosynthesis, Locking plate, X-ray*

INTRODUCTION

To recognize the distal radius fracture displacement and to choose the appropriate implants, a three-dimensional image of distal radius is important. It has been reported that there are several advantages of three-dimensional guidance for correction of the fracture and insertion of plate screws.[1-3] Surgical procedures tend to have better outcomes if preceded by appropriate planning. Generally, templates have been used for the preoperative planning of fracture managements. Digitization for the planning of fracture surgery has not been fully utilized, and sometimes tracing paper is still in clinical use. Therefore, we developed a three-dimensional (3D) digital pre-operative planning software for the osteosynthesis of distal radius fractures.[4] In this study, we hypothesized that the use of 3D digital preoperative plan-

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ning may improve radiographic outcomes for reduction and decrease the risk of correction loss. The objectives of this study were to determine the utility of 3D digital planning for the reduction of distal radius fractures by comparing the post-operative wrists with the healthy side wrists, and evaluate the correction loss after surgery by comparing radiographic parameters between 3D digital preoperative planning and conventional method.

METHODS

The study protocol received approval from our Institutional Review Board (No. 14-21). This study was registered as NCT02909647 at ClinicalTrials.gov. Informed consent was obtained from all individual participants included in the study. Sixty wrists of 60 distal radius fracture patients, who underwent osteosynthesis using volar locking plates (43 females, 17 males; age range 16–87, mean age 61.4 years), were evaluated. Patients were excluded if they had a previous history of traumatic injuries to the arm, both sides of their wrists were injured, and/or ulnar shaft fractures. The patients were randomly divided into two groups according to the order of hospital visits. Plain radiographs (posterior-anterior and lateral view) of bilateral wrists and CT scan of injured wrist were taken for both groups. Thirty patients in the plan group were prepared by 3D digital preoperative planning, and another thirty patients in the control group were prepared by standard preoperative assessment on plain radiograph and CT scans. One patient dropped out from the follow-up in the plan group. According to the preoperative CT scans, fractures were classified using the AO classification system.

Preoperative planning and ostheosynthesis

In the plan group, 3D digital preoperative planning and a surgical simulation were performed in order to determine the reduction and placement of the implants in addition to the plate/screw size prior to surgery. Reduction and placement of the implants were simulated using newly developed software by the authors (Zed-Trauma, LEXI Co., Ltd. Tokyo, Japan).[4] The planning of the software was based on digital imaging and communications in medicine (DICOM) data from CT scans. All preoperative planning group patients had preoperative CT scans. The CT comprised contiguous sections of 1 mm thickness. The software allows the surgeons to 1) visualize the fracture displacement, 2) simulate repositioning of the fragments, 3) place the plate and screws, 4) adjust the sizes of the implants, and 5) check the shape after

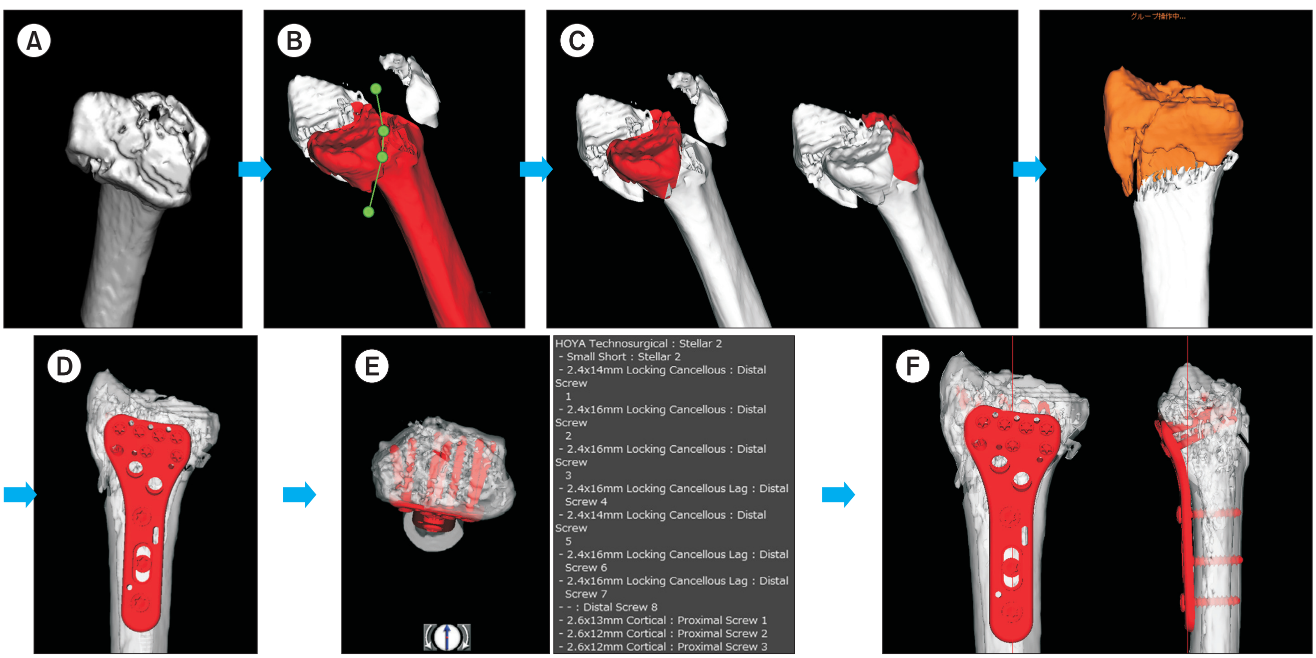

Fig. 1. Steps for the 3D preoperative planning. (A) After importing the DICOM images to the software, a 3D image of the distal radius was made. (B) Distal radius was segmented according to the fracture fragments using the cut function. (C) Each fragment was repositioned in accordance with fracture lines. After repositioning the fragments, the bone shape was checked three dimensionally. (D) The plate size and position were adjusted according to the fracture type and width of distal radius. (E) The longest possible screws that did not penetrate the extensor compartment or radiocarpal joint were determined. (F) The final image of the 3D preoperative planning.

the reduction and implant placement with the measuring of anatomical shape (Fig. 1). After entering the DICOM images to the software, the 3D image of the distal radius was made. Each distal radius fracture was segmented according to the main fracture fragments using the cut function. Each fragment was repositioned in accordance with fracture lines. After repositioning the fragments, bone shape was checked three dimensionally. Reduction of the fragment was performed to regain the volar tilt and the radial inclination, and less than a 2 mm step-off for the intra-articular displacement. The reduction shape was compared with the healthy side wrist X-ray (Fig. 2). Simulation of volar locking plate implantation was done using 3D templates by changing the size of the plates and screws. The Stellar II locking plate (HOYA Technosurgical, Inc., Tokyo, Japan) was used in this study. This plate system has small, medium, and large width sizes, and short and long lengths. The screws were available from 10 to 24 mm for the distal (2.4 mm diameter), and 10–20 mm for the proximal (2.6 mm diameter). A computer aided design model of different implant sizes was installed in the software. The plate size was chosen when it covered the distal fragment maximally and did not exceed the width of the distal radius. The screws lengths were chosen when they reached 75–100% of the distance between the volar cortex and dorsal cortex. After planning, the osteosynthesis was performed under general anesthesia. During the surgery, the operator referred to the reduction and placement of the plate by comparing images between the pre-operative plan and fluoroscopy. The surgeons tried to reproduce the planned position of the implant by checking the distances from the margin of the implant to the margin of the radius under the fluoroscopy. The screw sizes were finally determined with intraoperative measurement in reference to the preoperative plan. If there were differences between the measurement of the screw size during surgery and the preoperative plan, the shorter screw sizes were chosen.

In the control group, preoperative planning was performed using conventional posterior-anterior and lateral views of the radiographs. According to the healthy side wrist X-ray image, the plate size was chosen using the conventional template (Fig. 3). The reduction shapes were referred to the healthy side wrists. After planning, the osteosynthesis was performed under general anesthesia in the same manner as the plan group.

In the plan group, there were 17 operations performed by the resident/fellows, and 13 operations performed by the orthopaedics and hand surgery specialists. In the control group, there were 13 operations performed by the resident/fellows, and 17 operations performed by the orthopaedics and hand surgery specialists. When the surgery performed by the resident/fellows, the specialist supervised the surgery.

Evaluation

To evaluate the accuracy of the anatomical reduction, ulnar variance, volar tilt and radial inclination of the post-operative wrist X-rays were compared with those of the healthy side wrist in both the plan and control groups. The measurements were performed at one week, three and six months after surgery. The posterior-anterior view was obtained with the shoulder abducted 90°, the elbow flexed 90°, the ulna perpendicular to the humerus, and the forearm in the neutral position. The lateral view was obtained with the elbow flexed 90° and adducted against the trunk. The wrists were in a neutral position with no flexion, extension, or deviation in either view. Volar tilt was measured on a lateral view. The angle between a line along the distal radial articular

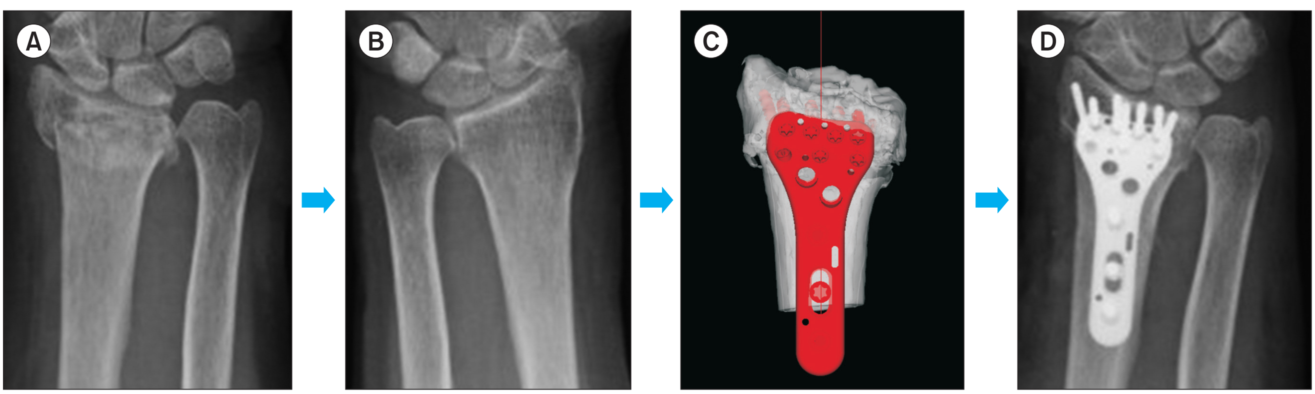

Fig. 2. An example image of 3D preoperative planning. (A) Initial X-ray of the injured wrist. (B) X ray of the healthy side wrist. (C) 3D image of the distal radius after the reduction and implant placement simulation. (D) X-ray after the osteosynthesis.

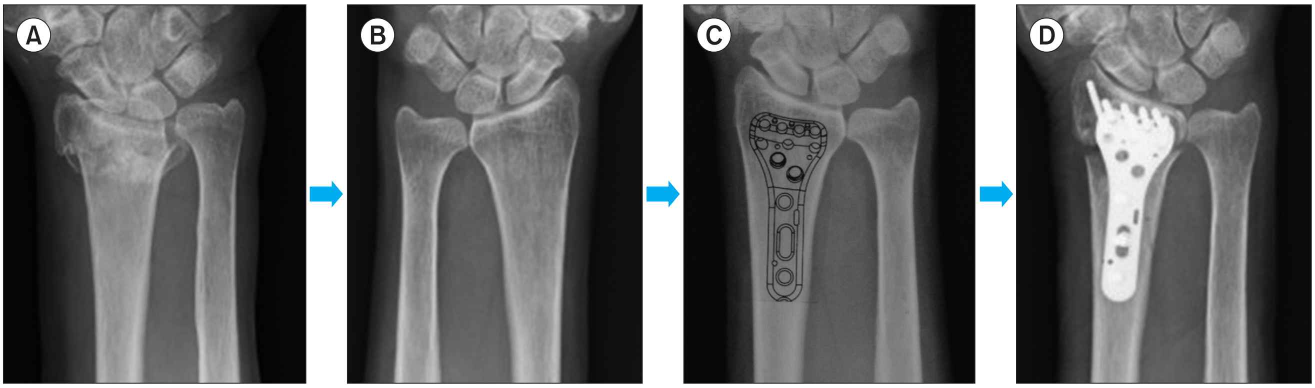

Fig. 3. An example image of conventional preoperative planning. (A) Initial X-ray of the injured wrist. (B) X-ray of the healthy side wrist. (C) Overlapping image of the healthy side distal radius with template placement. (D) X-ray after the osteosynthesis.

surface and a line perpendicular to the longitudinal axis of the radius at the joint margin was measured as volar tilt. Ulnar variance and radial inclination were measured on a posterior-anterior view. The distance between a line perpendicular to the long axis of the radius at its ulna side corner and a line at the distal edge of the ulnar head was measured as ulnar variance. The angle between one line connecting the radial styloid tip and the ulnar aspect of the distal radius and a second line perpendicular to the longitudinal axis of the radius was measured as radial inclination. The radiographic parameters were measured separately by one hand surgeon, and one resident.

Statistical analysis

The results are expressed as mean ± standard deviation. Before the analysis for the accuracy of the reduction, inter-rater reliability was evaluated between the hand surgeon and the resident. Intra-class correlation coefficient (ICC) was used to evaluate the inter-rater reliability. Since the ICC was high enough (0.92–0.96, $p < 0.01$), the hand surgeon's data were taken for the accuracy of the reduction. Accuracy of the anatomical reduction was evaluated by the absolute value of the difference between operated and healthy side wrists for the radiographic parameters at one week after the surgery. In addition, loss of corrections were defined as the differences between the measurements at one week and the measurements at three or six months. The accuracy of reduction and the loss of corrections were compared between the plan and control groups using Welch's t-test. For the loss of corrections in the volar tilts and the radial inclinations, the absolute values were compared among the groups. All analyses were performed using SPSS version 13.0 (SPSS, Chicago, IL, USA). p values of < 0.05 were considered significant.

RESULTS

In the plan group, there was one patient with A2 fracture, three patients with A3 fracture, one patient with B3 fracture, two patients with C1 fracture, ten patients with C2 fracture, and thirteen patients with C3 fracture. In the control group, there was one patient with A2 fracture, five patients with A3 fracture, one patient with B3 fracture, two patients with C1 fracture, eleven patients with C2 fracture, and ten patients with C3 fracture. There were 21 females and 9 males in the plan group (age range 17–86, with a mean age of 60.1 years). There were 22 females and 8 males in the control group (age range 16–87, with a mean age of 62.6 years). There were no significant differences in the distribution of age, sex and fracture type between the plan and control groups.

The results of the accuracy for the anatomical reduction are shown in Fig. 4. The differences of the ulnar variances were 0.92 ± 0.76 mm and 1.10 ± 0.94 mm in the plan and control group, respectively. The differences of the volar tilts were 2.53 ± 1.78 degrees and 4.00 ± 3.10 degrees in the plan and control group, respectively. The differences of the radial inclinations were 2.00 ± 1.58 degrees and 3.40 ± 3.00 degrees in the plan and control group, respectively. The differences between the operated and healthy side wrists were significantly lower in the plan group compared to the control group in the volar tilt and radial inclination ($p = 0.03$ for both volar tilt and radial inclination).

The results of the correction loss are shown in Fig. 5. The loss of corrections for the ulnar variances were 0.24 ± 0.30 mm and 0.43 ± 0.40 mm at three and six months after surgery in the plan group, respectively. The loss of corrections for the ulnar variances were 0.49 ± 0.59 mm and 0.72 ± 0.58 mm at three and six months after surgery

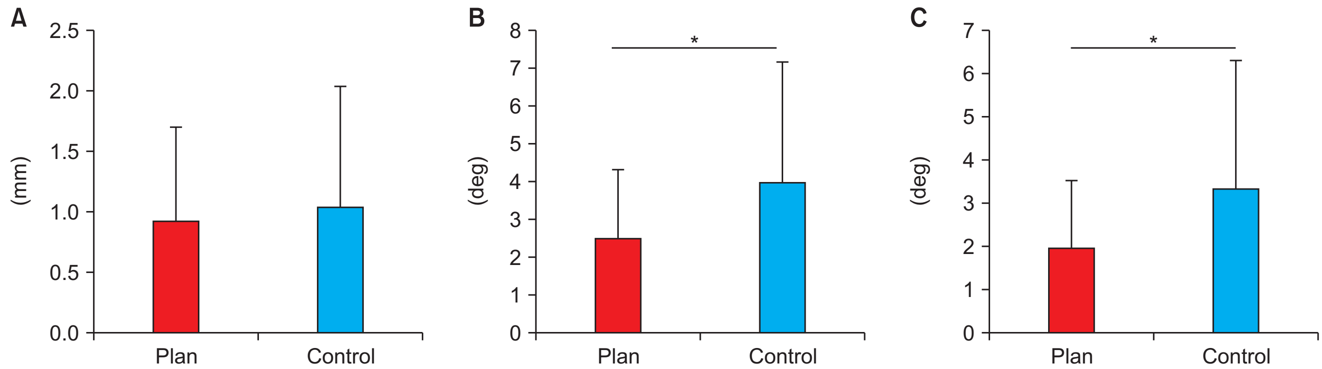

Fig. 4. Results of the accuracy for the reduction shape. (A) Ulnar variance. There were no significant differences between the plan and control groups. (B) Volar tilt. The differences between the operated and healthy side wrists were significantly lower in the plan group compared to the control group (**p* < 0.05). (C) Radial inclination. The differences between the operated and healthy side wrists were significantly lower in the plan group compared to the control group (**p* < 0.05).

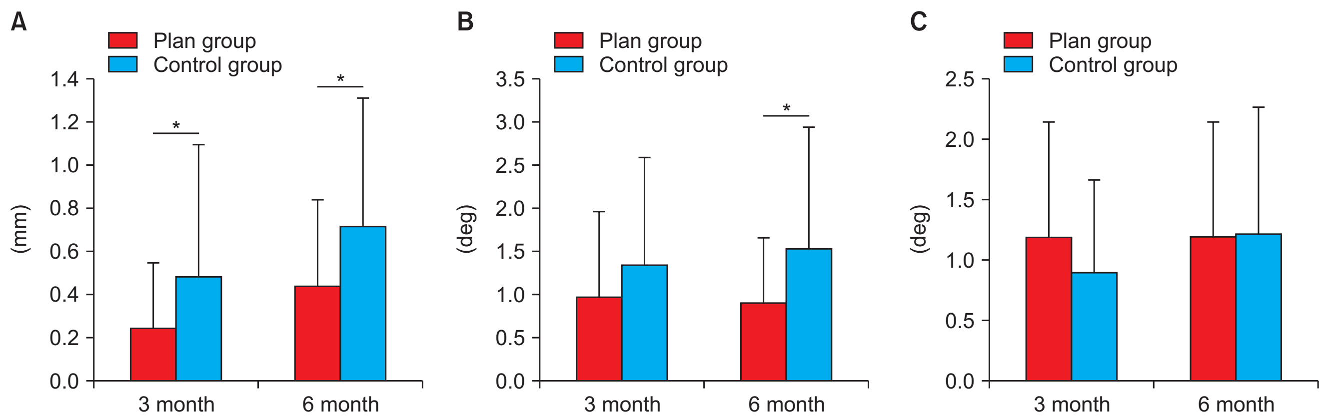

Fig. 5. Results of correction loss. Red bar shows the results of plan group. Blue bar shows the results of control group. (A) Ulnar variance. The loss of corrections were significantly smaller in the plan group compared to the control group at both three and six months after surgery (**p* < 0.05). (B) Volar tilt. The loss of corrections were significantly smaller in the plan group compared to the control group at six months after surgery (**p* < 0.05). (C) Radial inclination. There were no significant differences between the plan and control groups.

in the control group, respectively. The loss of corrections for the ulnar variances were significantly smaller in the plan group compared to the control group at both three and six months after surgery (*p* = 0.04 for both three and six months after surgery).

The loss of corrections for the volar tilts were 0.97 ± 0.98 degrees and 0.89 ± 0.75 degrees at three and six months after surgery in the plan group, respectively. The loss of corrections for the volar tilts were 1.37 ± 1.19 degrees and 1.54 ± 1.36 degrees at three and six months after surgery in the control group, respectively. The loss of corrections for the volar tilts were significantly smaller in the plan group compared to the control group at six months after surgery (*p* = 0.04).

The loss of corrections for the radial inclinations were 1.17 ± 0.97 degrees and 1.19 ± 0.94 degrees at three and six months after surgery in the plan group, respectively. The loss of corrections for the radial inclinations were 0.90 ± 0.76 degrees and 1.22 ± 1.01 degrees at three and six months after surgery in the control group, respectively. There were no significant differences between the plan and control groups.

DISCUSSION

The present study demonstrated that the 3D digital preoperative planning for the distal radius fractures provided smaller differences of the radiographic shape between the operated and healthy side wrists compared to the conventional planning. In addition, the loss of corrections for the ulnar variance and volar tilt were smaller in the 3D planning compared to the conventional planning.

The goal of distal radius fracture treatment is restoration of normal function with good joint stability.[5,6] Recently, great improvement has been achieved in the treatment of distal radius fractures with the use of volar locking plates.[7-10] Although fixation with volar locking plates is rigid, there are still some problems in terms of the loss of correction after fixation.[11-13] There are several reasons for the loss of correction. Very comminuted fragments cause late collapse of the distal radius. Poor fitting to the distal radius leads to improper positioning of the plate, and this results in fixation failure.[14] In addition, inappropriate implant choices may cause displacement after surgery. If the bony alignment is not properly restored, function may remain poor even after healing. Restoration of bony alignment is a minimum necessary requirement for treatment success, as it is closely related to bone healing.

In this study, we observed that 3D preoperative planning remained the reduction shape until 6 months after surgery compared to the control group. This may be because of appropriate implant choices, especially of the distal locking screws. The lengths of the distal locking screws are important as they relate to fixation strength.[15] It also relates to maintain reduction shape. It has been suggested that locked unicortical distal screws of at least 75% the length of bicortical screws produce construct stiffness similar to bicortical fixation.[16] In our previous study, we found that more appropriate screw choices were obtained in the plan group compared to the control group.[17] More than eighty-five percent of the screws were within the range of 75–100% in the 3D preoperative planning group. On the other hand, there were less than seventy-five percent of the screws within the range of 75–100% in the conventional planning group. It was suggested that the 3D image simulation allowed more appropriate choices for the screw lengths. The appropriate lengths of the screws hold mechanical stability and restore reduction shape. This may be one reason for the better accuracy of reduction shape and the smaller loss of correction in the plan group.

In addition to the screw choices, the size and the placement of the plates are other important factors. As positioning of the plate is closely related to the stability of the distal radius fragment, it is necessary to find an adequate position for the plate in each fracture. One benefit of 3D planning is that it allows visualization of the best plate fitting to the distal radius from all angles. In addition, the coverage of the distal radius was simulated through the placing of different plate sizes. It has been suggested that the plate needs to be positioned distally enough to provide sufficient strength for subchondral support. However, there is an increased risk of screw penetration into the radiocarpal joint at the same time. Using the 3D planning, such a risk may be avoided. Thus, 3D planning provides more confidence to the surgeon regarding the placement of the plate. This may be another reason for the decrease in the loss of correction in the plan group.

The anatomic features of the distal radius are very complex. The development of digital preoperative planning for orthopaedic trauma surgery has outdistanced the planning of joint arthroplasty. In most cases, classical tracing paper, or simple measurement on the image viewer, are still in clinical use. The benefits of the conventional method are simple, accustomed usage, low cost, and lower exposure to radiation. However, it is difficult to image the exact placement of the plate or the screw choices prior to surgery. Recently, 3D imaging methods for surgical planning in trauma surgery have been developed using CT scans.[1-3] It is useful when considering the geometry in the articular fracture. Even if the CT scan visualizes the 3D image of the fracture, it is still difficult to image proper reduction and placement of the implant. Three-dimensional pre-operative planning is good for pre-processing, visualization, which permits viewing and comprehending the fracture displacement, and manipulation.

The limitations of the present study should also be noted. First, this protocol requires the CT scan. It may be possible to reduce irradiation exposure for simple fractures by reducing image slices. In addition, satisfactory justification for the medical expenses through good clinical outcomes may be required. Second, there were still some differences in the radiographic parameters even when the 3D planning were used. This may be because there is still a gap between the three-dimensional image and the actual image of fluoroscopy in the surgical room. Development of a method to compare the 2D image of the X-ray and the 3D image of the CT scan may be required. Third, it is necessary to define adequate plate and screw sizes with biomechanical study. Fourth, different experience years of surgeons were another limitation. Finally, we did not compare these reduction shapes with clinical outcomes. Since the radiological shape is closely related to clinical outcome, we focused on the reproducibility and the reduction loss in this study. Evaluation is required as to whether this method improves clinical outcome in relation to the fracture healing.

In conclusion, we evaluated the clinical utility of 3D pre-operative digital planning by comparing the radiographic parameters of the distal radius between 3D planning and conventional planning after the osteosynthesis of distal radius fractures. It was found that there were better reproducibility for the reduction shape in the 3D planning compared to the conventional planning. In addition, the loss of corrections for the ulnar variance and volar tilt were smaller in the 3D planning compared to the conventional planning. These results suggest that 3D preoperative planning offers better reduction accuracy and reduces correction loss in the osteosynthesis of distal radius fractures.

CONFLICT OF INTEREST

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article. The software described in this study has been developed through a collaborative study between the corresponding authors' institution and a software company. One of the authors (YY) suggested the function necessary for the program. Another author (KA) belongs to the company wrote the program. There is no financial relationship between the authors' institution and the software company.

STATEMENT OF INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

STATEMENT OF HUMAN AND ANIMAL RIGHTS

The procedures described in this manuscript were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008. The protocol for this study was reviewed and approved by our Institutional Review Board.

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