3D imaging in corrective osteotomy of the distal radius
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CHAPTER 3

POSITIONING EVALUATION OF CORRECTIVE OSTEOTOMY FOR THE MALUNITED RADIUS. 3D CT ANALYSIS VERSUS 2D RADIOGRAPHIC ANALYSIS AND RELATION WITH CLINICAL OUTCOME

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ABSTRACT

In this paper we investigate retrospectively the postoperative position of the distal radius after a corrective osteotomy evaluated by two-dimensional compared to three-dimensional imaging techniques in the follow-up. We further investigate whether malposition correlates with clinical outcome.

Twenty-five patients who underwent a correction osteotomy were available for follow-up. The residual positioning errors of the distal end were determined retrospectively using standard two-dimensional radiographic evaluation and three-dimensional evaluation based on a CT scan of both forearms, the contralateral healthy radius serving as reference. For three-dimensional analysis, the use of an anatomical coordinate system for each reference bone allowed us to express the residual malalignment parameters in displacements ($\Delta x$, $\Delta y$, $\Delta z$) and rotations ($\Delta \varphi_x$, $\Delta \varphi_y$, $\Delta \varphi_z$) for aligning the affected bone in a standardized way with the corresponding reference bone. We investigated possible correlations between malalignment parameters and clinical outcome using patients questionnaires.

Two-dimensional radiographic evaluation showed a radial inclination of 24.9 ± 6.8°, a palmar tilt of 4.5 ± 8.6° and an ulnar variance of 0.8 ± 1.7 mm. For three-dimensional analysis, residual displacements were ($\Delta x$, $\Delta y$, $\Delta z$): 2.6±3 mm, 2.4±3 mm and -2.2±4 mm. Residual rotations were ($\Delta \varphi_x$, $\Delta \varphi_y$, $\Delta \varphi_z$): -6.2±10°, 0.3±7° and -5.1±10°. The large standard deviation is indicative of persistent malalignment in individual cases. Statistically significant correlations were found between three-dimensional rotational deficits and clinical outcome. These correlations were not found with two-dimensional evaluation parameters.

Considerable residual malalignments and the statistically significant correlations between malalignment parameters and clinical outcome confirm the need for better positioning techniques.
INTRODUCTION

One of the possible complications of a distal radius fracture is a malunion,1 which may result in a weak, deformed, stiff or painful wrist.2 In some cases a corrective osteotomy is needed to improve function and reduce the pain. In current corrective osteotomy surgery, conventional planning and evaluation parameters are usually based on two orthogonal radiographs, a lateral and a posteroanterior view of the wrist joint. These radiographs are used to determine the radial inclination, palmar tilt and ulnar variance, which are used to assess the rotations and translations needed to correct the position of the distal radius segment.3-5 Corrections are based either on population mean values or on corresponding parameters of the contralateral wrist. The latter showed to be a better reference for restoring the position of the distal radius.6-8 Planning, treatment and evaluation of a corrective osteotomy are not unambiguous since measurement of two-dimensional (2D) radiographic parameters is hampered by inter- and intraobserver variations. Moreover, the reliability of measurements from 2D images is hampered by overprojection and rotations around the longitudinal axis of the bone are hidden, possibly causing a misinterpretation of the correction parameters.9-12 The postoperative position after a corrective osteotomy of the malunited distal radius may seem adequate on conventional posteroanterior and lateral radiographs of the wrist but, due to the limitations of 2D imaging mentioned above, the distal radius can still be malpositioned after surgery. Recently, a number of computer-assisted three-dimensional (3D) methods have been proposed to measure malalignment before corrective surgery.13-19 An advantage of 3D techniques is the possibility to assess 6 malalignment parameters: 3 displacements along and 3 rotations around 3 orthogonal axes, not only the shortening and the 2 angulations as seen on 2D radiographs. Recent reports have shown a high intrinsic accuracy of these 3D methods.20;21

In this study we retrospectively investigate the postoperative position of the distal radius after a corrective osteotomy that was based on conventional 2D planning and 2D intraoperative evaluation. It is known from studies performed with 2D radiographs that the severity of a distal radius malunion is associated with higher disability, although statistically significant correlations are never found.22;23 We tested the null hypothesis of equal 3D positions in left and right radii. We further investigate whether 3D positioning parameters are correlated with clinical outcome.

MATERIALS AND METHODS

In this retrospective study all patients who underwent a corrective osteotomy of the distal radius that was planned and evaluated intraoperatively with the help of plain radiographs
in the years 2000-2010 were contacted for postoperative evaluation. Of these 45 patients five patients were unavailable for follow-up, five patients were excluded from this study because of a fracture of the contralateral wrist, six patients didn’t want to participate and four patients had other musculoskeletal diseases next to the distal radius fracture. The remaining 25 subjects (23 female/2 male, average age 59 years, range 43-75) were available with a mean follow-up of 39 months (range 6-86). Corrections had been planned with the corresponding radiographic parameters of the contralateral wrist (radial inclination, palmar tilt and ulnar variance). The patients were treated by 3 different surgeons.

For our study, all subjects underwent a CT scan of both forearms (Philips Brilliance 64 CT scanner, Cleveland, Ohio, voxel size 0.45 x 0.45 x 0.45 mm, 120 kV, 150 mAs, pitch 0.6). In addition, posteroanterior and lateral radiographs were made of both wrists. A single hand surgeon measured the radial inclination, palmar tilt and ulnar variance, using the 2D radiographs. This was done to exclude inter-observer variability. In the 3D evaluation, done by a single investigator experienced with the software, residual malalignment parameters were analyzed. The method of finding these 3D malalignment parameters is previously described by Dobbe et al.\textsuperscript{20} The accuracy of this 3D procedure has proven to be precise with a translation precision of (mean ± SD) 0.36 ± 0.13 mm and a rotation precision of 0.12 ± 0.07º. In this method, the mirrored CT image containing the healthy radius was segmented to create a virtual 3D model of the radius. Subsequently, a distal part of the bone model and a larger proximal part are selected and aligned with the CT image of the contralateral corrected radius of the subject by intensity-based image registration. The malalignment is then shown as the degree in which the poses of the distal segments differ. (Fig. 1A) This allows us to calculate the displacements ($\Delta x$, $\Delta y$, $\Delta z$) and rotations ($\Delta \varphi_x$, $\Delta \varphi_y$, $\Delta \varphi_z$) for aligning the affected bone with the reference bone. The 3D malalignment parameters were expressed in terms of an anatomical coordinate system that is aligned with the segmented model of each individual reference radius.\textsuperscript{24} This allows comparing the positioning parameters. All image analysis steps described above were performed with custom software.

For investigation of the relation between malalignment and clinical outcome, the following standard validated questionnaires were used: Disabilities of the Arm, Shoulder and Hand Questionnaire (DASH), the Michigan Hand Outcomes Questionnaire (MHOQ) and the Patient Rated Wrist and Hand Evaluation (PRWHE). Wrist and forearm function were evaluated by measuring flexion, extension, pronation, supination, radial and ulnar deviation.

We will compare the residual errors observed in this study with naturally occurring bilateral differences in the radius found in healthy individuals.\textsuperscript{25} The range of bilateral differences in healthy individuals is considered as an acceptable range for comparison with the results obtained in this study.

This study was approved by the Medical Ethical Committee of our hospital and informed consent was obtained from each subject.
Statistical Methods

We evaluated positioning using 2D and 3D techniques. The standard deviation (SD) was used to represent the variability in residual malalignment parameters. To assess the relationship between the 2D and 3D malalignment parameters, we performed univariate correlation analyses. We did the same for assessing correlations between these malalignment parameters and clinical outcome. To establish statistically significant differences we used paired t-tests. All statistical tests were 2-sided and a p-value below 0.05 was considered to indicate statistical significance.

RESULTS

Radiographic 2D evaluation

The results of the radiographic measurements (mean ± SD) for the whole group of 25 subjects at the time of follow-up are shown in table 1. It shows the radial inclination, the palmar tilt and the ulnar variance, for healthy and corrected radii. The high SD’s in the radiographic parameters for corrected radii compared to the unaffected radii are indicative for the variation due to planning and surgical treatment. Differences between radiographic parameters for healthy and corrected radii were calculated for each individual, resulting in a mean deficit and standard deviation for the whole group (table 2, last column).
Chapter 3

Evaluation of malalignment in 3D space

The null hypothesis of equal 3D positions in left and right radii can be rejected. Malalignment parameters obtained by 3D evaluation show residual errors in all six malalignment parameters. These are visualised in Fig. 2. For comparison, we also display naturally occurring differences between radii due to bilateral asymmetry from a previous 3D study in healthy individuals.25 (Table 2 and Fig. 2) Larger standard deviations were found for all parameters in the patient group compared to bilateral differences in healthy individuals. This confirms suboptimal reconstruction.

Correlations between 2D and 3D evaluation

Two radiographic evaluation parameters show statistically significant correlations with related 3D evaluation parameters. The radial inclination deficit correlates with parameter \( \Delta q_y \) \((r = 0.87, p < 0.05)\), the palmar tilt deficit with parameter \( \Delta q_x \) \((r = 0.78, p < 0.05)\). Although a high correlation was found, individual differences between 2D and the corresponding 3D parameter could be quite large for individual subjects as depicted by Fig.

<table>
<thead>
<tr>
<th>2D evaluation parameter</th>
<th>Healthy contralateral radius Mean ± SD</th>
<th>Corrected radius Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial inclination</td>
<td>24.9 ± 2.6 °</td>
<td>24.9 ± 6.8 °</td>
</tr>
<tr>
<td>Palmar tilt</td>
<td>12.6 ± 3.7 °</td>
<td>4.5 ± 8.6 °</td>
</tr>
<tr>
<td>Ulnar variance</td>
<td>0.1 ± 1.6 mm</td>
<td>0.8 ± 1.7 mm</td>
</tr>
</tbody>
</table>

Table 1. Radiographic evaluation parameters (mean ± SD) at the time of follow-up for the whole group of 25 subjects.

<table>
<thead>
<tr>
<th>Malalignment parameter (related 2D parameter)</th>
<th>25 patients Mean ± SD</th>
<th>20 healthy individuals Mean ± SD</th>
<th>Radiographic deficit in patients per individual Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta x )</td>
<td>2.6 ± 3.0 mm</td>
<td>-0.8 ± 1.2 mm</td>
<td></td>
</tr>
<tr>
<td>( \Delta y )</td>
<td>2.4 ± 3.1 mm</td>
<td>-0.0 ± 0.6 mm</td>
<td></td>
</tr>
<tr>
<td>( \Delta z )</td>
<td>-2.2 ± 4.6 mm</td>
<td>2.6 ± 2.0 mm</td>
<td></td>
</tr>
<tr>
<td>( \Delta q_x ) (Palmar tilt)</td>
<td>-6.2 ± 10.3 °</td>
<td>0.1 ± 1.0 °</td>
<td>8.1 ± 10.6 ° *</td>
</tr>
<tr>
<td>( \Delta q_y ) (Radial inclination)</td>
<td>0.3 ± 7.7 °</td>
<td>-0.6 ± 1.4 °</td>
<td>-0.0 ± 1.6 °</td>
</tr>
<tr>
<td>( \Delta q_z )</td>
<td>-5.1 ± 10.1 °</td>
<td>0.5 ± 5.0 °</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. 2D versus 3D malalignment parameters. The first column represents the whole group of 25 patients and shows 3D malalignment parameters of the corrected distal radius compared with the contralateral healthy wrist in each patient. The second column shows bilateral asymmetry parameters of the radius in a group of 20 healthy individuals from a previous 3D study.25 Also displayed are the related 2D radiographic evaluation parameters. Deficits between radiographic parameters for healthy and corrected radii were calculated per individual (last column). The symbol * indicates a statistically significant difference between the corrected and contralateral healthy radius (p < 0.05).
3. There was no statistically significant correlation between the ulnar variance deficit and parameter $\Delta z$ ($r = 0.17$, $p > 0.05$).

**Clinical outcome parameters**

Clinical outcome parameters are shown in Table 3. The DASH score was graded as excellent (0–24), good (25–49), moderate (50–74), or poor (75–100). According to this classification, 19 patients (76%) had an excellent outcome, 3 patients (12%) a good, 2 patients (8%) a moderate and 1 patient (4%) a poor outcome. These classifications were also seen for the other questionnaires.
Correlations between malalignment parameters and clinical outcome parameters

Correlation coefficients between the 2D or 3D malalignment parameters and clinical patient outcome are shown in table 4. The DASH, MHOQ and PRWHE scores, as well as the extension, pain and function outcome parameters show statistically significant correlations with one or more of the 3D rotational parameters (Δϕₓ, Δϕᵧ, Δϕz). No statistically significant correlation was found between the clinical outcome parameters and the displacement parameters Δx, Δy and Δz. There are also no statistically significant correlations between

<table>
<thead>
<tr>
<th>Clinical outcome parameter [best, worst]</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRWHE [0, 100]</td>
<td>29 ± 26</td>
</tr>
<tr>
<td>DASH [0, 100]</td>
<td>18 ± 22</td>
</tr>
<tr>
<td>MHOQ [100, 0]</td>
<td>82 ± 17</td>
</tr>
<tr>
<td>Extension [70, 0]</td>
<td>62 ± 16°</td>
</tr>
<tr>
<td>Flexion [75, 0]</td>
<td>61 ± 19°</td>
</tr>
<tr>
<td>Supination [90, 0]</td>
<td>84 ± 13°</td>
</tr>
<tr>
<td>Pronation [90, 0]</td>
<td>90 ± 0°</td>
</tr>
<tr>
<td>Pain [0, 50]</td>
<td>15 ± 12</td>
</tr>
<tr>
<td>Function [0, 50]</td>
<td>14 ± 15</td>
</tr>
</tbody>
</table>

Table 3. Outcome measurements of the patient group. For the DASH and PRWHE questionnaires 0 indicates a good hand function and 100 the worst possible wrist function. With the MHOQ questionnaire 100 is the best possible score and 0 indicates a bad wrist function. Pain and function are subscores from the PRWHE questionnaire (0 indicating no pain or good function and 50 indicating worst possible pain or function).
Positioning evaluation of corrective osteotomy

In this study we investigated, using accurate 3D imaging techniques, the position of the distal radius after a corrective osteotomy that was preoperatively planned and intraoperatively evaluated using established 2D radiographic assessment. In addition, we investigated correlations between residual malalignment parameters and clinical outcome. Surgery by different surgeons, different follow-up periods and the diversity of patient ages allow investigating general average and standard deviation in positioning parameters.

Clinical outcome and residual malalignments in this patient group, assessed by postoperative radiographic measurements, are similar to previous retrospective studies on corrective osteotomies of the malunited distal radius.26-28 On average, the radial inclination of the corrected radius compared well with the contralateral healthy side. This suggests an overall good result. However, a large standard deviation was observed (SD = 6.1), which indicates the inaccuracy of positioning for individual cases. The palmar tilt showed a large residual deficit between the healthy and corrected wrist and a large standard deviation (SD = 10.6).

The large standard deviation in the radiographic parameters could be explained by the fact that they are difficult to assess due to overprojection29,30 (Fig. 1B), and the fact that intraoperatively, it is sometimes difficult to bring the distal segment of the radius into flexion due to scar formation on the dorsal side of the wrist joint. In addition, the rotational deformities that were observed in this study have shown to affect the accuracy of measuring and evaluating the radial inclination and palmar tilt using plain radiographs.30 The

<table>
<thead>
<tr>
<th></th>
<th>DASH</th>
<th>MHOQ</th>
<th>PRWHE</th>
<th>Extension</th>
<th>Flexion</th>
<th>Pain</th>
<th>Function</th>
<th>Pronation</th>
<th>Supination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial inclination</td>
<td>0.28</td>
<td>-0.19</td>
<td>0.31</td>
<td>0.14</td>
<td>0.26</td>
<td>0.23</td>
<td>0.28</td>
<td>0.09</td>
<td>-0.17</td>
</tr>
<tr>
<td>Palmar tilt</td>
<td>-0.36</td>
<td>0.24</td>
<td>-0.36</td>
<td>-0.31</td>
<td>-0.02</td>
<td>-0.32</td>
<td>-0.35</td>
<td>-0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>Ulnar variance</td>
<td>0.19</td>
<td>-0.09</td>
<td>0.09</td>
<td>-0.10</td>
<td>-0.25</td>
<td>0.03</td>
<td>0.10</td>
<td>-0.19</td>
<td>0.09</td>
</tr>
<tr>
<td>(\Delta x)</td>
<td>-0.12</td>
<td>0.01</td>
<td>-0.08</td>
<td>0.14</td>
<td>-0.09</td>
<td>-0.05</td>
<td>-0.06</td>
<td>-0.21</td>
<td>0.13</td>
</tr>
<tr>
<td>(\Delta y)</td>
<td>0.23</td>
<td>-0.32</td>
<td>0.33</td>
<td>0.20</td>
<td>-0.10</td>
<td>0.35</td>
<td>0.33</td>
<td>0.04</td>
<td>-0.03</td>
</tr>
<tr>
<td>(\Delta z)</td>
<td>0.07</td>
<td>0.01</td>
<td>0.04</td>
<td>0.14</td>
<td>0.03</td>
<td>0.12</td>
<td>0.03</td>
<td>0.30</td>
<td>-0.14</td>
</tr>
<tr>
<td>(\Delta \phi x)</td>
<td>-0.29</td>
<td>0.26</td>
<td>-0.43</td>
<td>* -0.40</td>
<td>* -0.09</td>
<td>-0.45</td>
<td>* -0.43</td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>(\Delta \phi y)</td>
<td>-0.40</td>
<td>* 0.30</td>
<td>-0.39</td>
<td>* -0.11</td>
<td>-0.17</td>
<td>-0.32</td>
<td>-0.37</td>
<td>-0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>(\Delta \phi z)</td>
<td>-0.42</td>
<td>* 0.44</td>
<td>* -0.39</td>
<td>* -0.42</td>
<td>* -0.23</td>
<td>-0.28</td>
<td>-0.38</td>
<td>* -0.30</td>
<td>* -0.16</td>
</tr>
</tbody>
</table>

Table 4. Correlation coefficients between 2D or 3D malalignment parameters and patient outcomes. The symbol * indicates a statistically significant correlation (p < 0.05) between a 2D or 3D malalignment parameter and clinical outcome parameter.
large variations observed in parameter $\Delta \phi_z$, which is not observable on radiographs, affect measuring the radial inclination and palmar tilt from 2D radiographs.\textsuperscript{30} When investigating rotational malalignments for individual cases, the 3D malalignment parameters can be exceptionally large, up to 26°.

There were statistically significant correlations between the radial inclination deficit assessed per individual and the parameter $\Delta \phi_y$ and also between the palmar tilt deficit and parameter $\Delta \phi_x$. It is logical to find these correlations when projecting the 3D bone on the $xz$ and $yz$ planes in Fig. 1A. It yields a representation of the posteroanterior and lateral view as in standard radiographs. Although it is logical to find a relatively high correlation between abovementioned parameters, it is not high enough to indicate total similarity between 2D and 3D parameters as visualized in Fig. 3.

The fact that there was no statistically significant correlation between the ulnar variance deficit and parameter $\Delta z$ can be explained by the fact that $\Delta z$ represents the bilateral difference in total length of both radii while the ulnar variance reflects the relative position of the radius to the ulna. These are not to be compared with each other.

In this study, finding a correlation between malalignment parameters and clinical outcome is hampered by the fact that surgery is accompanied by soft tissue trauma with possible issues such as neuropathy, tendon problems, TFCC or intercarpal ligament tears, which also influence clinical outcome.\textsuperscript{1,2} Two patients had a follow-up of less than 1 year, which may slightly affect clinical results. But since we mainly focus on positioning of the distal radius this will hardly affect our analysis. The retrospective nature of this study did not enable us to include the preoperative assessment of the severity of the preoperative deformities. Neither did we include inter- and intraobserver variability in our study. Of course, also the imaging technique of CT has it disadvantages such as additional time, cost and extra radiation. Another shortcoming of CT imaging is the presence of metal artifacts caused by a fixation plate, which was sometimes still in situ. In Fig. 4 we demonstrate the alignment procedure of the contralateral healthy radius model with the CT image of the corrected radius by intensity-based image registration. The effect of the plate on the matching procedure of the bone segments turned out to be negligible.

For future studies we recommend investigating prospectively if preoperative 3D planning of radial corrective osteotomies contributes to better positioning of the radius anatomy and better clinical outcome than the conventional 2D planning and evaluation techniques. To our knowledge, this is the first study that shows that angular deformities actually coexist with rotational deformities in distal radius malunions. This confirms that 2D radiographs are not accurate in planning a corrective osteotomy since rotational deformities affect the appearance of the distal radius in 2D radiographs and renders estimating the radial inclination and palmar tilt inadequate.\textsuperscript{30} In addition, this study demonstrates a statistically significant correlation between 3D rotational parameters and clinical outcome. This
Positioning evaluation of corrective osteotomy

Fig 4. The matching procedure of the contralateral healthy radius model (green line) with the CT image of the corrected radius by intensity-based image registration. The plate did not affect the ability to match the bone segments. Fig. A is the transverse section, Fig. B the sagittal section and Fig. C the coronal section view of the CT image.

does the need of restoring rotational deficits that are unseen on 2D images, using 3D planning and surgical techniques for better positioning in 3D space.
REFERENCES


