3D imaging in corrective osteotomy of the distal radius
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CHAPTER 1

GENERAL INTRODUCTION AND OUTLINE OF THE CHAPTERS

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BACKGROUND

An osteotomy is a surgical procedure in which a bone is cut to shorten, lengthen, or change its alignment. Osteotomy is an ancient surgical skill recognized as a surgical technique that could address a deformity, thereby improving function and appearance. A carefully planned and executed osteotomy can restore and preserve the patient's joint function and avoid the need for joint replacement surgery.

In medicine, various osteotomy techniques are known for correction of deformity, closure of bone defects and preservation of joint function. These range from skull to the hallux. All techniques have in common the need for appropriate imaging as well as a carefully thought out and executed surgical plan. Pre-operative planning is essential in the success of osteotomy surgery. This thesis will demonstrate the need for adequate imaging prior to the procedure and will focus on corrective osteotomy of the malunited distal radius.

A malunited radius is a condition that may occur after a radius fracture, and sometimes causes wrist complaints such as pain and limited function. Since the functionality of the hand and wrist is essential in daily life and almost any profession, reduced wrist functionality will have a direct impact on the social functioning of the patient involved as well as the economic value due to the inability to work, hospital stay, extramural aftercare and surgical revision procedures. Younger patients, particularly manual workers, do not easily tolerate the hand deformities and malfunction that result from poorly treated radial fractures. The higher life expectancy, with the resultant extended working life, has resulted in increased requests for treatment of malunited fractures in both young and older patients.

Good and effective treatment of wrist problems can improve the quality of care, the quality of life for the involved patients, and will increase labour participation. In the end, this will reduce the society's expenses due to workers compensation, medical expenses, and productivity losses.

In this thesis we investigate current surgical techniques and develop improved techniques for corrective osteotomy of the malunited distal radius. In order to give an introduction to this thesis, the anatomy of the wrist, etiology, clinical impact, surgical treatment and imaging techniques of malunited distal radius fractures will first be described in this chapter.

Functional anatomy of the wrist

The wrist (carpus) contains eight bones: the scaphoid, lunate, triquetrum, pisiform, trapezium, trapezoid, capitate and the hamate. The proximal transverse row forms a mobile connection between the two forearm bones and the carpus. It contains the scaphoid, lunate and triquetrum from radial to ulnar and these carpal bones articulate with the radius. (Figure 1) It allows multiple axes of motion (flexion, extension, pronation, supination, and radial or ulnar deviation).
The radius and the ulna are the long bones of the forearm. These two are connected over almost their entire length by a broad syndesmosis, the interosseous membrane of the forearm. This membrane reinforces and stabilizes the forearm together with the triangular fibrocartilage complex (TFCC) and the anular ligament. The anular ligament of the radius is a strong band of fibers, which encircles the distal end of the radius, and retains it in contact with the radial notch of the ulna.

The distal radioulnar (DRU) joint is formed by the connection between the ulnar groove in the radius (sigmoid notch) and the head of the ulna. The DRU joint, a pivot joint, permits pronation and supination of the wrist, together with the proximal radioulnar (PRU) joint. The articulation depends on the relative lengths of the radius and ulna. The carpal articular surfaces of the radius and ulna are at the same longitudinal level in most of the cases (ulnar-neutral variant). There is also the ulnar-negative variant in which the distal ulnocarpal articular surface of the ulnar head is shorter relative to the lunate facet of the carpal articular surface of the radius. In the ulnar-positive variant, the ulnar head extends past the distal radial articular surface toward the wrist. (Figure 3) Hereby the high pressure of the ulna on the carpus may be expected to cause injuries to the TFCC and also cause...
Any difference in length between the distal ends of the radius and ulna will significantly influence the biomechanics of the DRU joint and the wrist. Motion in the wrist involves highly complex movements of the individual carpal bones relative to one another and relative to the radius. Alterations in anatomy can cause a range of problems, for example when the distal radius is malunited.

**Malunion of the distal radius**

A malunion is union with incorrect anatomical alignment of the segments of a fractured bone. Fractures of the distal radius are approximately 27% of all limb fractures. A typical fracture of the distal radius is often induced when people fall on the outstretched hand (a so called FOOSH). (Figure 2) Approximately 5% of all distal radius fractures result in a symptomatic malunion of the bone. (Figure 3) In these cases, the radius is often shortened and deformed with wrong angulations of the distal end of the bone relative to the proximal part of the bone.
Clinical implications of a malunion

A malunion has implications for the clinical condition of the patient’s wrist. There are several causes that may contribute to symptoms of the wrist, such as nerves, blood vessels, muscles, tendons, ligaments and bones. Especially the osseous component can have a major impact on wrist function. A shortened and deformed radius often causes an ulnar-positive variant, also called “ulna plus”, a dorsal tilt and a reduced inclination of the radius on a radiograph. Due to the changed anatomy, there can be a mismatch in the anatomical relationships between the radius, the ulna and the carpal bones. This may cause pain, reduced range of motion, reduced grip strength, and can cause carpal instability and eventually osteoarthritis. These symptoms can be caused by changes in the DRU joint mechanics. Because of the disturbed relation there can be an ulnar abutment and wrong position of the carpus. This creates pain and motion limitation complaints.

Conventional imaging of the distal radius

Skeletal diagnoses usually are performed with two-dimensional (2D) radiographs. A routine radiographic work-up of the wrist involves two standardized radiographs of both wrists. This
Chapter 1

consists of a lateral view and a posteroanterior (PA) view.\textsuperscript{16} Radiographs must be made by using reproducible, controlled techniques. A neutral PA projection of the wrist is obtained with the arm abducted to the body in 90 degrees, the elbow flexed 90 degrees, and the hand held flat on the detector surface with no ulnar or radial deviation and no flexion or extension. A neutral lateral projection is obtained with the arm and wrist positioned as for a PA view of the wrist, except that the beam is directed parallel to the table, centered on the radial styloid.\textsuperscript{17} There is a number of wrist measurements that are important to the hand surgeon. The ones that are relevant to the (malunited) distal radius will be described below in detail.\textsuperscript{17}

Radial inclination – The angle measured between the distal articular surface of the radius and a line perpendicular to the long axis of the radius (Figure 4). It is measured on a PA view. Radial inclination is an independent variable in predicting functional outcome following distal radius fractures. Patients treated for distal radial fractures who have a radial inclination of less than 5 degrees have poorer results than those with normal or near normal inclination.\textsuperscript{18} Normal angles of radial inclination range between 16 degrees and 28 degrees, with a mean of 25 degrees.\textsuperscript{17}

Volar tilt – The tilt of the distal end of the radius, as determined from a lateral view. Again the angle measured between the distal articular surface of the radius and a line perpendicular to the long axis of the radius (Figure 4). Volar tilt is sometimes also called palmar tilt. It’s most common use is in assessing initial and residual deformities associated with fractures of the distal radius and in planning operative correction of malunited radii. Normal variations have been reported to vary between 0 degrees and 22 degrees with a mean of 15 degrees.\textsuperscript{17}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Standard radiographic measurements of the distal radius. Shown from left to right are the radial inclination and ulnar variance on the PA view and the volar tilt on the lateral view.}
\end{figure}
**Ulnar variance** – The relative axial position of the distal articular surfaces of the radius and ulna, determined from a PA view (Figure 4). Ulnar variance is defined as neutral, positive (plus), or negative (minus) on the basis of whether the distal articular surface of the ulna is aligned with the distal articular surface of the radius, or lies distal (ulnar plus) or proximal (ulnar minus) to it. (Figure 3) Ulnar variance differs among ethnic, gender, and age groups. In typical fractures of the distal radius, the ulnar variance is useful in describing shortening and serves as a useful prognosticator of functional outcome.

Corrective osteotomy of the distal radius has been introduced to restore the relation between the radial and ulnar distal ends. The small changes in ulnar variance that result from this surgical procedure can have a major effect on mechanical transfer characteristics. A change in ulnar variance of 1 mm or less can alter mechanical transfer characteristics by more than 25%.

**Conventional treatment of a malunited distal radius**

When surgery is indicated surgeons try to restore function and reduce pain as much as possible. A corrective radius osteotomy procedure is used to correct misalignment of the radial bone. The goal of this procedure is to restore the proper biomechanical functions of the wrist and hand by correcting the length and angulations of the deformed radius, since there is a relation between function and pain. Achieving acceptable results requires careful preoperative planning. In traditional planning of distal radius osteotomies, the lengths and angles of radiographic measures of the patient’s wrist are obtained from plain radiographs by simply measuring the shortening and reduced angulation of the distal radius. These lengths and angles are used to determine the amount by which the distal radius must be translated and rotated to restore its anatomically correct alignment.

The surgical procedure involves cutting the malunited distal radius near its original fracture site and restoring the original position of the distal radius segment according to the obtained radiographic measurements (Figure 5). The new position is often supported by a wedge-shaped bone graft or bone substitute, followed by fixation of the osseous structures with a fracture-fixation plate. Sometimes no supporting structures are used, and the fixation is solely by a fixed-angle fracture-fixation plate.

**Recent developments in imaging for corrective osteotomy**

As described above, in traditional planning of corrective osteotomies of the distal radius, the lengthening and angles to be corrected are obtained from plain radiographs. However, preoperative planning of a corrective osteotomy using radiographs is suboptimal because 2D images hide rotations around the longitudinal axis of the bone. Overprojection further hampers determining the three standard radiographic parameters. When planning a corrective osteotomy, the limitations of 2D imaging may cause a misinterpretation of the correction parameters. Six parameters are required for optimal planning of repositioning
the radial distal segment in 3D space: three displacements along three orthogonal axes and three rotations around these axes. A malunited fracture of the distal radius requires 3D repositioning. Therefore 3D imaging is required for optimal planning and performing a corrective osteotomy. This allows correction of all six repositioning parameters, not only the shortening and the angulations as seen on 2D radiographs.

In the last decade, many computer aided 3D methods for planning and performing corrective osteotomy of the distal radius are proposed in the literature. We have seen an increase in the number of publications on the use of computerized methods for the surgical procedure. With these recent techniques, new and advanced opportunities are possible in the treatment of distal radius malunions.

**AIMS AND OUTLINE OF THE CHAPTERS**

The goal of this thesis is threefold. At first, possible pitfalls of conventional corrective osteotomy surgery are determined and quantified (Part I). In addition, 3D planning methods (Part II) and new surgical techniques (Part III) are investigated to improve 3D positioning of bone segments in corrective osteotomy surgery.
Part I - Conventional 2D practice

Part one of this dissertation deals with conventional practice. Chapter 2 is an overview of long-term follow-up surgery data in the region of Amsterdam for the conventional corrective osteotomy procedure of the radius. This inventory of hardware removal and re-operation rates is useful as reference data in comparing new and improved techniques with the conventional technique, and helps establishing possible improvements. Our hypothesis is that the hardware removal and re-operation rates are higher in our long-term follow-up than in previous short-term follow-up studies.

Conventional corrective osteotomy is based on 2D planning and 2D intraoperative evaluation. Chapter 3 describes the results of a retrospective study on 25 patients to investigate the positioning accuracy of distal radius corrective osteotomies. We determine in a quantitative fashion the residual malposition after conventional surgery using 3D imaging postoperatively. We test the null hypothesis of equal 3D positions in affected and contralateral healthy radii as a reference. We further investigate whether correlations exist between 3D positioning parameters and clinical outcome. In that way we can investigate the need for 3D planning and evaluation in the treatment of a malunited distal radius.

Another important issue that influences the accuracy of the conventional technique is the bone fixation in the corrective osteotomy procedure. Fixation is often established with a pre-contoured anatomical plate. The aim of Chapter 4 is to investigate whether these anatomical plates really provide accurate positioning in 3D space. We hypothesize that positioning is influenced by the differences in morphology between radii, different plate shapes and subjective placement of the plate by the physician. This experimental explorative study is performed on artificial radii created using CT scans of healthy subjects.

Part II - Towards 3D planning

In Part two of this thesis we investigate 3D methods for optimal planning of a corrective osteotomy. Chapter 5 gives an overview of computer-assisted 3D corrective osteotomy methods that has recently been reported in the literature. In these techniques the malunited radius is restored with the help of the unaffected mirrored contralateral radius, which serves as the best available reference, compared to population mean values. However, the assumption of perfect bilateral symmetry between the left and right forearm bones was never investigated in 3D. Obviously it should be properly examined whether it is correct to use the contralateral radius as a reference in 3D planning methods. Chapter 6's objective is to quantify, in 3D, the bilateral symmetry of the radius and the ulna in healthy individuals. Virtual 3D models of both their radii and ulnae are used to investigate the symmetry between right and left forearm bones. This can be useful in further improving computer-assisted planning of radius or ulna osteotomies.

In Chapter 7 we describe a method to include the ulnae for improving the alignment between distal radius and ulna in correction osteotomy of the radius. We did this study on
the same subject group as in Chapter 6, creating virtual models of all radii and ulnae and using them in simulations of a corrective osteotomy procedure.

**Part III - New 3D techniques**

In Part three we present two new techniques for corrective osteotomy of the distal radius that rely on 3D imaging in the preoperative planning and 3D positioning during surgery. **Chapter 8** describes a patient-tailored fixation plate that is designed with custom software. This type of plate only fits in one way on the patient’s bone geometry and realigns the bone segments as planned. This method uses pre-operative 3D imaging to plan positioning of the segments of the radius and to design the plate. The aim of this study is to evaluate the accuracy of this method using artificial bone models.

We also describe another technique with 3D pre-operative planning that has potential to be minimally invasive, in **Chapter 9**. In this procedure an additional intra-operative 3D scan makes it possible to transfer the pre-operative plan to the actual bone during surgery. Tools are developed to correct the distal radius pose in six degrees of freedom. Small incisions in this technique render this method minimally invasive. **Chapter 9** is an experimental study to test the accuracy and reproducibility of this method on artificial radii and a cadaver arm.

**Chapter 10** is a summary of the results and conclusions presented in this thesis. It finally lists recommendations for future work.
REFERENCES


