Advancements in classification, treatment and outcome of radial head fractures

Guitton, T.G.

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This thesis shows that advancements in technical analysis, imaging modalities, increased interest in psychosocial aspects of treatment and the availability of long-term outcome data can help improve classification, treatment and outcome in fractures of the radial head. It is science that created these advancements and through adequate scientific evaluation of these advancements we can continue creating more effective treatments for patients.
Stellingen

BEHORENDE BIJ HET PROEFSCHRIFT

“Advancements in Classification, Treatment and Outcome of Radial Head Fractures”

1. Every great advance in science has issued from a new audacity of the imagination. (John Dewey, 1859 – 1952)

2. If in doubt, resect. (B.F. Morrey)

3. The volume and proximal articular surface area of the radial head can be estimated based on anatomical measurements and gender. (This thesis)

4. Small fragments are more common in partial radial head than in whole radial head fractures. (This thesis)

5. About half of the Mason Type 2 radial head fractures would not satisfy the Broberg and Morrey criteria to be considered Type 2 fractures. (This thesis)

6. The threshold of 3 fragments in the decision between open reduction-internal fixation and prosthetic replacement may not help guide management. (This thesis)

7. Three-dimensional CT images are easier for surgeons to interpret. (This thesis)

8. Increasing levels of sophistication in imaging and modeling improved the sensitivity for diagnosis of fracture characteristics and decreased observer variation between surgeon and first assistant. (This thesis)

9. Fracture classification and characterization based on 3D imaging and models are more accurate and reliable. (This thesis)

10. Patients recover greater motion and do so more rapidly after injury when they are confident and feel good about stretching their arm. (This thesis)

11. Post injury activities and occupation are not important risk factors for the development or advancement of radiographic arthrosis. (This thesis)

12. If you never missed an airplane, you wasted too much time of your life at airports. (Andrei Shleifer)

13. It’s all in the head, the radial head.

Thierry G. Guitton

Amsterdam, 21 April 2011
Advancements in Classification, Treatment and Outcome of Radial Head Fractures

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Advancements in Classification, Treatment and Outcome of Radial Head Fractures

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. D.C. van den Boom
ten overstaan van een door het college voor promoties ingestelde commissie, in het openbaar te verdedigen in de Agnietenkapel
op donderdag 21 april 2011, te 14.00 uur

door

Thierry Guillaume Guitton

geboren te Delft
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Faculteit der Geneeskunde

A mes êtes les plus chers:
mes parents,
mes frères et sœur

Faculteit der Geneeskunde
Preface

Thierry continues the tradition of the Amsterdam-Boston collaborative. I know that my PhD students don’t arrive with the skills they leave with, but as I write this preface I can’t clearly remember what things were like when Thierry started—perhaps because my pride is so great in how they are finishing. Thierry is juggling a dozen active projects at a time—I can rely on him for energy, skill, and enthusiasm. He will end up with over double the number of publications than will be part of his PhD thesis including papers that branch in the appropriate use of pathology testing of ganglion cysts, surgical site infections, and measures of quality and safety and how they are influenced by patient complexity including transfer from another hospital.

To complete the PhD work Thierry had to bring to fruition the quantitative 3D-CT process. That required fine-tuning both the technical aspects and the methods of statistical analysis. It also required the invention of a method for estimating intact bone volumes in which Thierry all succeeded.

Thierry single handedly brought the Science of Variation Group to fruition. When the web developer hit problem after problem, Thierry discovered a way to use readily available commercial web survey tools to do the job cheaper, easier, and very reliably. The international enthusiasm for the work of this group is really heartening to dedicated scientists such as Thierry and I expect our collaborative will make quick work of many of the current questions about observer variation. Which of course will only raise new questions—but that’s what we’ve trained Thierry for.

The process of executing so many scientific experiments, presenting them publicly and then getting them published in peer-reviewed scientific journals hones the scientific skills. The mark of success is the enthusiasm and confidence with which a graduating PhD student such as Thierry takes on new projects and also takes on the role of a leader and manager for new PhD students, short-term visitors, and even some of the local residents and fellows.

It gives me great pride to see Thierry’s abilities in action and of course my hope is that we will continue to collaborate throughout our careers, and that he will always share my love for science. Science is what humans developed to keep from fooling themselves and to keep from being fooled by others. A useful tool to be sure and science’s accomplishments are undeniable, but when the data are counter-intuitive—when they challenge our preferences and customs—many of us become uncomfortable. Not so Thierry. Having completed his PhD, Thierry now has the confidence, the comfort, and the capability to pursue more experiments, and I expect his contributions to our understanding and management of illness to be substantial, and his efforts are greatly admired and appreciated.

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# Table of Contents

**PART I CURRENT ISSUES**  
Chapter 1 General Introduction  
*Guitton TG*

**PART II CLASSIFICATION**  
Chapter 2 Quantitative Measurements of the Volume and Surface Area of the Radial Head  
*Guitton TG, van der Werf HJ, Ring D.*  
Chapter 3 Quantitative Three-Dimensional Computed Tomography Measurement of Radial Head Fractures  
*Guitton TG, van der Werf HJ, Ring D.*  

**PART III TREATMENT**  
Chapter 4 Diagnostic Accuracy of Two-Dimensional and Three-Dimensional Imaging and Modeling of Radial Head Fractures  
*Guitton TG, Brouwer KM, Dyer G, Zurakowski D, Mudgal C, Ring D.*  
Submitted  
Chapter 5 Interobserver Reliability of Radial Head Fracture Classification: Two-Dimensional vs. Three-Dimensional Computed Tomography  
*Guitton TG, Ring D.*  
Science of Variation Group.  
In revision J Bone Joint Surg Am

**PART IV OUTCOME**  
Chapter 7 Incidence and Risk Factors for the Development of Radiographic Arthrosis After Traumatic Elbow Injuries  
*Guitton TG, Zurakowski D, van Dijk NC, Ring D.*  

**PART V GENERAL DISCUSSION**  
Chapter 8 Discussion  
*Guitton TG*

**PART VI SUMMARY**  
Summary  
*Guitton TG*

**APPENDICES**  
Bibliography  
Acknowledgements  
Curriculum vitae

<table>
<thead>
<tr>
<th>PART</th>
<th>CONTENT</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CURRENT ISSUES</td>
<td></td>
</tr>
<tr>
<td>Chapter 1</td>
<td>General Introduction</td>
<td>10</td>
</tr>
<tr>
<td>II</td>
<td>CLASSIFICATION</td>
<td></td>
</tr>
<tr>
<td>Chapter 2</td>
<td>Quantitative Measurements of the Volume and Surface Area of the Radial Head</td>
<td>11</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Quantitative Three-Dimensional Computed Tomography Measurement of Radial Head Fractures</td>
<td>12</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Diagnostic Accuracy of Two-Dimensional and Three-Dimensional Imaging and Modeling of Radial Head Fractures</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td><em>Guitton TG, Brouwer KM, Dyer G, Zurakowski D, Mudgal C, Ring D.</em> Submitted</td>
<td></td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Interobserver Reliability of Radial Head Fracture Classification: Two-Dimensional vs. Three-Dimensional Computed Tomography</td>
<td>14</td>
</tr>
<tr>
<td>III</td>
<td>TREATMENT</td>
<td></td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Attitude Towards Stretch Pain of the Elbow After Radial Head Fracture</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td><em>Guitton TG, Vranceanu A, Ring D.</em> Submitted</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>OUTCOME</td>
<td></td>
</tr>
<tr>
<td>Chapter 7</td>
<td>Incidence and Risk Factors for the Development of Radiographic Arthrosis After Traumatic Elbow Injuries</td>
<td>16</td>
</tr>
<tr>
<td>V</td>
<td>GENERAL DISCUSSION</td>
<td></td>
</tr>
<tr>
<td>Chapter 8</td>
<td>Discussion</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td><em>Guitton TG</em></td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>SUMMARY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summary</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Samenvatting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glossary</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Guitton TG</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Acknowledgements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Curriculum vitae</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td><em>Guitton TG</em></td>
<td></td>
</tr>
</tbody>
</table>
Part I: Current Issues

CHAPTER 1
Introduction

Thierry G. Guitton
Introduction

With the evolution from homo-sapiens to the human being of today the elbow evolved from a weight bearing joint to a complex non-weight bearing articulation. The elbow joint is now a so-called ginglymus or hinge joint and consists of the humerus, radius and ulnar bones. In combination with the development of the brain, the human became able to perform complex motions with this joint. From an anatomical point of view the elbow is very complex; it consists of relatively small bones, complex shapes of articulations and numerous adjacent neurovascular structures that all increase the difficulty of operative treatment.

Paul of Aegina (625-690 A.D.) made the first description of radial head fractures: “The ulna and radius are sometimes fractured together and sometimes one of them only, either in the middle or at one end as at the elbow or the wrist”[6]. However, Sir Astley Cooper, an English surgeon and anatomist who made historical contributions to medicine, never recognized this injury in his book titled: “Dislocations and Fractures” in 1822 [3]. Earlier recognition of this injury was probably hindered because of “thick muscle covering” [46,47]. On the other hand, the often poor results of radial head fracture treatment were noted early: Helferich recommended resection of the radial head to prevent late deformity in 1899 [28].

The incidence of radial head fractures is reported to be between 1.7 to 5.4 percent of all fractures [14,16,15]. Radial head fractures are considered common injuries, found in nearly 20% of all elbow fractures [16]. Loss of elbow motion after a radial head fracture can have a substantial impact on upper extremity function and people’s overall health status [44]. A relatively simple radial head fracture can cause great impairment and disability. With the increased emphasis in healthcare on quality of life, there has been an increased interest in development of treatments for radial head fractures. As life expectancy increases, the older population continues to grow and at the same time, live more active lives. As a consequence, the incidence of radial head fractures can be expected to increase [9]. As a result there will be an increased scientific, clinical, and economic interest in the treatment of radial head fractures.

The classification of radial head fractures underwent several changes over the past years. Scharplatz and Allgower based the classification of elbow fractures on the direction of force of the injury [46]. Early classification of radial head fractures by Carstam [16], Bakalin [1] and Mason [45] were only based on radiographs. They failed to take associated injuries into account. At this point, the most commonly used classification system is that proposed by Mason [45]. Mason classified fractures of the radial head as nondisplaced (Type 1), displaced partial head (Type 2), and displaced whole head fractures (Type 3). Several authors suggested a fourth category in which there is involvement of an elbow dislocation [5,14,24,55]. More complex sub classifications are proposed based on different degrees of displacement and comminution [15]. Berg and Morrey modified Mason’s classification as follows [6]. Type 1 fractures involve less than 30% of the articular surface or are displaced fewer than 2 millimeters; Type 2 fractures are partial head fractures involving at least 30% of the articular surface and displaced at least 2 mm; Type 3 fractures are displaced articular fractures involving the entire head of the radius; and Type 4 fractures have an associated elbow dislocation [53]. As most classification systems are imperfect, there is often debate in distinguishing between fracture types. For example, the percentage of involvement of the radial head or the amount of displacement that should be present for a Mason 2 fracture is arbitrary. As of today, no “ideal” classification for radial head fractures exists [5]. More detailed analysis with sophisticated techniques may help to clarify these issues.

To my knowledge, measurement of proximal articular surface area and radial head volume has not been attempted. If a system was developed which quantified fracture fragment size and injury patterns, and added the ability to estimate percentage involvement, it would make classification systems more intuitive for clinicians.

The technological advances in imaging of the upper-extremity have taken an immense leap in the last decade. Our group has developed a technique to quantitatively investigate broken bones with the use of Computed Tomography (CT). This Quantitative Three-dimensional CT (Q3D-CT) modeling technique creates a polygon mesh. This is a collection of vertices, edges and faces that defines the shape of a polyhedral object in 3D computer graphics and solid modeling, consisting of triangles, only explicitly representing the surface. In other words, a hollow 3D model of solely the outer surface of the bony structures and fragments can be generated. This Q3D-CT modeling technique has several potential opportunities. First, it provides the opportunity to learn more about fracture patterns. For example, one can calculate volume and articular surfaces of bones. Secondly, more detailed and quantitative information can be derived from this technique concerning the specific anatomical aspects of bone that could assist the clinician in reconstruction surgery.

Anteroposterior (AP) and lateral radiographs may not provide an accurate representation of the individual fracture pattern of radial head fractures [6]. The addition of a 45 degree oblique radiograph is helpful in recognizing the size and orientation of the fracture fragments. However, the value of Magnetic Resonance Imaging (MRI) and CT scans remain under continuous scrutiny [33]. Several retrospective studies have demonstrated improved injury characterization with two-dimensional (2D) CT images as compared to standard radiographs alone. These studies found that 3D reconstructions of CT scans may have advantages over standard 2D images [10,27]. Three-dimensional reconstructions are relatively new, and are becoming more read-
ily available in most hospitals. Three-dimensional reconstructions might be more intuitive and may lead to improved identification of fracture characteristics such as fragments, fracture edges and articular surfaces. Three-dimensional physical models of elbow fractures can now be created with the use of special 3D printers. Three-dimensional physical models can even increase the advantages of the 3D reconstructions. Three-dimensional imaging and 3D physical models should allow better pre-operative planning in terms of implants and equipment. Additionally, the surgeon will have better mental and psychomotor preparation. Three-dimensional imaging is also more intuitive for patients and could lead to better understanding and improved decision making and compliance. High quality prospective and multi-rater studies could identify the potential advantages from 3D imaging and 3D physical models over radiographs and 2D-CT.

Immobilization of three to four weeks, passive motion and avoidance of “operative treatment”, removal of the fracture fragment and excision of the entire head for severe comminution were all recommended treatments for radial head fractures in the early 1900’s. Evidence can now be found for nearly any type of treatment. Although the radial head has been subject to research in the past, the majority consists of retrospective studies and case series. There is a lack of high quality randomized and comparative trials available. Therefore the debate regarding the best treatment continues. The focus has mainly been on the technical side of management. There is an increased interest in the recent literature in orthopedics on the psychosocial aspect in treatment of elbow trauma. The psychosocial aspects in treatment of radial head fractures could help unveil the ideal management. It was found that psychosocial factors (depression in particular) may best explain the discrepancy between impairment and disability. As many psychosocial factors are amenable to treatment, additional research along these lines is merited. For example, it can be counter-intuitive to intentionally cause pain in the setting of an injury. Vulnerability is enhanced by automatic thoughts such as “pain indicates harm”, “the pain is permanent”, or other aspects of a maladaptive pain response that psychologists have termed pain catastrophizing. There is a strong interaction between depression and pain catastrophizing and both may be important. This needs further investigation.

Post-traumatic arthritis is a form of arthritis that is caused by forced inappropriate motion of a joint or ligament that is damaged because of a fracture. An intra-articular fracture such as a radial head fracture may increase the forces on the articular cartilage, and the articular surface will wear out faster, finally leading to arthritis. Little has been published regarding risk factors for arthritis after elbow injury, especially in the long term. Data from multiple long-term follow-up studies of injured elbows provide the opportunity to assess the risk factors for post-traumatic elbow arthritis after radial head fracture.

The advancements in analyzing techniques, 3D imaging and modeling, increased interest in psychosocial aspects of treatment and the recent availability of multiple long term outcome studies gives us the opportunity to further investigate the classification, treatment and outcome of radial head fractures. This all could lead to improved treatment and possible better outcomes for patients. The aim of this thesis is to apply these advancements to the radial head 1) to gain further insight in classification, treatment and outcome of radial head fractures and 2) to function as a model for general improvements in orthopedic trauma surgery.

In conclusion, the purpose of this thesis is: 1) to validate the Q3D-CT modeling technique; 2) to apply this new Q3D-CT modeling technique to improve the understanding of radial head fracture morphology; 3) to evaluate prospectively with a multi-rater study the influence of 3D images on classification and treatment of radial head fractures; 4) to further investigate the psychosocial aspects in radial head fracture treatment; 5) to identify predictors for long term consequences of radial head fractures.

Outline of the Chapters

CHAPTER 2
QUANTITATIVE MEASUREMENTS OF THE VOLUME AND SURFACE AREA OF THE RADIAL HEAD
Thierry G. Guitton, MSc, Huub J. van der Werf, MD, David Ring, MD PhD

The morphology of the healthy radial head has been investigated with calliper ruler, osteometric board, coordinator measuring machine (CMM), X-ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and Computer-Aided Design (CAD) software in the past. We developed a quantitative 3-dimensional computed tomography (Q3D-CT) modeling technique that can measure size, shape and proximal articular surface area.

In chapter 2, we will validate our Q3D-CT modeling technique and investigate the hypothesis that analysis of normal, unfractured radial heads in patients with CT scan obtained for other reasons (intact radial head) will allow us to develop a linear regression model capable of estimating the volume and proximal articular surface area of the radial head prior to fracture based on 1 or more of the following: radial head diameter, radial neck diameter, coronoid length diameter, height, weight and gender.
Radial head fractures are usually classified according to the size and displacement of the fracture fragments into partial and whole head fractures as per the Mason classification system. The quantitative aspects of the classification of these injuries, such as the thresholds of 30% surface area and 2 millimeter displacement are relatively arbitrary and based on radiographs. Additionally, the classification of radial head fractures according to Broberg and Morrey’s modification of the Mason classification has substantial observer variation. Three-dimensional computed tomography models provide more detailed information of the fractured bone and provide an opportunity to quantify fracture characteristics better than radiographs.

In chapter 3, we applied the Q3D-CT analysis technique to a consecutive series of adult patients with a fracture of the radial head with the objective of developing quantitative assessments of radial head fracture fragments that might help clarify current classification systems and decision-making.

Optimal management of radial head fractures is debated, but accurate preoperative radiological characterization of the fracture may facilitate management. Prior studies have demonstrated improved agreement in characterization and classification of various fractures with 3D-CT compared to 2D-CT images and radiographs. These studies were based upon retrospective data and the reference standard was based upon surgeon recollection and the medical record (e.g. operative notes). We believe that we can measure the accuracy of 3D-CT imaging better prospectively. In addition, 3D physical models, that are constructed based on CT images, can actually be held in the hand and may add even more to the evaluation of fracture characteristics and surgical planning.

In chapter 4, we will investigate if the classification and characterization of fractures of the radial head is more accurate with 3D than 2D-CT images and radiographs, using a prospective study design with intraoperative inspection as the reference standard.

The classification of radial head fractures according to Broberg and Morrey’s modification of the Mason classification has substantial interobserver variation. Treatment decisions for radial head fractures are often based on radiological criteria and measurements according to Broberg and Morrey’s modification of the Mason classification. Evidence suggests that more sophisticated images such as 3D-CT improve intraobserver reliability more than interobserver reliability. A major limitation of most studies of observer variation is the use of only a few observers, most of them typically relatively junior surgeons.

In chapter 5, a new collaboration motivated to better understand interobserver variation, consisting of observers who have completed all training and are independently treating patients, provides an opportunity to further investigate interobserver variability and how to reduce it. We will investigate if 3D-CT images improve the interobserver reliability of the classification and characterization of radial head fractures over 2D-CT and radiographs.

Isolated stable and minimally displaced fractures of the radial head (Types 1 and 2 of the Broberg-Morrey modification of the Mason Classification) are common fractures that are usually treated non-operatively. The most common sequel of these fractures is elbow stiffness. In our experience, the elbow stiffness may be a result of excessive immobilization or ineffective stretching exercises. Research suggests that fear of pain, thinking the worst in response to noiception (pain catastrophizing) and pain anxiety may be important determinants of recovery after an acute fracture. Similarly, depression hinders recovery after fracture. In chapter 6, the influence of patients who agree or disagree that pain is useful for recovery will be evaluated. This prospective study was designed to test the hypothesis that agreement with the idea that “stretching of the elbow beyond the point were it becomes painful is important in recovery” leads to greater elbow range of motion one month after injury.
Radiographic arthrosis is a common sequela of elbow trauma resulting from direct cartilage injury, instability, and articular incongruity. It is understood that over the long term, many patients develop radiographic signs of arthrosis after elbow trauma, although symptoms vary and few patients present for treatment. Not much has been published regarding risk factors for arthrosis after elbow injury, especially in the long term.

In chapter 7, data from multiple long-term follow-up studies of injured elbows provide the opportunity to assess the risk factors for posttraumatic elbow arthrosis on radiographs.

Summary of Introduction
The purpose of this doctoral thesis is to apply the advancements in technical analysis, imaging modalities, psychosocial aspects and long term data to the treatment of radial head fractures. More specifically, it is my goal to increase our knowledge on classification, treatment and outcome of radial head fractures. This goal will be achieved by addressing the following study questions:

CHAPTER 2
**General aim:** To investigate if Q3D-CT modeling technique based on anatomical and demographic data, that can measure size, shape, and proximal articular surface area, can be used to develop formulas that could predict the volume and proximal surface area of the intact radial head in patients with fractures of the radial head.

**Specific study question:** Are linear regression models capable of estimating the volume and proximal articular surface area of the radial head prior to fracture based on one or more of the following: radial head diameter, radial neck diameter, coronoid length diameter, height, weight and gender?

CHAPTER 3
**General aim:** To quantitatively analyze radial head fracture fragment morphology on Q3D-CT images in terms of size, shape, and articular surface area.

**Specific study question:** Do partial head (Mason 2) fractures and whole head fractures (Mason 3) have the same percentage of small fracture fragments by volume and surface area criteria?

CHAPTER 4
**General aim:** To investigate if classification and characterization of fractures of the radial head is more accurate with 3D-CT images and 3D models than 2D-CT images and radiographs, using a prospective study design with intraoperative inspection as the reference standard.

**Specific study question:** Do 3D-CT images and 3D models predict fracture characteristics more accurately than 2D-CT images and radiographs?

CHAPTER 5
**General aim:** To investigate in a large web-based collaborative of experienced orthopaedic surgeons if 3D-CT images improve the interobserver reliability of the classification of radial head fractures according to the Broberg and Morrey modification of the Mason classification.

**Specific study question:** Do 3D-CT images improve the interobserver reliability of the classification and characterization of radial head fractures over 2D-CT and radiographs.

CHAPTER 6
**General aim:** To investigate if agreement with the idea that “stretching of the elbow beyond the point were it becomes painful is important in recovery” leads to greater elbow range of motion one month after injury.

**Specific study question:** Does agreement that painful stretches are an important part in recovery leads to greater motion one month after injury?

CHAPTER 7
**General aim:** To assess the risk factors for posttraumatic elbow arthrosis on radiographs after elbow injury in the long term.

**Specific study question:** Do different types of elbow injuries have rates of radiographic arthrosis (independent of function or outcome) that are comparable at equivalent follow-up times?
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Part II: Classification

CHAPTER 2
Quantitative Measurements of the Volume and Surface Area of the Radial Head

Thierry G. Guitton, MSc
Huub J. van der Werf, MD
David Ring, MD PhD

Abstract

Purpose: We investigated the hypothesis that a quantitative 3-dimensional computed tomography (Q3D-CT) modeling technique based on anatomical and demographic data that can measure size, shape, and proximal articular surface area can be used to develop formulas that could predict the volume and proximal surface area of the intact radial head in patients with fractures of the radial head.

Methods: We used a consecutive series of 50 computed tomography (CT) scans with a slice thickness of 1.25 mm or less obtained in patients with fracture of the distal humerus, but no injury to the radial head, to create 3-dimensional models (3D). The volume and proximal articular surface area of the radial head were measured, and predictive formulas based on anatomical measurements and genders were calculated using multiple linear regression.

Results: There were significant correlations between total radial head volume and proximal radial head articular surface area for height, weight, radial head diameter, radial neck diameter, coronoid diameter, and gender. Multiple linear regression modeling resulted in formulas that could account for 89% of the variation in radial head volume and 75% of the variation in proximal articular surface area.

Conclusions: The volume and proximal articular surface area of the radial head can be estimated based on anatomical measurements and gender. This may lead to better estimates of lost fragments when it is not possible to directly model the fractured radial head and CT scan of the opposite limb is not available.

Level of evidence: Level IV, Diagnostic Study

Introduction

The morphology of the healthy radial head has been investigated with calliper ruler, osteometric board, coordinator measuring machine (CMM), X-ray, CT scan, Magnetic Resonance Imaging (MRI) and Computer-Aided Design (CAD) software in the past. Prior studies found differences between genders and no side-to-side differences. Some studies have small numbers of subjects and used non-digital measurement tools or old skeletons and others use non-standard software with low quality CT scans. Three-dimensional CT models provide more detailed information. We developed a quantitative 3-dimensional computed tomography (Q3D-CT) modeling technique that can measure size, shape and proximal articular surface area.

When this Q3D-CT method is used to analyze fractured radial heads, and in the absence of a CT scan of the opposite elbow, a method for estimating the total volume and proximal articular surface area of the unfractured head of the radius will allow estimation of the percentage of head that is fractured. Such percentages are used in classifications and affect management decisions on the basis of interpretation or measurements from plain radiographs, which may be less precise than calculations made from CT images.

We investigated the hypothesis that analysis of normal, unfractured radial heads in patients with a CT scan obtained for other reasons (intact radial head) would allow us to develop a linear regression model capable of estimating the volume and proximal articular surface area of the radial head based on one or more of the following: radial head diameter, radial neck diameter, coronoid length diameter, height, weight, and gender.

Materials and Methods

Inclusion and Exclusion Criteria
A search of a billing database between 2002 and 2008 identified 228 patients with a fracture of the distal humerus but an intact radial head. The 50 adult patients with a CT scan that had a slice thickness between 0.62 and 1.25 mm were included in our analysis. There were 19 men and 31 women, with an average age of 54 years (range, 19-92 years). A total of 26 patients injured their right elbow and 24 injured their left elbow.

Modelling Technique
Digital Imaging and Communications in Medicine (DICOM) is a standard for handling, storing, printing, and transmitting information of CT scans. Several different CT scanners were used and scanners could scan up to 140 kV and 500 to 700 mA.
with slices from 8 to 64/Dual Source. The DICOM files were obtained through Vitrea 2 software (Vital Images, Plymouth, MN). Vitrea is a visualization solution that creates 3-dimensional reconstructions from CT scans. The DICOM files were exported for further processing into Matlab 7.7 (MathWorks, Natick, MA), a numerical computing environment. With Matlab the CT slices (DICOM) were converted into regular pictures so they were suitable for further processing. A special code written by the Massachusetts General Hospital 3D Imaging Service aids in this process and identifies higher densities with a consistent algorithm in the CT slices (in essence, bony structures). In addition, data describing the relationship between the slides and the higher densities were saved. The created images and the additional created data were then uploaded into Rhinoceros 4.0 (McNeel North America, Seattle, WA). Rhinoceros is a 3-dimensional modeling tool based on Non-Uniform Rational B-Spline (NURBS), a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. Rhinoceros stacked the images on top of each other, taking their relationship into account. During the image processing in Matlab, the higher densities (bony structures) are automatically highlighted with points on every single CT slice. The actual CT slice is depicted behind the pointwise representation of the bone in the software. Depiction of the CT slice with the points on top of them allows precise identification of all bony structures and fragments, even if they were impacted. The software puts new points in each CT slice, keeping them at the same level as the automatically generated points. After all points were set, we drew lines that then represented the actual outer border of the bone, and so created a wire model (Figure 1A). The line drawings are an automated feature in the software that follows the automatically generated pointwise representation of bony structures. We then used this wire model to create a polygon mesh (Figure 1B). This is a collection of vertices, edges, and faces that defines the shape of a polyhedral object in 3D computer graphics and solid modeling, consisting of triangles only explicitly representing the surface. In other words, a hollow 3D model of solely the outer surface of the bony structures and fragments was generated.

**Evaluation**

After the 3-dimensional models were created, we measured the volume and proximal articular surface area from the radial head. Volumetric measurements and surface area measurements are a standard feature in Rhinoceros 4.0. To calculate the radial head volume, we separated the radial head from the shaft with a plane perpendicular to the proximal articular surface (articulating with the capitellum) and placed a cutting plane at the distal border of the cartilage of the articular circumference of the radial head, because we thought this was in the most distinct landmark of the radial head-neck margin (Figure 1C). The proximal articular surface area was calculated using the same cut-off points and done by selecting all the meshes that represented the proximal articular surface area of the radial head (Figure 1D). In addition to these volumetric and proximal articular surface area measurements, the diameter of the radial head and neck was measured. This was also done for the coronoid process by measuring the distance between the medialmost aspect of the coronoid (parallel to the radial-ulnar articulation) and the lateralmost aspect of the ulna (proximal to the radio-ulnar articulation at the origin of the radio-ulnar notch). Hereon, we refer to this distance as the coronoid diameter. Given that the radial head and neck are slightly elliptical, we used the maximum diameter of the radial head and neck. It is often possible to measure the maximum radial head and neck diameters in the fractured radius, which provides additional parameters that can be used to predict the volume or proximal articular surface area of the intact radial head to estimate the percentage of the radial head that is fractured.
Statistical Analysis
Continuous data are presented as the mean standard deviation (SD) and are reported in millimeters. Volumes are reported in cubic millimeters (mm³) and proximal articular surface area in square millimeters (mm²). Differences in continuous variables were evaluated using Student’s t-test for independent groups. For bivariate analysis, the relationships between the radial head volume and articular surface, and continuous variables (age, height, weight, radial head diameter, radial neck diameter, and coronoid diameter), were evaluated one at a time using Pearson r correlations. We evaluated dichotomous variables (gender and side) using the Mann-Whitney U-test. Linear regression analysis was used to determine formulas for the prediction of radial head volume and surface areas based on basic measurements and demographic factors that would be available in patients with a fracture of the radial head. Two models were determined: a model with the strongest outcome and the strongest model without the variable radial head diameter. Multivariable analysis of variance was performed to identify the F statistic for the selected model, where the F ratio compares the variation of the dependent variable that is explained by the model to the part of variation that is not accounted for by the model. Significance of the F statistic below 0.05 indicates that the predictors in the selected model provide useful information about the dependent variable.

Goodness-of-fit was assessed using adjusted R-squared, which measures the proportion of variation in the dependent variable that is explained by the model, with a correction for the number of explanatory variables. As a measure of the accuracy of the strongest model, the difference between actual (as calculated by the software in the reconstructed model) and predicted radial head volume and articular surface for the 50 elbows was calculated and the middle 95% confidence interval (2.5% and 97.5% percentile ranks) was computed. In addition, to compare 2 calculated experimental values to each other as a quantitative indicator of quality, we calculated the average relative percent difference for both strongest models. To quantify the repeatability of the automated software algorithm, 1 observer built 1 radius bone model 5 times consecutively. The coefficient of variation, standard deviation (SD), mean, and 95% confidence interval (CI) are reported for the radial head volume, radial head articular surface, radial head diameter, and radial neck measurements. As another measure of accuracy, we tested our empiric formula for articular surface area to the basic mathematical formula assuming the radial head is round (πr² formula).

A power analysis indicated that a minimum sample size of 50 patients would provide 90% statistical power (β = 0.1, α = 0.05) to detect a moderate correlation (ρ>0.40) of radial head diameter and radial head volume.

Results
Table I shows the results from all subjects and the comparisons between men and women for age, height, weight, radial head, and neck diameters and volumes.

Men and women compared
There was a significant statistical difference between man and women between height (p<0.05), weight (p<0.05), radial head volume (p<0.01), radial head surface (p<0.01), radial head diameter (p<0.01), and radial neck diameter (p<0.01). There was no statistical difference between age (p<0.06) in men and women.

Table I. Overall Results and Comparisons Between Men and Women

<table>
<thead>
<tr>
<th>All Patients</th>
<th>Men</th>
<th>Women</th>
<th>Men and Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N = 50)</td>
<td>(N = 19)</td>
<td>(N = 31)</td>
<td>Compared</td>
</tr>
<tr>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Age, (y)</td>
<td>53</td>
<td>22</td>
<td>46</td>
</tr>
<tr>
<td>Height, (m)</td>
<td>1.68</td>
<td>0.15</td>
<td>1.74</td>
</tr>
<tr>
<td>Weight, (kg)</td>
<td>73</td>
<td>16.0</td>
<td>78</td>
</tr>
<tr>
<td>Radial Head diameter, (mm)</td>
<td>22</td>
<td>2.2</td>
<td>23</td>
</tr>
<tr>
<td>Radial Neck diameter, (mm)</td>
<td>15</td>
<td>1.6</td>
<td>16</td>
</tr>
<tr>
<td>Radial Head Volume, (mm³)</td>
<td>3327</td>
<td>901</td>
<td>4301</td>
</tr>
<tr>
<td>Radial Head Surface, (mm²)</td>
<td>385</td>
<td>83</td>
<td>441</td>
</tr>
</tbody>
</table>

* = Significant difference

Radial head volume (Tables II, III)
There were significant correlations between total radial head volume and height (r = 0.44; p<0.001), weight (r = 0.29; p<0.05), radial head diameter (r = 0.83; p<0.001), radial neck diameter (r = 0.74; p<0.001), coronoid diameter (r = 0.78; p<0.001), and gender (p<0.01). The strongest multivariable model (F = 118.3; p<0.001) consisted of the variables radial head diameter, coronoid diameter, and gender, and accounted for 88.3% of the variation in radial head volumes. The strongest model without the variable radial head diameter consisted of the variables radial neck diameter, coronoid diameter, and gender, and accounted for 86.2% of the variation in radial head volumes (F = 95.4; p<0.001).
There was significant correlation between total radial head surface and height (r = 0.40; p<0.001), weight (r = 0.37; p<0.001), radial head diameter (r = 0.82; p<0.001), radial neck diameter (r = 0.68; p<0.001), coronoid diameter (r = 0.71; p<0.001), and gender (p<0.001). The strongest multivariable model (F = 44.9; p<0.001) consisted of the variables radial head diameter, coronoid diameter, and gender, and accounted for 74.5% of the variation in radial head articular surfaces. The strongest model without the variable radial head diameter consisted of the variables radial neck diameter, coronoid diameter, and gender, and accounted for 66.0% of the variation in radial head articular surfaces (F = 29.8; p<0.001).

**Modeling/predictions**

The following fitted equation resulted for radial head volume:

\[
\text{Radial Head Volume} = -1926.64 + 146.50 \times \text{Radial Head } \varnothing + 70.72 \times \text{Coronoid } \varnothing + 769.78 \times \text{Gender}
\]

The following fitted equation resulted for radial head surface:

\[
\text{Radial Head Surface} = -212.15 + 19.81 \times \text{Radial Head } \varnothing + 5.43 \times \text{Coronoid } \varnothing + 32.85 \times \text{Gender}
\]

The predictive linear model estimated the radial head volumes between 507 mm³ more and 575 mm³ less than the actual volumes based on 95% CI, and the average relative difference was 0.53%. The predictive linear model estimated the radial head surface area between 75 mm² more and 81 mm² less than the actual volumes based on 95% CI, and the average relative percent difference was 0.51%.

We tested the basic mathematical formula assuming the radial head is round. If we compare R² (the variability explained) we found 0.75 for our empiric formula and 0.66 for the π r² formula.

The 5 consecutively built models had a mean radial head volume of 3179
mm³ (SD = 16.4 mm³, 95% CI = 3159 - 3199 mm³) and a CV of 0.5%. The mean radial head articular surface was 592 mm² (SD = 0.8 mm², 95% CI = 591 - 593 mm²) and a CV of 0.14%. The radial head and radial neck diameter measurements variation was zero because all 5 readings were identical and thus, based on the sample data, the repeatability was 100% (Table IV).

Table IV. Measurements of Repeatability

<table>
<thead>
<tr>
<th>Model</th>
<th>Volume (mm³)</th>
<th>Articular Surface (mm²)</th>
<th>Radial Head Diameter (mm)</th>
<th>Radial Neck Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3161.42</td>
<td>592.44</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>2</td>
<td>3199.95</td>
<td>591.27</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>3</td>
<td>3168.77</td>
<td>591.74</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>4</td>
<td>3172.43</td>
<td>593.36</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>5</td>
<td>3192.29</td>
<td>592.50</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>Mean</td>
<td>3178.97</td>
<td>592.18</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>SD</td>
<td>16.37</td>
<td>0.80</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>95% CI</td>
<td>3159 - 3199</td>
<td>591 - 593</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CV</td>
<td>0.50%</td>
<td>0.14%</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Volume = mm³, articular surface = mm², diameter = mm, SD = standard deviation, 95% CI = confidence interval, CV = coefficient of variation.

Discussion

The limitations of this investigation include the fact that the accuracy of this method depends on the quality of the CT scan. Because CT scans do not account for articular cartilage, our measurements will differ from those based on MRI or direct measurements of fresh cadaveric bone. We did not thoroughly evaluate inter- and intra-observer variability in creation of the models because our method was time and resource intensive and, based on experience with 2 observers doing several models during training, the method leaves limited room for bias. When one person created the same model five times, we found very little variation in the measures of volume and surface area. The differences between surface area calculated using our formula and that using simple geometry are probably reflect the ovoid shape of the radial head.

There was no correction for hypertrophy of the dominant elbow (due to exercise) as described by Jones because there were no known athletes in the cohort. In the final multivariable models height, weight and radial neck diameter did not significantly contribute to the fit of the model (as gauged by adjusted R²) and were therefore not used.

The strong points of this investigation include the fact that we used a relatively large number of CT scans and a consistent algorithm was used for bone identification (on CT slides) and automated curve and polygon mesh creation, which left limited room for judgment or bias on the part of the individual creating the model. The relatively small standard deviations of the measured volumes and surface areas, the relatively narrow 95% CI of the predictive linear models, and the fact that our multivariable models account for over 70% of the variability of volume and surface area, all indicate that we can make reasonable and useful estimation of these parameters in fractured radial heads.

Our finding of a significant difference in radial head volume and surface area between men and women is consistent with Mall and colleagues. Furthermore, we found correlations between radial head and radial neck diameters as did Ryan.

We produced equations capable of estimating the volume and proximal articular surface area of the intact radial head--the basis of parameters usually available in fractured radial heads--with an average relative percent difference of 0.5%. The ability to estimate the volume and surface area of the bone prior to fracture, provides useful information when we analyze a fractured radial head. For instance, it allows us to measure the percentage of the surface area involved in the fracture, which is 1 criterion in Broberg and Morrey's modification of Mason's classification. Keeping in mind the many shortcomings of our approach, we believe that it will nonetheless improve our analysis and characterization of radial head fracture patterns.

These Q3D-CT methods are, at least initially, more important for clinical research. We are using this technique to study fracture fragment size and injury pattern, and the ability to estimate percentage involvement helps make the results more intuitive for clinicians. Classifications and management decisions often refer to 30% of the surface area for instance, but it’s not clear that this is an important cutoff, that we can make this measurement accurately from radiographs, or that it is representative of the fracture patterns that actually occur. More detailed analysis with these sophisticated techniques may help to clarify these issues. Additional work is needed to better define the accuracy and reliability of our method and determine how sensitive it is to the quality of the CT scan and the person doing the analysis.
References

CHAPTER 3
Quantitative Three-Dimensional Computed Tomography Measurement of Radial Head Fractures

Thierry G. Guitton, MSc
Huub J. van der Werf, MD
David Ring, MD PhD

Abstract

Background: We developed a method to quantitatively analyze fracture fragment morphology on three-dimensional computed tomography images (Q3D-CT) in terms of size, shape, and articular surface area.

Methods: We analyzed 46 adult patients with a computed tomography scan of a fractured radial head with Q3D-CT. We defined an unstable fracture as complete loss of cortical contact of at least 1 fragment. Of the patients, 3 had a Mason type 1 fracture (all stable), 26 had a type 2 fractures (7 stable [27%] and 19 unstable [73%]), and 17 had a type 3 fracture (all unstable). The volume and articular surface area of each articular fracture fragment were measured. A small fragment was defined as having a volume of less than 100 mm³ or an articular surface of less than 100 mm².

Results: Partial head fractures (Mason type 2) (26 fractures) are usually multi-fragmented (19 of 26 [73%]) and often have small fragments by volume (32 fragments) and surface area (46 fragments) criteria, particularly when the fracture is displaced and unstable. Only 4 of the 17 patients (25%) with whole-head fractures (Mason type 3) had greater than 3 fragments, but 9 of 17 fractures (69%) with 3 or fewer fragments had small fragments.

Conclusions: According to this initial application of Q3D-CT analysis, partial-head fractures are often complex and difficult to repair (small fragments), and most whole-head fractures have 3 or fewer fragments, but many of those fragments are small and may be difficult to repair.

Level of evidence: Level IV, Diagnostic Study

Introduction

Mason classified fractures of the radial head as nondisplaced (Type 1), displaced partial head (Type 2), and displaced whole head fractures (Type 3). Broberg and Morrey modified Mason’s classification as follows: Type 1 fractures involve less than 30% of the articular surface or are displaced fewer than 2 millimeters; Type 2 fractures are partial head fractures involving at least 30% of the articular surface and displaced at least 2 mm; Type 3 fractures are displaced articular fractures involving the entire head of the radius; and Type 4 fractures have an associated elbow dislocation. The thresholds of 30% surface area and 2 millimeter are relatively arbitrary and based on radiographs and the classification of radial head fractures according to Broberg and Morrey’s modification of the Mason classification has substantial observer variation. Three-dimensional computed tomography (3D-CT) models provide more detailed information of the fractured bone and provide an opportunity to quantify fracture characteristics better than radiographs.

We developed a Q3D-CT modeling technique that can measure fragment size, shape and articular surface area. We then used this technique to analyze fractures of the radial head with the objective of developing quantitative assessments of radial head fracture fragments that might help clarify current classification systems and decision-making. Specifically, we tested the null hypothesis that partial head (Mason 2) fractures and whole head fractures (Mason 3) have the same percentage of small fracture fragments that might be difficult to repair by volume and surface area criteria.

Materials and Methods

The Massachusetts General Hospital Institutional Review Board has approved the human protocol for this investigation under No. 1999P008705. All investigations were conducted in conformity with ethical principles of research, and informed consent for participation in the study was obtained.

Inclusion and Exclusion Criteria

A search of billing records identified 72 patients with a fracture of the radial head that were evaluated with computed tomography (CT) between 2002 and 2008. Forty-six CT scans had a slice thickness between 0.62 and 1.25 mm deemed adequate for three-dimensional modelling. Several different CT scanners were used with up to 140 kV and 500-700 mAs and slices from 8 to 64/Dual Source.

There were 24 men and 22 women with an average age of 47 years (range, 22 to 79 years). Eighteen patients injured their right elbow, 28 injured their left elbow. Fifteen patients had an isolated radial head injury, 16 patients dislocation with frac-
tures of the radial head and coronoid (terrible triad), 13 patients a posterior olecranon fracture-dislocation, and 2 patients had dislocation of the elbow with a fracture of the radial head. Twenty-four patients were treated with a radial head prosthesis, 7 with open reduction and internal fixation and 15 non-operatively.

Classification
The radial head fractures were classified based on radiographs and CT-scans taken immediately after injury according to Broberg and Morrey’s modification of the classification of Mason, but excluding the Type 4 category 1, 6. Three patients had a type 1 fracture, 26 patients a type 2 fracture, and 17 patients a type 3 fracture. Unstable fractures are defined as having separation (complete loss of cortical contact) of at least one radial head fracture fragment 10.

Modelling Technique
DICOM (Digital Imaging and Communications in Medicine) files were obtained through Vitrea (Vitrea 2 software; Vital Images, Inc., Plymouth, MN) and exported for further processing into Matlab (MATLAB 7.7; The MathWorks, Inc., Natick, MA) (Figure 1A). In this process higher densities were identified with a consistent algorithm in the CT-slices (in essence bony structures). The created images and the additional created data were then uploaded into Rhinoceros (Rhinoceros 4.0; McNeel North America, Seattle, WA). Rhinoceros stacked the images (jpeg) on top of each other taking their relationship into account. During the image processing in Matlab, the higher densities (in essence bony structures) are automatically highlighted with points on every single CT-slice (Figure 1B). The actual CT-slice is depicted behind the point-wise representation of the bone in the software. Lines were drawn which then would represent the actual outer border of the bone and so created a wire model (Figure 1C). This wire model was then used to create a hollow 3D model of solely the outer surface of the bony structures (Figure 1D).

Evaluation
After the 3D models were created, the volume and articular surface area of each fracture fragment and the remaining un-fractured bone were measured. Volumetric measurements and surface area measurements are a standard feature in Rhinoceros (Rhinoceros 4.0; McNeel North America, Seattle, WA). The articular surface area calculations were done by selecting all the meshes which represented the proximal articular surface of the particular fragment.

Only fragments that were separated from the rest of the radius were measured. The volume of the intact radius was arbitrarily cutoff by the limit of the CT in a way that hindered meaningful measurement of this part 7. The volumetric measure-
**Statistical Analysis**
Continuous data are presented as the mean (range). Mean fragment volume and articular surface area were calculated for every Mason fracture type. Relative references are reported as percentages.

**Results**
In this study, 17 fractures created 2 fracture fragments, 15 created 3 fracture fragments and 14 created 4 or more fracture fragments (Table I). The fractures were classified as unstable in 36 patients and stable in 10 patients. All Mason Type 1 fractures were stable. Seven Mason Type 2 fractures were stable and 19 were unstable (loss of cortical contact). (Figure 2) All Mason Type 3 fractures were unstable.

**Table I. Mason Type and Number of Fracture Fragments**

<table>
<thead>
<tr>
<th>Mason Type</th>
<th>2 Fragments</th>
<th>3 Fragments</th>
<th>≥4 Fragments</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason 1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Mason 2</td>
<td>7</td>
<td>9</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Mason 3</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>46</td>
</tr>
</tbody>
</table>

**Table II. Fracture Fragment by Volumetric Criteria**

<table>
<thead>
<tr>
<th>Mason Type</th>
<th>2 Fragments</th>
<th>Minor (100–500 mm³)</th>
<th>Small (&lt;100 mm³)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason 1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Mason 2</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Mason 3</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>28</td>
</tr>
</tbody>
</table>

**Table III. Volume-Specific Fracture Fragment Characteristics**

<table>
<thead>
<tr>
<th>Mason Type</th>
<th>Mean Estimated Bone Loss by Volume (mm³)</th>
<th>No. of Small Fragments by Volume Criterion</th>
<th>No. of Small Fragments by Volume Criterion per Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason 1</td>
<td>98</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mason 2</td>
<td>450</td>
<td>8</td>
<td>0.89</td>
</tr>
<tr>
<td>Mason 3</td>
<td>514</td>
<td>24</td>
<td>2.40</td>
</tr>
<tr>
<td>Total</td>
<td>1,149</td>
<td>39</td>
<td>0.85</td>
</tr>
</tbody>
</table>

By use of the volume measurement criterion, 39 of 125 fracture fragments (31%) were classified as small (<100 mm³) (Table II). Moreover, 21 fractures (46%) had at least 1 small fracture fragment. The mean number of small fracture fragments was 0.85 per fracture (Table III).

**Table IV. Fracture Fragment by Articular Surface Area**

<table>
<thead>
<tr>
<th>Mason Type</th>
<th>2 Fragments</th>
<th>Minor (100–500 mm²)</th>
<th>Small (&lt;100 mm²)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason 1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Mason 2</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Mason 3</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>28</td>
</tr>
</tbody>
</table>

**Table V. Volume-Specific Fracture Fragment Characteristics**

<table>
<thead>
<tr>
<th>Mason Type</th>
<th>Mean Estimated Bone Loss by Volume (mm²)</th>
<th>No. of Small Fragments by Volume Criterion</th>
<th>No. of Small Fragments by Volume Criterion per Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mason 1</td>
<td>98</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mason 2</td>
<td>450</td>
<td>8</td>
<td>0.89</td>
</tr>
<tr>
<td>Mason 3</td>
<td>514</td>
<td>24</td>
<td>2.40</td>
</tr>
<tr>
<td>Total</td>
<td>1,149</td>
<td>39</td>
<td>0.85</td>
</tr>
</tbody>
</table>

By use of the surface area measurement criterion, 65 of 96 fracture fragments (68%) were classified as small (<100 mm²) (Table IV). Moreover, 31 fractures (67%) had at least one small fracture fragment. The mean number of small fracture fragments was 1.4 per fracture (Table V).
Mason Type 2 (Partial Head Fractures)

Among the 26 partial head fractures (Mason Type 2), the mean articular surface area of the fractured part of the radial head was 107 mm$^2$ (range, 42 to 180 mm$^2$) and the mean volume was 818 mm$^3$ (range, 164 – 1956 mm$^3$). These data correspond to an estimated percentage of total intact surface area of 31% (range, 11 to 53%) and volume of 25% (range, 4 to 59%), respectively.

The fracture fragments had a mean articular surface area of 61 mm$^2$ (range, 21 to 136 mm$^2$), and a mean volume of 444 mm$^3$ (range, 45 to 1540 mm$^3$). Of the fractures, 19 fractures (73%) had 3 or 4 fracture fragments. Unstable fractures were more often fragmented. Small fracture fragments were more common among fragmented fractures (Tables II and IV).

Mason Type 3

Among the 17 whole-head fractures (Mason Type 3), the mean articular surface area of the fractured part of the radial head was 286 mm$^2$ (range, 204 to 414 mm$^2$) and the mean volume was 2529 mm$^3$ (range, 1353 – 3960 mm$^3$). These data correspond to an estimated percentage of total intact surface area of 83% (range, 59 to 97%) and volume of 81% (range, 47 to 100%), respectively, meaning that there is an estimated 17% loss of bone (e.g. small unidentified fragments) by volume and 19% by surface area criteria. Only 4 fractures (24%) created more than 3 fragments (Figure 3). More fragmented fractures had small fragments and greater estimated bone loss.

Discussion

Quantitative analysis of CT scans provided measurements of the volume and articular surface area of radial head fracture fragments. The strengths of our article include the fact that we developed this technique with widely used software. A consistent algorithm was used for bone identification (on CT slides) and automated curve and polygon mesh creation, which left limited room for judgment or bias on the part of the individual creating the model.

The limitations of this article include the fact that we could not use the opposite arm to determine the volume and surface area of the unfractured radial head.
Therefore, all measures expressed as a percentage of the entire head are estimates based on formulae determined in a separate study of intact radial heads. In addition, our definition of a small fracture fragment was arbitrary. Given these important limitations, this should be considered pilot work from which no management decisions can be made.

We found that partial-head fractures (Mason 2) are usually multi-fragmented (73%) and often have small fragments that may be difficult to repair using both volume and surface area criteria (23 fractures [88%]), particularly when the fracture is displaced and unstable. Small fragments are more common in partial than in whole head fractures, at least among the unstable fractures associated with elbow dislocation or fracture of the ulna. This finding is important because partial-head fractures are often considered straightforward to repair and irreparable partial-head fractures are rarely discussed.

Another important finding is that, according to the surface area criterion, many of the Mason 2 fractures involved less than a third of the radial head (12 out of 26). This means that about half of these fractures would not satisfy the Broberg and Morrey criterion of greater than 30% of the articular surface area to be considered Type 2 fractures.

Among whole-head fractures (Mason 3), only 4 (25%) had greater than 3 fragments, but 9 (69%) of the fractures with 3 or fewer fragments had small fragments. Furthermore, 7 of 13 fractures were estimated to have more than 10% bone loss by volumetric criteria of 13 fractures by articular surface criteria—which may indicate lost small fragments. Because even whole-head fractures with fewer than 3 fragments can have small fragments, the threshold of 3 fragments in the decision between open reduction-internal fixation and prosthetic replacement may not help guide management in all cases.

Conclusions

Quantitative analysis of 3D-CT scans is a useful technique for analyzing articular fracture pattern and morphology. Using this technique, we identified that partial-head fractures (Mason 2) frequently involve less than a third of the radial head surface area, partial-head fractures have more small and difficult-to-repair fragments than whole-head fractures (Mason 3), and whole head fractures with more than 3 fragments are relatively uncommon but some 3-fragment fractures have small fragments. These findings may influence our conception and classification of radial head fractures. For now, this technique is primarily designed for research purposes and not for patient care, but with further development Q3D-CT might prove useful in management decisions for individual patients.

References

CHAPTER 4
Diagnostic Accuracy of Two-Dimensional and Three-Dimensional Imaging and Modeling of Radial Head Fractures

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Chaitanya Mudgal, MD
David Ring, MD PhD

Submitted
Abstract

Background: This investigation tests the hypothesis that classification and characterization of fractures of the radial head is more accurate with (3D) than (2D) computed tomography (CT) images and radiographs, using a prospective study design with intraoperative inspection as the reference standard.

Methods: Treating surgeons and first assistants completed a questionnaire assigning a fracture type according to the Broberg and Morrey modification of Mason’s classification, evaluating selected fracture characteristics, and electing preferred management four times: Initially based upon radiographs and 2D images alone, a second time based on radiographs, 2D and 3D-CT images, a third time on radiographs, 2D, 3D-CT and 3D physical models, and a final time after surgery based on intra-operative visualization of the fracture. The agreement between surgeon and first assistant as well as the sensitivity and specificity were calculated for 2D-CT and radiographs, 3D-CT, and 3D physical models as compared to the intraoperative direct observation.

Results: The addition of 3D-CT reconstructions and 3D physical models to standard radiographs and 2D-CT scans improved the reliability of fracture classification according to the Broberg and Morrey modification of the Mason classification (kappa values, 2D-CT = 0.23, 3D-CT = 0.26, and 3D model = 0.37; all p < 0.05). The addition of the 3D-CT and the 3D physical model significantly improved the sensitivity compared to 2D-CT (all p < 0.01) for fracture line separating the entire head from the neck, comminution of the radial neck, fracture involving the articular surface, articular fracture gap greater than 2 millimeters, impacted fracture fragments, greater than 3 articular fragments, and articular fragments judged too small to repair.

Conclusion: Increasing levels of sophistication in imaging and modeling improved the sensitivity for diagnosis of fracture characteristics using the intraoperative interpretation of the operating surgeon as a reference standard. Fracture classification, characterization, and proposed treatment were also noted to be less variable with more sophisticated imaging and modeling.

Level of Evidence: Diagnostic, Level I

Introduction

Optimal management of radial head fractures is debated, but accurate preoperative radiological characterization of the fracture may facilitate management. Prior studies have demonstrated improved agreement in characterization and classification of various fractures with three-dimensional computed tomography (3D-CT) compared to two-dimensional computed tomography (2D-CT) images and radiographs. These studies were based upon retrospective data and the reference standard was based upon surgeon recollection and the medical record (e.g. operative notes).

Three-dimensional models that are constructed based on CT images and can be held in the hand and, may facilitate fracture characterization and surgical planning. Computer-generated bone models have been used in the planning of osteotomy of multidirectional distal radius malunions. This investigation tests the hypothesis that 3D-CT images identify and predict fracture characteristics more accurately than 2D-CT images and radiographs, using a prospective study design with intraoperative inspection as the reference standard. A secondary hypothesis was that 3D physical models predict fracture characteristics more accurately than 2D and 3D-CT images and radiographs.

Material and Methods

Inclusion and Exclusion Criteria

Under an Institutional Review Board (IRB) approved protocol, we prospectively included patients between 2007 and 2010 with a radial head fracture seen at two Level I trauma centers. Inclusion criteria were 1) fracture of the radial head; 2) election of operative treatment; 3) availability of CT scan; 4) age of 18 years or older. Exclusion criteria were pregnant women and patients unable to give informed consent. Forty-one patients satisfied the inclusion and exclusion criteria. Two patients were excluded for incomplete questionnaires, resulting in a final cohort of 39 patients.

Among the 39 patients, the mean age was 52 years (range, 23 to 92 years). There were 18 men (46%) and 21 (54%) women. The radial head fracture was an isolated injury in 4 patients (10%), and was associated with an elbow dislocation in 7 (18%) patients, an elbow dislocation and coronoid fracture (the so-called terrible triad injury) in 15 patients (38%), a posterior-olecranon-fracture dislocation (POFD) in 8 patients (21%), metaphyseal fracture of the proximal ulna (posterior Monteggia fracture) in 1 patient (3%), a complex fracture of the distal humerus in 1 patient (3%), an Essex-Lopresti lesion in 1 patient (3%), an anterior-transolecranon-fracture dislocation in 1 patient (3%), and a capitellum/trochlea fracture in 1 patient (3%). The left side was injured in 22 patients (56%) and the right side in 17 patients (44%). Twenty-three patients (59%) fractured their elbow in a fall from a standing height, 13 (33%)...
from a greater height, 2 (5%) patients in a motor vehicle collision (MVC) and one (3%) in a crush injury.

Evaluation
3D-CT reconstructions were ordered for all patients. CT scans were sent to Medical Modeling LLC (Golden, CO) for same-day manufacture of the 3D physical model reconstructions. The treating surgeons completed a questionnaire assigning a fracture type according to the Broberg and Morrey modification of Mason’s classification and important fracture characteristics and management. Broberg and Morrey modified Mason's classification as follows: Type 1 fractures involve less than 30% of the articular surface or are displaced fewer than 2 millimeters; Type 2 fractures are partial head fractures involving at least 30% of the articular surface and displaced at least 2 millimeters; Type 3 fractures are displaced articular fractures involving the entire head of the radius; and Type 4 fractures have an associated elbow dislocation.

The questionnaire was completed four times: initially based upon radiographs and 2D images alone; a second time based on radiographs, 2D and 3D-CT images; a third time on radiographs, 2D, 3D-CT and 3D physical models; and a fourth time based on intra-operative visualization of the fracture characteristics. The fourth questionnaire completed by the surgeon represented the reference standard. Both the surgeon and the first assistant rated the fractures, allowing us to calculate interobserver agreement. Sensitivity and specificity were calculated for 2D-CT and radiographs, 3D-CT, and 3D physical models as compared to the intraoperative direct observation of the surgeon.

Statistical Analysis
Interobserver agreement regarding fracture characteristics and treatment proposal was measured for each method by the chance-corrected kappa (κ) coefficient with strength of agreement assessed using the benchmarks of Landis and Koch'. Logistic regression was applied using a generalized estimating equations (GEE) strategy in order to account for the same 39 cases evaluated by multiple surgeons using each of 4 different methods (2D, 2D/3D, 2D/3D with physical model, direct operative view) with a binomial distribution used for binary yes/no fracture characteristics and a multinomial logit distribution for Broberg-Morrey classification (Types I-IV) and treatment plan (5 options: nonoperative management; Open Reduction and Internal Fixation (ORIF) with wires, screws or pins; ORIF with plate and screws; radial head excision; radial head replacement/arthroplasty). Differences between the methods were determined using the maximum likelihood Wald chi-square test with a two-tailed p < 0.05 as the criterion for statistical significance. Power analysis revealed that a minimum sample size of 30 fractures would provide 80% power (a = 0.05, b = 0.20) to detect significant intra- and inter-observer agreement using the kappa coefficient as well as in comparing diagnostic characteristics between the two imaging modalities.

Sensitivity, specificity, and accuracy for detection of each of the fracture characteristics and type of treatment with two-dimensional images, 3D reconstructions and 3D Model was calculated with the intraoperative findings of the attending surgeon as the gold standard. The statistical significance of these differences was evaluated using McNemar’s test for paired binary data. Statistical analysis was performed using SPSS version 18.0 (SPSS Inc./IBM, Chicago, IL).

Source of Funding
No funding was received in direct support of this study. An agreement approved by our Human Research Committee and Research Contracting Department, Medical Modeling LLC (Golden, CO) provided free 3D physical models.

Results
The addition of 3D-CT reconstructions and 3D models to standard radiographs and 2D-CT scans improved the reliability of fracture classification according to the Broberg and Morrey modification of the Mason classification, diagnosis of comminution of the radial neck, involvement of the articular surface, articular gap or step of 2 millimeters or greater, central impaction of the articular surface, presence of more than 3 articular fragments, presence of articular fragments too small to repair, and proposed treatment (Table I).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>2D CT</th>
<th>2D/3D CT</th>
<th>2D/3D CT With Model</th>
<th>Operative View (Gold Standard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broberg-Morrey</td>
<td>0.23*</td>
<td>0.26*</td>
<td>0.37*</td>
<td>0.38*</td>
</tr>
<tr>
<td>Fracture line</td>
<td>0.69†</td>
<td>0.54†</td>
<td>0.59†</td>
<td>0.54†</td>
</tr>
<tr>
<td>Comminution</td>
<td>0.37*</td>
<td>0.48†</td>
<td>0.57†</td>
<td>0.40†</td>
</tr>
<tr>
<td>Articular surface</td>
<td>0.12</td>
<td>0.28</td>
<td>0.22</td>
<td>0.28</td>
</tr>
<tr>
<td>Gap &gt;2 mm</td>
<td>0.37†</td>
<td>0.59†</td>
<td>0.57†</td>
<td>0.37†</td>
</tr>
<tr>
<td>Impaction</td>
<td>0.17</td>
<td>0.24</td>
<td>0.12</td>
<td>0.23</td>
</tr>
<tr>
<td>≥3 fragments</td>
<td>0.29</td>
<td>0.50†</td>
<td>0.64†</td>
<td>0.57†</td>
</tr>
<tr>
<td>Small fragments</td>
<td>0.26</td>
<td>0.34†</td>
<td>0.33†</td>
<td>0.42†</td>
</tr>
<tr>
<td>Proposed Treatment</td>
<td>0.47†</td>
<td>0.53†</td>
<td>0.67†</td>
<td>0.85†</td>
</tr>
</tbody>
</table>

Data are kappa (κ) values based on 39 cases evaluated by two independent surgeons. Guidelines for strength of observer agreement: κ = 0.0-0.20 (slight); κ = 0.21-0.40 (fair); κ = 0.41-0.60 (moderate); κ = 0.61-0.80 (substantial); κ = 0.81-1.00 almost perfect. Significant interobserver agreement beyond chance level (p < 0.05; 1 p < 0.01).
The addition of 3D-CT and the 3D models to 2D-CT and radiographs led to significant improvements in sensitivity for diagnosis of fracture line separation of the entire articular surface from the radial neck, comminution of the radial neck, involvement of the articular surface, articular gap or step of 2 millimeters or greater, central impaction of the articular surface, presence of more than 3 articular fragments and to the presence of articular fragments too small to repair (all \( p < 0.01 \), Table II). There were no significant changes in specificity between the three methods.

**Table II. Sensitivity and Specificity Characteristics for 2D and 3D CT Methods**

<table>
<thead>
<tr>
<th>Variable</th>
<th>2D CT Alone</th>
<th>2D/3D CT</th>
<th>2D/3D CT with Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Specificity</td>
<td>Sensitivity</td>
</tr>
<tr>
<td>Fracture Line</td>
<td>85 (91-99)</td>
<td>100 (90-100)</td>
<td>95* (78-100)</td>
</tr>
<tr>
<td>Comminution</td>
<td>98 (91-83)</td>
<td>93 (79-99)</td>
<td>81* (67-97)</td>
</tr>
<tr>
<td>Articular Surface</td>
<td>94 (84-99)</td>
<td>67 (16-98)</td>
<td>97 (16-98)</td>
</tr>
<tr>
<td>Gap &gt;2 mm</td>
<td>93 (81-99)</td>
<td>78 (46-96)</td>
<td>96 (46-96)</td>
</tr>
<tr>
<td>Impaction</td>
<td>57 (52-80)</td>
<td>88 (72-97)</td>
<td>84 (67-95)</td>
</tr>
<tr>
<td>&gt;3 Fragments</td>
<td>55 (54-74)</td>
<td>82 (60-95)</td>
<td>85 (66-96)</td>
</tr>
<tr>
<td>Small Fragments</td>
<td>74 (56-88)</td>
<td>83 (57-97)</td>
<td>85 (57-97)</td>
</tr>
<tr>
<td>Proposed Treatment</td>
<td>74 (56-88)</td>
<td>83 (57-97)</td>
<td>89* (47-93)</td>
</tr>
</tbody>
</table>

*Statistically significant compared to sensitivity for 2D CT alone (all \( p < 0.01 \)). There were no significant differences detected in specificity between the three methods.

The values are percentages with results are based on attending surgeon for each method compared to intraoperative direct view gold standard \((N = 39 \text{ paired cases})\). *Statistically significant compared to sensitivity for 2D CT alone \((all \ p < 0.01)\).
Discussion

The strengths of this investigation include the prospective design, the relatively large number of patients, and an intra-operative reference standard. The limitations of this investigation include the fact that images were usually rated after surgery (in part due to the inherent delay in receiving the physical 3D model), so that ratings of the radiological images were—in essence—retrospective; the injuries were relatively complex resulting in a spectrum bias in terms of all fractures of the radial head, although our work is representative of the types of fractures that would be studied with CT and operated on; two patients (one with addition of a capitellum/trochlea fracture and one anterior-transolecranon fracture dislocation) had non-displaced fractures of the radial neck, which are relatively unusual—both fractures were seen only on operative exposure; and multiple physicians were involved in the ratings at two sites, which makes the results more generalizable, but less consistent. These data should also be interpreted in light of the fact that the first assistant was usually a resident or fellow, so that the observer variability may largely reflect differences in training and experience.

It is not always feasible to have models available prior to operative treatment at this point, but 3D reconstructions of computed tomography images can be easily produced by surgeons using the DICOM (Digital Imaging and Communications in Medicine) files from the patient’s CT scan. Three-dimensional reconstructions are made from CTscans and therefore do not require additional scanning and do not expose the patient to additional radiation. It has been calculated at the investigators institution, that the cost for additional 3D reconstructions are an additional 20% of the cost of a CT-scan. Free software such as OsiriX™ is available which makes it possible for every orthopedic surgeon to quickly and easily create 3D reconstructions themselves with minimal training.

This study found that increasing levels of sophistication in imaging/modelling: 1) improved the sensitivity for diagnosis of numerous fracture characteristics using the surgeon’s interpretation of the intraoperative findings as the reference standard; and 2) decreased observer variation between surgeon and first assistant. This is in concordance with prior studies that have demonstrated improved agreement in characterization and classification of fractures with 3D-CT compared to 2D-CT and radiographs alone. Prior studies that addressed the classification of radial head fractures specifically found substantial observer variation when fractures were evaluated by radiographs only. However, these studies differed in that they are based upon retrospective data in small groups of observers/patients and the reference standard was based upon surgeon recollection and the medical record (e.g. operative notes).

We interpret this combination of findings to indicate that fracture classification and characterization based on 3D imaging and models is more accurate and reliable, essentially helping to narrow the experience and training gap. While experienced surgeons sometimes suggest that little is added by more sophisticated imaging, science is establishing that more sophisticated imaging does improve our understanding of the injury. However, recommendations regarding the use of a new technology should be based on both diagnostic performance characteristics and clinical impact. The next steps are to investigate whether more sophisticated imaging leads to more effective treatment as measured by fewer complications with less functional impairment.
References


CHAPTER 5
Interobserver Reliability of Radial Head Fracture Classification: Two-Dimensional vs. Three-Dimensional Computed Tomography

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Abstract

Background: The Broberg and Morrey modification of the Mason classification of radial head fractures has substantial interobserver variation. This study used a large web-based collaborative of experienced orthopaedic surgeons to test the hypothesis that three-dimensional reconstructions of computed tomography scans (3D-CT) improve the interobserver reliability of the classification of radial head fractures according to the Broberg and Morrey modification of the Mason classification.

Methods: Eighty-five orthopaedic surgeons evaluated twelve radial head fractures and were randomly assigned to review either radiographs and two-dimensional computed tomography scans (2D-CT) or radiographs, and 3D-CT images to determine the fracture classification, fracture characteristics and treatment plans. The kappa multirater measure (κ) was calculated to estimate agreement between observers.

Results: 3D-CT had moderate and 2D-CT had fair agreement among observers for the Mason classification (κ3D = 0.49 vs. κ2D = 0.37; p = < 0.001). Among seven fracture characteristics (fracture line, comminution, articular surface involvement, gap/step of 2mm or greater, central impaction, recognition of three articular fragments and articular fragments to small to repair) there was a significant difference in kappa value between 3D-CT and 2D-CT for three variables (articular fragments too small to repair [κ3D = 0.61 vs. κ2D = 0.47; p = < 0.001], recognition of three articular fragments [κ3D = 0.61 vs. κ2D = 0.38; p = < 0.001] and central impaction [κ3D = 0.15 vs. κ2D = 0.22; p = 0.006]). Among treatment recommendations there was fair agreement for both 3D-CT and 2D-CT (κ3D = 0.40 vs. κ2D = 0.26; p = < 0.001).

Conclusion: Although 3D-CT led to some small but significant decreases in interobserver variation, there is still a notable degree of disagreement regarding classification and characterization of radial head fractures. Improvements in imaging may not be sufficient to optimize interobserver agreement.

Level of Evidence: Diagnostic Level III

Introduction

The classification of radial head fractures according to Broberg and Morrey’s modification of the Mason classification 1 has substantial interobserver variation 10, 12. As with classification and characterization of most fractures the interobserver variation is greater than the intraobserver variation. Evidence suggests that more sophisticated images such as 3D-CT improve intraobserver reliability more than interobserver reliability 3, 4. A major limitation of most studies of observer variation is the use of only a few observers, most of them typically relatively junior surgeons.

A new collaboration motivated to better understand interobserver variation 11 consists of observers who have completed all training and are independently treating patients. This provides an opportunity to further investigate interobserver variability and how to reduce it.

Treatment decisions for radial head fractures are often based on radiological criteria and measurements according to Broberg and Morrey’s modification of the Mason classification 5, 9. This investigation tested the hypothesis that 3D-CT images improve the interobserver reliability of the classification and characterization of radial head fractures over 2D-CT and radiographs.

Materials and Methods

Study Design

Independent observers (all orthopaedic surgeons) from several countries were invited to evaluate twelve cases from a convenience sample of radial head fractures (selected to represent a full spectrum of radial head fracture morphologies and overall injury patterns) in an online survey: they were randomly assigned to review either radiographs and 2D-CT or radiographs and 3D-CT and then to determine the fracture classification, fracture characteristics and treatment plans. The randomization sequence was determined by a computer random number generator (Windows Excel; Microsoft, Redmond, WA). The study was performed under a protocol approved by the Institutional Research Board at the principal investigators hospital.

This was the inaugural study from a nascent collaborative called the Science of Variation Group (SOVG). The objectives of the collaborative are to study variation in the definition, interpretation, and classification of injury and disease. The Science of Variation Group has created a web-based platform that facilitates large international interobserver studies. With multiple fully trained surgeons from diverse countries and institutions participating in studies, this approach should provide a powerful forum for studying, understanding, and ultimately reducing interobserver variation in aspects of patient care.
Observers
A total of 206 surgeons were invited via e-mail to join the Science of Variation Group. We used lists of various professional organizations as well as friends and acquaintances (along with their friends and acquaintances) to identify surgeons to invite for participation. We welcome any interested surgeon to join. Other than an acknowledgement as part of the author collaborative in the paper, no incentives were provided. One-hundred surgeons were interested in participation and logged on to the website. Forty-eight surgeons were randomized to 2D-CT scans and radiographs and fifty-two to 3D-CT scans and radiographs. Four weekly reminders to complete the online survey were e-mailed. Eighty-eight surgeons completed the study, from which 3 observers were excluded because of inability to view the online study due to hospital restriction. This study presents an analysis of the eighty-five observers that completed the study; 39 in the 2D-CT group and 46 in the 3D-CT group.

Fractures
Radiographs and computed tomography scans of radial head fractures were identified from a list of all cases treated by the senior investigator between 2000 and 2006 at one level-1 trauma center. The scanning technique was evaluated to determine suitability for 3D reconstructions (slice thickness between 0.62 and 1.25 mm, no metal implants). Inclusion criteria were: 1) Radial head fracture; 2) CT scan appropriate for 3D reconstruction; 3) Age 18 or older. Inadequate quality of the CT scan prompted exclusion from the study. Radiographs and CT scans of radial head fractures from 30 patients were blinded by an independent research fellow for use in this study. Two of the authors (one subspecialty trained upper extremity surgeon and one research fellow in upper extremity trauma) selected twelve cases that had radial head fractures of different size, morphology, and location; representing most of the different patterns of traumatic elbow instability with radial head fracture. Radiographs, 2D-CT, and 3D-CT reconstructions were uploaded to the research group’s website. The 3D-CT reconstructions were created with use of Vitrea imaging software (Vital Images, Minneapolis, Minnesota). For each case, videos with 2D-CT and 3D-CT images along the sagittal, coronal and axial cuts were created. The 3D-CT videos included a reconstruction of the entire elbow and a reconstruction with the distal humerus subtracted. Observers could scroll through the videos or play them automatically.

Evaluation
Observers logged in independently on the website. Upon login to the website, they were asked to provide demographic and professional information: 1) location of practice; 2) years in independent practice; 3) training of surgical trainees; 4) number of radial head fractures treated per year, and; 5) clinical specialty. Subsequently, observers were asked to classify the fractures according to Broberg and Morrey’s modification of the Mason classification 15. Type 4 fractures were excluded, since we were interested in the radial head fracture independent of associated injuries. Observers were provided with the original description and corresponding images of the classification system.

The observers were also asked 7 questions regarding fracture characteristics:
1) Does the fracture line separate the entire articular surface from the radial neck? 2) Is there any comminution of the radial neck? 3) Does the fracture involve the articular surface? 4) Is there an articular step or gap of greater than 2 millimeters? 5) Is there any central impaction of the articular surface, 6) Are there more than 3 articular fragments? 7) Are any of the fragments too small to repair? They were also asked their preferred management: 1) Non-operative management; 2) Open reduction and internal fixation with screws, wires or pins; 3) Open reduction and internal fixation with plate and screws; 4) radial head excision; 5) radial head replacement (arthroplasty). Observers were blinded to clinical information. Observers could comment on each case and all questions had to be completed in order to continue with the next case. The observers completed the study at their own time and pace.

Statistical Analysis
The kappa multirater measure (κ) was used to estimate agreement among surgeons with respect to fracture classification, fracture characteristics and treatment approach. It is a commonly used statistical method to describe chance-corrected agreement in a variety of intra-observer and interobserver studies 2,7,13. Agreement among observers was calculated with use of the multirater kappa measure described by Siegel and Castellan 16. Kappa values were interpreted using the guidelines proposed by Landis and Koch 17: values of 0.01 to 0.20 indicate slight agreement; 0.21 to 0.40, fair agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and more than 0.81, almost perfect agreement. Zero indicates no agreement beyond that expected due to chance alone, –1.00 means total disagreement, and +1.00 represents perfect agreement 2,13. Two-sample independent Z-tests were performed for each variable to compare the kappa for 2 dimensional CT with that of 3 dimensional CT. Since the samples compared in this study were not independent (the same set of fractures were rated by the 2D-CT and 3D-CT group), this method produced conservative estimates of the p-values. A post-hoc power analysis was performed using nQuery Advisor (version 7.0, nQuery Advisor, Statistical Solutions, Saugus, MA) to identify the power of each comparison and the sample size necessary to achieve 80% given both effect size and rater ratio remain constant at each iteration (Table V).
Sources of Funding
No funding was received in direct support of this study.

Results
Observer Demographics
A total of 85 observers participated in this investigation. The observer demographics are summarized in table I. Among the others surgeons there were 3 hand surgeons (no wrist), 2 trauma surgeons and 3 upper extremity surgeons (hand, wrist, elbow and shoulder).

Table I. Observer demographics

<table>
<thead>
<tr>
<th>Variable</th>
<th>2-Dimensional CT (N = 39)</th>
<th>3-Dimensional CT (N = 46)</th>
<th>Total (N = 85)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Australia</td>
<td>1</td>
<td>3</td>
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</tr>
<tr>
<td>Canada</td>
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<td>5</td>
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<td>Europe</td>
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</tr>
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<td>United States</td>
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<td>70</td>
</tr>
<tr>
<td>Other</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Years in practice</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0-5</td>
<td>11</td>
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<td>Specialization</td>
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<td></td>
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<tr>
<td>General orthopaedics</td>
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<td>5</td>
<td>3</td>
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<tr>
<td>Orthopaedic traumaology</td>
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<td>31</td>
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<td>Shoulder and elbow</td>
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<td>18</td>
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</tr>
<tr>
<td>Hand and wrist</td>
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<td>36</td>
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Classification

The interobserver variation for classification of the fractures according to Broberg and Morrey’s modification of the Mason classification was fair with use of 2D-CT scans and moderate with use of 3D-CT reconstructions (κ2D = 0.37, SE 0.010, and κ3D = 0.49, SE 0.023; p < 0.001) (Table IIA-B).

Fracture Characteristics
Agreement on central impaction of the articular surface was fair with use of 2D-CT scans and slight with use of 3D-CT reconstructions (κ2D = 0.22, SE 0.027, and κ3D = 0.15; SE 0.010; p = 0.006). Interobserver agreement on presence of more than 3 art-

Table IIA. Interobserver Agreement 2-Dimensional CT

<table>
<thead>
<tr>
<th>Variable</th>
<th>Categorical</th>
<th>κ</th>
<th>95% CI</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broberg and Morrey Modified Mason Classification</td>
<td>Fair</td>
<td>0.37</td>
<td>(0.35, 0.39)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Fracture line</td>
<td>Moderate</td>
<td>0.41</td>
<td>(0.31, 0.51)</td>
<td>0.139</td>
</tr>
<tr>
<td>Comminution radial neck</td>
<td>Fair</td>
<td>0.33</td>
<td>(0.25, 0.41)</td>
<td>0.328</td>
</tr>
<tr>
<td>Articular surface involvement</td>
<td>Slight</td>
<td>0.02</td>
<td>(-0.46, 0.49)</td>
<td>0.961</td>
</tr>
<tr>
<td>Step/gap &gt;2 millimeters</td>
<td>Substantial</td>
<td>0.65</td>
<td>(0.58, 0.71)</td>
<td>0.015</td>
</tr>
<tr>
<td>Central impaction</td>
<td>Fair</td>
<td>0.22</td>
<td>(0.13, 0.31)</td>
<td>0.006*</td>
</tr>
<tr>
<td>Three articular fragments</td>
<td>Fair</td>
<td>0.38</td>
<td>(0.35, 0.40)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Too small to repair</td>
<td>Moderate</td>
<td>0.47</td>
<td>(0.44, 0.49)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Proposed Treatment</td>
<td>Fair</td>
<td>0.26</td>
<td>(0.24, 0.29)</td>
<td>&lt;0.001*</td>
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Table IIB. Interobserver Agreement 3-Dimensional CT

<table>
<thead>
<tr>
<th>Variable</th>
<th>Categorical</th>
<th>κ</th>
<th>95% CI</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broberg and Morrey Modified Mason Classification</td>
<td>Moderate</td>
<td>0.49</td>
<td>(0.45, 0.54)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Fracture line</td>
<td>Moderate</td>
<td>0.50</td>
<td>(0.43, 0.58)</td>
<td>0.139</td>
</tr>
<tr>
<td>Comminution radial neck</td>
<td>Fair</td>
<td>0.38</td>
<td>(0.31, 0.45)</td>
<td>0.328</td>
</tr>
<tr>
<td>Articular surface involvement</td>
<td>Poor</td>
<td>0.00</td>
<td>(-0.81, 0.80)</td>
<td>0.961</td>
</tr>
<tr>
<td>Step/gap &gt;2 millimeters</td>
<td>Substantial</td>
<td>0.73</td>
<td>(0.63, 0.82)</td>
<td>0.015</td>
</tr>
<tr>
<td>Central impaction</td>
<td>Slight</td>
<td>0.15</td>
<td>(0.09, 0.16)</td>
<td>0.006*</td>
</tr>
<tr>
<td>Three articular fragments</td>
<td>Substantial</td>
<td>0.61</td>
<td>(0.59, 0.63)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Too small to repair</td>
<td>Substantial</td>
<td>0.61</td>
<td>(0.59, 0.63)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Proposed Treatment</td>
<td>Fair</td>
<td>0.40</td>
<td>(0.35, 0.45)</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>
ticular fragments was fair with use of 2D-CT scans and substantial with use of 3D-CT reconstructions (κ2D = 0.38, SE 0.01, and κ3D = 0.61, SE 0.010; p < 0.001). Agreement on presence of fragments too small to repair was moderate with use of 2D-CT scans and substantial with use of 3D-CT reconstructions (κ2D = 0.47, SE 0.013, and κ3D = 0.61, SE 0.010; p < 0.001) (Table IIIA-B).

Treatment

Interobserver agreement on treatment was fair with both 2D-CT scans and 3D-CT reconstructions (κ2D = 0.26, SE 0.012, and κ3D = 0.40, SE 0.013; p < 0.001) (Table II).

Observer demographics and Mason classification

When classifying fractures according to the Mason classification agreement among United States observers was fair with use of 2D-CT scans and moderate with use of 3D-CT reconstructions (κ2D = 0.32, SE 0.01, and κ3D = 0.52, SE 0.03; p < 0.001) (Table IIIA-B).

Agreement among observers who were in practice 5 or fewer years was moderate with use of 2D-CT scans and substantial with use of 3D-CT reconstructions (κ2D = 0.44, SE 0.03, and κ3D = 0.62, SE 0.18; p = 0.039). Agreement among observers who were in practice from 6 to 10 years was fair with use of 2D-CT scans and moderate with use of 3D-CT reconstructions (κ2D = 0.32, SE 0.05, and κ3D = 0.53, SE 0.05; p = 0.002). Agreement among observers who were in practice from 11 to 20 years was fair with use of 2D-CT scans and moderate with use of 3D-CT reconstructions (κ2D = 0.46, SE 0.05, and κ3D = 0.45, SE 0.04; p = 0.011).

Agreement among observers who treated 6 to 10 radial head fractures per year was fair with use of 2D-CT scans and moderate with use of 3D-CT reconstructions (κ2D = 0.46, SE 0.05; p = 0.063). Agreement among observers who treated 11 to 20 radial head fractures per year was moderate with both 2D-CT scans and 3D-CT reconstructions (κ2D = 0.45, SE 0.04; p < 0.05). Agreement among observers who treated more than 20 radial head fractures per year was substantial with both 2D-CT scans and 3D-CT reconstructions (κ2D = 0.44, SE 0.04; p = 0.063).

Agreement among observers who treated 5 or fewer radial head fractures per year was fair with both 2D-CT scans and 3D-CT reconstructions (κ2D = 0.27, SE 0.03, and κ3D = 0.32, SE 0.14; p = 0.76). Agreement among observers who treated 6 to 10 radial head fractures per year was fair with use of 2D-CT scans and moderate with use of 3D-CT reconstructions (κ2D = 0.39, SE 0.04, and κ3D = 0.48, SE 0.04; p = 0.063). Agreement among observers who treated 11 to 20 radial head fractures per year was moderate with both 2D-CT scans and 3D-CT reconstructions (κ2D = 0.45, SE 0.05; p = 0.66). Agreement among observers that treated more than 20 radial head fractures per year was substantial with both 2D-CT scans and 3D-CT reconstructions (κ2D = 0.46, SE 0.06, and κ3D = 0.52, SE 0.05; p = 0.44).

Table IIIA. Differences in Agreement on Broberg and Morrey modification of the Mason classification between Observer demographics and Imaging Modality

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Categorical</th>
<th>χ²</th>
<th>SE</th>
<th>P-Value</th>
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<td>Europe</td>
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<td>Moderate</td>
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<td>0.05</td>
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<td>United States</td>
<td>28</td>
<td>Fair</td>
<td>0.32</td>
<td>0.03</td>
<td>&lt; 0.001</td>
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<tr>
<td>Other</td>
<td>5</td>
<td>Moderate</td>
<td>0.44</td>
<td>0.07</td>
<td>0.561</td>
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<tr>
<td>Years in practice</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>11</td>
<td>Moderate</td>
<td>0.44</td>
<td>0.07</td>
<td>0.039</td>
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<tr>
<td>6-10</td>
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<td>Fair</td>
<td>0.32</td>
<td>0.05</td>
<td>0.002</td>
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<td>11-20</td>
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<td>0.02</td>
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<td>0.10</td>
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<td>Fractures per year</td>
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<td>&lt; 0.001</td>
</tr>
<tr>
<td>Other</td>
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<td>Moderate</td>
<td>0.47</td>
<td>0.09</td>
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N = Number of Observers, SE = standard error; P-value < 0.05 = Significant compared to 3-Dimensional CT

Table IIIB. Differences in Agreement on Broberg and Morrey modification of the Mason classification between Observer demographics and Imaging Modality

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Categorical</th>
<th>χ²</th>
<th>SE</th>
<th>P-Value</th>
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<td>Practice</td>
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<tr>
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<td>Moderate</td>
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<td>United States</td>
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<td>0.08</td>
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<td>0.05</td>
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<td>0.47</td>
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<td>&lt; 0.05</td>
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<tr>
<td>Shoulder and elbow</td>
<td>4</td>
<td>Fair</td>
<td>0.30</td>
<td>0.11</td>
<td>0.107</td>
</tr>
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<td>Hand and wrist</td>
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<td>0.03</td>
<td>&lt; 0.001</td>
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<tr>
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<td>Fair</td>
<td>0.35</td>
<td>0.11</td>
<td>0.396</td>
</tr>
</tbody>
</table>

N = Number of Observers, SE = standard error; P-value < 0.05 = Significant compared to 2-Dimensional CT
The collaborative, internet based approach has facilitated large, international studies of inter-rater variation 6, 8. Additionally, only fully trained surgeons, many with substantial clinical experience participated. Inclusion of surgeons from multiple countries and continents should increase the generalizability of the results. Using high-speed internet connections and improved compression techniques, we were able to provide high quality reproduction images and movies via the internet.

There are many weaknesses in this study. First, the quality of the radiographs was limited to what had been obtained at the time of injury, which reflects usual practice, but not what might be achieved with specific protocols. In addition, we provided limited information about the patient and the injury. There was also a spectrum bias by selecting cases to represent the known variety of injuries, with the result that less common complex fractures were over represented compared to the more common minimally or slightly displaced fractures. Our study reflects what would be expected with relatively complex fractures of the radial head—the reliability would be expected to be higher if we included more of the non-displaced or minimally displaced fractures that makeup the majority of radial head fractures.

Another shortcoming is the fact that a small number of observers either uncommonly or never treat radial head fractures, but we did not plan for exclusions on this basis and therefore did not do so after the fact to avoid introducing bias. The power is based on the total number of observations allowing us to use a smaller number of cases and thereby decrease burden and increase participation of observers. Given the small kappa differences between 2D and 3D for certain questions (e.g. articular surface involvement) and the large variabilities, power was low, and huge sample sizes would be required for 80% power for detecting differences between 2D and 3D given the levels of agreement observed. For other questions (e.g. three articular fragments), the observed power was very high with the numbers of surgeons participating and even fewer would have attained the traditional 80% power. Finally, this is an artificial research situation given that in clinical practice patients would have both the two and three-dimensional reconstructions available to them.

We speculate that the very poor agreement regarding articular surface involvement might reflects misunderstanding of the question-based on comments received as part of the survey some observers probably thought we were referring to involvement of the part of the radial head that articulates with the lesser sigmoid notch of the ulna. The poor agreement regarding central impaction likely reflects the lack of a precise or consistent definition of this term. The findings of this study are otherwise consistent with prior studies on the distal humerus, distal radius and the coronoid 3, 4, 8.

Three-dimensional reconstructions are made from CT-scans and there-
before do not require additional scanning or expose the patient to additional radiation. It has been calculated that for additional 3D reconstructions an additional 20% of the costs of a CT-scan. Free software such as OsiriX is available which makes it possible for every orthopedic surgeon to quickly and easily create 3D reconstructions themselves with minimal training.

Three-dimensional CT images led to small but significant decreases in variation between observers for fracture classification and some fracture characteristics compared to 2D-CT, but a notable amount of variation remains even with more sophisticated imaging. Our belief that 3D-CT images are easier for surgeons to interpret is supported by the observation that 3D-CT produced a higher agreement for Broberg and Morrey’s modification of the Mason classification than previously reported in the literature and 3D-CT was associated with less disagreement in classification than 2D-CT across various cultures, training, subspecialty and levels of experience. Nonetheless agreement was only fair or moderate at best even with 3D-CT. Furthermore, some might interpret this data as showing much less influence one interobserver variation than one might guess.

Other potential sources of interobserver variation include unfamiliar or unclear definitions, and differences in culture, training, and exposure. In our opinion, the fact that well-trained, experienced observers indicate that there are variations in these factors that lead different experts to see different things in sophisticated images. In other words, reducing interobserver variation seems to depend on something more than better imaging. Additional research to identify and reduce sources of observer variation in the interpretation of diagnostic images is merited.

References

Attitude Towards Stretch Pain of the Elbow After Radial Head Fracture

Thierry G. Guitton, MSc
Ana-Maria Vranceanu, PhD
David Ring, MD PhD

Submitted to Clin Orthop Relat Res
Abstract

Hypothesis: This study was designed to test the hypothesis that agreement with the idea that “stretching of the elbow beyond the point where it becomes painful is important in recovery” leads to greater elbow range of motion one month after injury.

Methods: Seventy-one patients with an isolated Broberg and Morrey modified Mason Type 1 or Type 2 radial head fracture seen within 14 days after injury were enrolled prospectively. They completed the Pain Catastrophizing Scale (PCS), Center for Epidemiologic Studies Depression Scale (CES-D) and were asked to rate their agreement with a statement regarding pain and recovery from their injury on a 5-point Likert scale, which were collapsed into 3 categories (disagree, neutral, agree) to facilitate statistical power. One-month later, patients completed the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire and elbow and forearm motion were measured with a goniometer.

Results: Nine patients (12.6%) disagreed with the role of pain in recovery, 6 (8%) were neutral, and 56 (78.9%) agreed. Patients that disagreed with the role of stretch pain in recovery were older (p = 0.031), had more depressive symptoms (CES-D; p = 0.047), and achieved less elbow extension (p = 0.050) and forearm rotation (p = 0.017) approximately one month after injury.

Conclusions: A negative attitude towards stretch pain during recovery from fracture of the radial head is associated with less elbow motion one month after injury. Future studies should address the ability to improve recovery by encouraging a change in pain paradigm.

Introduction

Isolated, stable, minimally displaced fractures of the radial head (Types 1 and 2 of the Broberg and Morrey modification of the Mason Classification) are common fractures that are usually treated non-operatively. The most common sequel of these fractures is elbow stiffness. In our experience, the elbow stiffness may be a result of excessive immobilization or ineffective stretching exercises.

It can be counter-intuitive to intentionally cause pain in the setting of an injury. Vulnerability and protectiveness are enhanced by automatic thoughts such as “pain indicates harm”, “the pain is permanent”, or other aspects of a maladaptive response to nociception that psychologists have termed pain catastrophizing. Research suggests that fear of pain, thinking the worst in response to nociception (pain catastrophizing) and pain anxiety may be important determinants of recovery after an acute fracture. Similarly, depression hinders recovery after fracture. We tested the hypothesis that agreement that painful stretches are an important part in recovery leads to greater motion one month after injury. Secondarily, we tested the hypothesis that depression and pain catastrophizing correlate with lack of agreement that painful stretches are important, as well as less motion and more disability one month after injury.

Materials and Methods

Inclusion and Exclusion Criteria

Under an IRB (Institutional Review Board) approved protocol, we prospectively include patients with a radial head fracture seen at one Level 1 trauma center. Inclusion criteria were 1) A non-operatively treated fracture of the radial head; 2) Type 1 or Type 2 according to the Broberg and Morrey modification of Mason’s classification; 3) Seen within 14 days of injury; 4) Skeletal maturity; 5) Cognitive and physical ability to follow exercise instructions; 6) Isolated injury and 7) No clinical or radiographic evidence of injury to the medial elbow ligaments. Exclusion criteria were pregnant women and patients unable to give informed consent. Patients with prior elbow injury, disease, or arthritis were not excluded. Eighty-five patients satisfied the inclusion and exclusion criteria. Fourteen patients did not return 1 month after injury resulting in a final cohort of 71 patients.

Among the 71 patients, the average age was 44.4 years (range, 19 to 72 years). There were 18 men (25.4%) and 53 (74.6%) women. Sixty-five fractures were Mason type 1 (91.5%) and six were Mason type 2 (8.5%). Thirty-four patients (47.9%) injured their right elbow and 37 (52.1%) their left elbow. The dominant side was injured in 38 cases (53.5%) and the non-dominant side in 33 cases (46.5%). Fifty-seven patients (80.3%) fractured their elbow in a fall from a standing height, 3 (4.2%) from a greater...
height and 11 (15.5%) patients suffered from a multi-vehicle accident (MVA). Forty-eight patients (67.6%) were white-collar workers. Six doctors participated in the care of these patients, from which one doctor treated 56 (78.9%) patients. The average follow-up was 33.6 days (range, 13 to 70 days).

Evaluation

Patients were approached during the initial outpatient visit to an orthopaedic surgeon and informed consent was obtained. The patients completed the Pain Catastrophizing Scale (PCS) and the Center for the Epidemiological Study of Depression Instrument (CES-D). The Pain Catastrophizing Scale (PCS) is a reliable and valid 13-item questionnaire, developed by Sullivan et al. to measure the extent to which people think the worst in response to pain in clinical and nonclinical populations. Each PCS item is rated on a 4-point scale: 1 (not at all) to 4 (all the time). The 13 items are summed to create a total score. The CES-D scale is a reliable and valid 19-item self-report scale designed to measure depressive symptoms in the general population.

Subjects were also asked to rate their agreement with the following statement regarding recovery from their injury: “Do you think that you should perform the exercise beyond the point where it gets painful to reach the best possible recovery following your fracture?” with use of a 5-point Likert scale (5 = strongly agree, 4 = agree, 3 = neutral, 2 = disagree, and 1 = strongly disagree).

During the routine one-month follow-up with their treating surgeon, all enrolled subjects completed the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire to measure upper extremity specific disability with a lower score indicating less disability. In addition, the elbow flexion arc and range of forearm rotation was measured with a goniometer by a research fellow that was not involved with the treatment of that patient.

Rehabilitation

During the initial outpatient visit, patients were advised to actively move the elbow into as much flexion, extension, supination and pronation as possible and to self-assist by pushing with the uninjured hand (or a wall or desk as a fulcrum) in order to stretch the elbow to achieve greater motion. Additionally, patients were instructed that weight bearing on the elbow, lifting, and grasping and that pain control either physically e.g. cold application or using pain medication was allowed. They were advised to return to deskwork, but limit forceful activities or risk of another fall. Additionally, patients were instructed that the pain might make them feel protective and cautious, but that it was a false alarm as no harm could come from these stretches and that they were an important and helpful part of recovery. The instructing doctor (blinded) was a hand fellowship trained orthopedic surgeon.

Statistical Analysis

Power analysis indicated that a minimum sample size of 18 subjects (6 in each group) would provide 80% statistical power to detect a significant difference in elbow flexion-extension arc, assuming an effect size of 2.0 or greater (mean difference of 20 degrees, standard deviation of 10 degrees) (alpha = 0.05, beta = 0.20) using one-way ANOVA. Two-tailed p values of <0.05 were considered to be significant.

Frequencies were used to describe demographics, fracture characteristics and outcome variables. Two main sets of analyses were conducted. In the first set, we used analyses of variance to look for differences in depression, pain catastrophizing, disability, elbow flexion and forearm rotation by category of response to the statement about pain. Due to a small number of responses in some of the categories, and in order to achieve statistical power (at least 6 participants per group), we combined the strongly agree and agree categories, as well as the strongly disagree and disagree categories. In the second set, we used Spearman correlations to test the relationship between ranked level of agreement with the pain statement and the outcome variables.

Results

Nine patients (12.6%) disagreed with the role of pain in recovery, 6 (8%) were neutral, and 56 (78.9%) agreed. Demographics, fracture characteristics and outcome variables were compared between patients who agreed, were neutral or disagreed that pain was useful for recovery. Patients who disagreed with the role of pain in recovery were older than those who were neutral or agreed with the role of pain in recovery (F = 3.79, p = 0.03). Patients who were neutral regarding the role of pain had more depressive symptoms than those who agreed or disagreed with the role of pain in recovery (F = 3.12, p = 0.047).

Patients who disagreed that pain is important in recovery had less one-month post-injury pronation (F = 4.29, p = 0.016), elbow extension (F = 3.12, p = 0.05) and combined forearm motion (F = 4.27; p = 0.017). There was no statistical difference between groups in PCS (p = 0.17), DASH (p = 0.20), elbow flexion (p = 0.34), and flexion-extension arc (p = 0.19). There was no statistical difference in time from injury to final evaluation (p = 0.67) (Table I).

There was a significant correlation between 5-point Likert ranked agreement with the role of pain in recovery and PCS (r = -0.26, p = 0.03), a trend toward significance for CES-D total score (r = -0.12, p = 0.07), and no correlation with DASH (r = -0.10, p = 0.39), one month post-injury elbow flexion (r = -0.027, p = 0.82), extension (r = 0.13, p = 0.28), pronation (r = -0.12, p = 0.30), supination (r = -0.053, p = 0.66), flexion-extension arc (r = -0.12, p = 0.32) or arc of forearm rotation
There was a significant correlation between CES-D score and PCS score ($\rho = 0.47$, $p < 0.001$).
In spite of these shortcomings, we did find that a patient’s paradigm with respect to the role of pain in recovery predicted motion one month after injury and that a patient’s paradigm had small but significant correlation with pain catastrophizing. The lack of correlation between attitude and disability might be due to the small number of patients in the neutral (9) and disagree (6) categories versus the agree category (55). There is a nearly 11 point difference in the means DASH score in patients that agree (17.4) or are neutral (17.3) about the role of pain and those that disagree (28.0), which seems clinically important. Of note is that the mean DASH for patients that disagree is higher than what has been reported in patients with fractures, while the mean DASH for the other categories is lower (21).

A small subset of patients get stiff after radial head fractures and we probably need a larger study to adequately study these issues. If additional studies corroborate the role of automatic thoughts and beliefs (intuition, “gut feelings”) in recovery from injury, as well as the correlation of these thoughts with maladaptive responses to nociception or depression, then there is room for improvement in our teaching and coaching of post-injury exercises. As revered hand surgery pioneer Paul Brand noted in his book “The Gift of Pain”, nociception exists for our protection. It’s no surprise that pain after injury can make us feel vulnerable and protective. The key may be to help our patients change their mindset from vulnerability to recovery, seeing a painful exercise more as a useful stretch exercise and the post-exercise pain more as that rewarding ache after a great work out.

Conclusion
This study found that a negative attitude towards stretch pain during recovery from fracture of the radial head is associated with less elbow motion one month after injury. Future studies should address the ability to improve recovery by encouraging a change in pain paradigm.

References


CHAPTER 7

Incidence and Risk Factors for the Development of Radiographic Arthrosis After Traumatic Elbow Injuries

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C. Niek van Dijk, MD PhD
David Ring, MD PhD

Abstract

Purpose: Radiographic arthrosis is a common sequela of elbow trauma. Few studies have addressed risk factors for radiographic arthrosis after elbow injury, especially in the long term. Data from multiple long-term follow-up studies of patients with surgically treated elbow fractures provided us with an opportunity to assess risk factors for long-term radiographic arthrosis after elbow injury.

Methods: During a 5-year period, we obtained radiographs during a research-specific evaluation of 139 patients (81 men and 58 women) 10 or more years (median, 19.5 y; range, 10–34 y) after surgical treatment of an elbow fracture as part of multiple retrospective studies. Radiographic arthrosis was graded according to the system of Broberg and Morrey. Bivariate and multivariable analyses evaluated risk factors for radiographic arthrosis.

Results: Of 139 patients, 75 had radiographic evidence of arthrosis at final evaluation and 32 had moderate or severe radiographic arthrosis. Mechanism of injury, age, gender, follow-up time, occupation, and limb dominance were not associated with radiographic arthrosis. Multiple logistic regression analysis identified the type of injury as the only independent predictor of moderate to severe radiographic arthrosis. Patients with a bicolumnar fracture of the distal humerus, a capitellum/trochlear fracture, or an elbow fracture–dislocation were 8.0, 7.3, and 5.2 times more likely (odds ratio), respectively, to develop radiographic evidence of moderate or severe radiographic arthrosis than the average patient in this cohort.

Conclusions: Distal humerus fractures (both columnar and capitellum/trochlea) and elbow fracture–dislocations are more likely than fractures of the olecranon and radial head to develop moderate or severe radiographic arthrosis in the long term.

Level of Evidence: IV, prognostic study

Introduction

Radiographic arthrosis is a common sequela of elbow trauma resulting from direct cartilage injury, instability, and articular incongruity. It is understood that over the long term, many patients develop radiographic signs of osteoarthrosis after elbow trauma, although symptoms vary and few patients present for treatment. There is a limited relationship between radiographic evidence of arthrosis and impairment or disability. Not much has been published regarding risk factors for radiographic arthrosis after elbow injury, especially in the long term. Data from multiple long-term follow-up studies of injured elbows provided the opportunity to assess the risk factors for posttraumatic elbow arthrosis on radiographs. Our null hypothesis was that different types of elbow injuries have rates of radiographic arthrosis (independent of function or outcome) that are comparable at equivalent follow-up times.

Patients and Methods

Patients

During a 5-year period (2005–2010), we collected radiographs and clinical data from a research-specific, long-term evaluation of patients who had surgical treatment of displaced and unstable elbow fractures between 1975 and 1998 as part of 7 retrospective studies. All 7 studies were performed at one institution in The Netherlands and were approved by the institutional review board. Inclusion criteria for the present study were: (1) surgically treated elbow fracture, (2) age greater than 18 years at the time of injury, and (3) date of evaluation more than 10 years after the initial injury or surgery. Among the 235 patients in the prior studies, 139 satisfied the inclusion and exclusion criteria and made up the study cohort.

There were 81 men and 58 women, with a mean age of 38 years at the time of injury (range, 18–73 years). The dominant arm was involved in 69 patients. Twenty-nine patients were employed as laborers at the time of injury; 110 were nonlaborers.

Injuries included fracture–dislocation of the elbow in 29 patients, distal humerus columnar fracture in 29, isolated radial head fracture in 20, proximal ulna/olecranon fracture in 54, and capitellum/trochlear fracture in 7.

According to the AO comprehensive classification of fractures, 2 distal humerus columnar fractures were classified as type B and 27 as type C. Among the capitellum fractures, there were 7 type B. Among the ulna/olecranon fractures, there were 49 type B and 5 type C, according to the AO classification. All isolated radial head fractures were type 2 (partial articular, displaced more than 2 mm), according to the Broberg and Morrey modification of Mason’s classification. Among fracture dislocations of the elbow, there were 13 posterior olecranon, 6 anterior olecranon, and 10 dislocations with associated fracture of the radial head (2 with concomitant fracture of the coronoid—the so-called terrible triad).
Patients were injured in a fall from a standing height in 52 cases, in a fall from a greater height in 37 cases, in a bicycle accident in 16 cases, from a direct blow in 8 cases, and in a motor vehicle collision in 26 cases. A total of 129 patients had open reduction and plate and screw fixation and 10 had excision of a radial head fracture.

Evaluation
Investigators who were not involved in patients' care evaluated each radiograph at a mean of 19 years (range, 10–34 y) after the injury. Two independent observers (both orthopedic surgeons) evaluated anteroposterior and lateral radiographs of the involved elbow once for radiographic arthrosis, according to the system of Broberg and Morrey: grade 0 indicates no radiographic arthrosis, grade 1 indicates slight joint-space narrowing with minimum osteophyte formation, grade 2 indicates moderate joint-space narrowing with moderate osteophyte formation, and grade 3 indicates severe degenerative change with gross destruction of the joint. The senior author reviewed all discrepancies in a blinded manner and made a final determination. We did not measure interobserver variability as part of this study.

Statistical Analysis
Continuous data are presented as the mean when they are normally distributed; otherwise, the median and interquartile range are reported. The number of patients in the severe group was too small (n = 9) and we thought that pooling moderate or severe and mild or no grades was a more reasonable approach for analysis of factors associated with the development of radiographic arthrosis. We compared independent variables such as demographics and fracture characteristics one at a time between patients with moderate or severe and mild or no radiographic arthrosis by bivariate analysis to examine associations, including unpaired Student's t-test for age, Mann-Whitney U test for follow-up time (owing to skewness), and Fisher's exact test or Pearson chi-square for categorical data such as injury type, and injury mechanism. We entered variables into multivariable analysis using stepwise logistic regression (backward selection) to identify factors that were independently associated with moderate or severe arthrosis. We used the Wald test (distributed as chi-square) to assess significance of predictors and the Hosmer-Lemeshow test to evaluate regression model fit to the data. Odds ratios were calculated with the 95% confidence interval for significant predictors. Power analysis indicated that a minimum sample size of 80 patients with radiographic arthrosis provided 80% power (α = 0.05, β = 0.20) to identify significant predictors based on the odds ratio and for evaluating 8 variables using multivariable logistic regression. Two-tailed values of p < 0.05 were considered statistically significant.

Results
Among the 139 patients, 32 had moderate or severe radiographic arthrosis and 107 had mild or no radiographic arthrosis on final radiographs. Median follow-up was not significantly different among patients with moderate or severe radiographic arthrosis and with mild or no radiographic arthrosis (18 vs 19 y; p = 0.23). Duration of follow-up was not significantly different between injury types (p > 0.10). Bivariate analysis indicated an association between the presence of moderate or severe radiographic arthrosis and injury type (p = 0.001). Mechanism of injury, age, gender, follow-up time, occupation, and limb dominance were not associated with severe or moderate radiographic arthrosis (Table I).

Table I. Bivariate Analysis: Comparison Between Patients With Moderate or Severe Arthrosis Versus Mild or No Arthrosis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Moderate or Severe Arthrosis (N = 32)</th>
<th>Mild or No Arthrosis (N = 107)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, (y)</td>
<td>40.2 ± 15.5</td>
<td>37.1 ± 14.1</td>
<td>0.22</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td>0.88</td>
</tr>
<tr>
<td>Male</td>
<td>19 (59)</td>
<td>62 (58)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>13 (41)</td>
<td>45 (42)</td>
<td></td>
</tr>
<tr>
<td>Dominance, (n [%])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>18 (56)</td>
<td>51 (48)</td>
<td>0.43</td>
</tr>
<tr>
<td>Nondominant</td>
<td>14 (44)</td>
<td>56 (52)</td>
<td></td>
</tr>
<tr>
<td>Occupation, (n [%])</td>
<td></td>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td>Nonlaborer</td>
<td>23 (72)</td>
<td>87 (81)</td>
<td></td>
</tr>
<tr>
<td>Laborer</td>
<td>9 (28)</td>
<td>20 (19)</td>
<td></td>
</tr>
<tr>
<td>Injury Type, (n [%])</td>
<td></td>
<td></td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Proximal ulna/olecranon</td>
<td>5 (16)</td>
<td>49 (45)</td>
<td></td>
</tr>
<tr>
<td>Distal humerus fracture</td>
<td>13 (41)</td>
<td>16 (15)</td>
<td></td>
</tr>
<tr>
<td>Elbow dislocation with fracture</td>
<td>10 (31)</td>
<td>19 (18)</td>
<td></td>
</tr>
<tr>
<td>Capitellum/trochlea fracture</td>
<td>3 (9)</td>
<td>4 (4)</td>
<td></td>
</tr>
<tr>
<td>Radial head fracture</td>
<td>1 (3)</td>
<td>19 (18)</td>
<td></td>
</tr>
<tr>
<td>Mechanism, (n [%])</td>
<td></td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Fall–standing height</td>
<td>11 (35)</td>
<td>41 (38)</td>
<td></td>
</tr>
<tr>
<td>Fall–greater height</td>
<td>10 (31)</td>
<td>27 (25)</td>
<td></td>
</tr>
<tr>
<td>Motor vehicle accident</td>
<td>9 (28)</td>
<td>15 (14)</td>
<td></td>
</tr>
<tr>
<td>Bicycle accident</td>
<td>1 (3)</td>
<td>13 (12)</td>
<td></td>
</tr>
<tr>
<td>Direct blow injury</td>
<td>1 (3)</td>
<td>7 (7)</td>
<td></td>
</tr>
<tr>
<td>Follow-up, (y)</td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Median</td>
<td>18</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Interquartile range</td>
<td>14 – 22</td>
<td>15 – 24</td>
<td></td>
</tr>
<tr>
<td>Full range</td>
<td>10 – 31</td>
<td>10 – 34</td>
<td></td>
</tr>
</tbody>
</table>

*Statistically significant.
Figure 1 illustrates the number of patients with moderate or severe radiographic arthrosis and the injury type. Multiple logistic regression confirmed that injury type was the only factor independently associated with radiographic arthrosis ($p < 0.001$). The odds of moderate or severe radiographic arthrosis were greater for distal humerus fractures, capitellum/trochlear fractures, and fracture–dislocations than for isolated fractures of the radial head or olecranon (Table II).

**Table II. Multivariate Analysis: Type of Injury is Predictive of Moderate or Severe Arthrosis**

<table>
<thead>
<tr>
<th>Injury Type</th>
<th>Odds Ratio</th>
<th>95% CI</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal ulna/olecranon (reference category)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Distal humerus fracture</td>
<td>8.0</td>
<td>2.5 – 25.8</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Elbow dislocation with fracture</td>
<td>5.2</td>
<td>1.8 – 17.0</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Capitellum/trochlea fracture</td>
<td>7.3</td>
<td>1.5 – 42.6</td>
<td>0.02*</td>
</tr>
<tr>
<td>Radial head fracture</td>
<td>0.5</td>
<td>0.1 – 4.7</td>
<td>0.56</td>
</tr>
</tbody>
</table>

*Statistically higher risk of moderate or severe arthrosis than proximal ulna/olecranon reference group. Analysis is adjusted for age, gender, dominance, occupation, mechanism of injury, treatment, and length of follow-up (all $p > 0.10$).

**Discussion**

Injury type was the only significant independent predictor of moderate or severe radiographic arthrosis. Different injury types may lead to more severe degrees of articular surface injury and realignment. Distal humerus fractures and capitellum/trochlear fractures create the greatest articular injury and were associated with the greatest risk of radiographic arthrosis. Radial head fractures and proximal ulna/olecranon fractures were associated with lower incidence of radiographic arthrosis. Unfortunately, we could not accurately or reliably measure intra-articular displacement and comminution from records available decades after treatment of these injuries. These findings are all consistent with the previous literature on posttraumatic elbow radiographic arthrosis, which notes that intra-articular distal humerus fractures are a common source of posttraumatic elbow radiographic arthrosis.

Consistent with prior data, none of these patients requested surgery specifically to address radiographic arthrosis. Most patients develop radiographic signs of posttraumatic radiographic arthrosis after elbow trauma, but only a few present for treatment.

Radiographic arthrosis was not related to follow-up time, age, hand dominance, occupation, gender, or mechanism of injury. This suggests that postinjury activities and occupation are not important risk factors for the development or advancement of radiographic arthrosis. This finding is reassuring and enabling, although counterintuitive.

The limitations of this report include the fact that we have only cross-sectional (rather than longitudinal) data and that we did not address symptoms and dysfunction. We based assessment of arthrosis on radiographs alone, and we acknowledge the known limited relationships among radiographic evidence of arthrosis and symptoms, impairment, and disability. Interobserver variability for the radiographic arthrosis rating was not measured. Unfortunately, available reproductions of the initial injury radiographs and initial postoperative radiographs were inadequate to quantify articular incongruity, intra-articular comminution, or fracture severity, and we do not have sufficient numbers to analyze the influence of subclassification of each injury type (eg, most of the injuries in each category were of a single AO type). For instance, nearly all of the columnar distal humerus fractures were type C according to the AO classification, and we did not feel confident about measures of articular incongruity. In addition, there were a large number of surgeons involved and fixation was often performed with older techniques that would be considered nonstandard at this time.

Consequently, this study looks broadly at general types of injuries rather than at the influence of articular incongruity or fracture pattern and concludes that isolated fractures of the radial head and olecranon are less prone to moderate or severe...
vere radiographic arthrosis in the long term than fractures of the distal humerus and fracture–dislocations. This finding is expected; nevertheless, the data objectively document and quantify the differences using long-term evaluations that are hard to come by.

References

Part V: General discussion

CHAPTER 8
Discussion

Thierry G. Guitton
Discussion

Advancements in technology, further insight into patient related factors, and the availability of long-term functional outcome data potentially allowed us to improve the classification, treatment and outcome of radial head fractures. We applied these recent advancements to radial head fracture treatment: 1) to gain further insight in radial head fractures and 2) to function as a model for general improvements in orthopedic trauma surgery.

This discussion will be continued with a more detailed address of each chapter separately and finally summarized in a conclusion:

CHAPTER 2

This chapter was the successful validation of our Q3D-CT modeling technique. Additionally, we derived linear regression models capable of estimating the volume and proximal articular surface area of the radial head prior to fracture. The limitations of this investigation included the fact that the accuracy of this Q3D-CT modeling technique depended on the quality of the CT scan. Because CT scans do not account for articular cartilage, our measurements will differ from those based on MRI or direct measurements of fresh cadaveric bone. We did not thoroughly evaluate inter- and intra-observer variability in creation of the models because our method was time and resource intensive and, based on experience with 2 observers doing several models during training; the method leaves limited room for bias. When one person created the same model five times, we found very little variation in the measures of volume and surface area. The differences between surface area calculated using our formula and that using simple geometry probably reflect the ovoid shape of the radial head. In the final multivariable models height, weight and radial neck diameter did not significantly contribute to the fit of the model (as gauged by adjusted R²) and were therefore not used.

The strong points of this investigation included the fact that we used: 1) a relatively large number of CT scans; 2) a consistent algorithm for bone identification (on CT slides); and 3) automated curve and polygon mesh creation, which left limited room for judgment or bias on the part of the individual creating the model. The relatively small standard deviations of the measured volumes and surface areas, the relatively narrow 95% confidence intervals of the predictive linear models, and the fact that our multivariable models account for over 70% of the variability of volume and surface area, all indicated that we could make reasonable and useful estimation of these parameters in fractured radial heads.

To our knowledge, measurement of proximal articular surface area and radial head volume has not been attempted. We produced equations capable of estimating the volume and proximal articular surface area of the intact radial head—on the basis of parameters usually available in fractured radial heads—with an average relative percent difference of 0.5%. The ability to estimate the volume and surface area of the bone prior to fracture provides useful information when we analyze a fractured radial head. For instance, it allowed us to measure the percentage of the surface area involved in the fracture, which is one criterion in Broberg and Morrey’s modification of Mason’s classification. Keeping in mind the many shortcomings of our approach, we believe that it will, nonetheless improve our analysis and characterization of radial head fracture patterns.

These Q3D-CT methods are, at least initially, more important for clinical research. We will be using this technique to study fracture fragment size and injury pattern, and the ability to estimate percentage involvement helps make the results more intuitive for clinicians. For instance, in radial head fracture classifications and management, decisions often refer to 30% of the surface area, but it’s not clear that this is an important cutoff, that we can make this measurement accurately from radiographs, or that it is representative of the fracture patterns that actually occur. More detailed analysis with these sophisticated techniques may help to clarify these issues. This Q3D-CT modeling technique can be applied to any intact or fractured bone in the human body and therefore has a huge potential in orthopedic trauma surgery, but additional work is needed to better define the accuracy and reliability of our method and determine how sensitive it is to the quality of the CT scan and the person doing the analysis.

CHAPTER 3

In this chapter, quantitative analysis of CT scans provided measurements of the volume and articular surface area of radial head fracture fragments. The strengths of this investigation include the fact that we developed this technique with widely used software. A consistent algorithm was used for bone identification (on CT slides) and automated curve and polygon mesh creation, which left limited room for judgment or bias on the part of the individual creating the model.

The limitations of this paper include the fact that we could not use the opposite radial head for volume and surface area estimates, and the estimates of bone loss based on formulae are less precise. Additionally, we used both volume and articular surface area measurement. The volume measurements are straightforward whereas the articular surface area measurements may be less reliable. Finally, our definition of a small fragment was a mathematical and arbitrary categorization that, from our experience seems reasonable, but might not reflect the actual clinical situation.

We found that partial head (Mason 2) fractures are usually multi-fragmented (73%) and often have small fragments that are difficult to repair by volume and
surface area criteria (23 fractures [88%]) particularly when the fracture is displaced and unstable. We conclude that small fragments are most common with partial head fractures, at least among the unstable fractures associated with elbow dislocation or fracture of the ulna. Interestingly, small partial head fractures have not been addressed much in the literature, and it may be commonly assumed that these are more straightforward to repair simply because a large part of the articular surface is not fractured.

Another important finding is that, according to the surface area criterion, many of the Mason 2 fractures involved less than a third of the radial head (12 out of 26). This means that about half of these fractures would not satisfy the Broberg and Morrey criterion of greater than 30% of the articular surface area to be considered Type 2 fractures 3, 19.

Quantitative analysis of 3D-CT scans is a useful technique for analyzing articular fracture pattern and morphology. Using this technology we identified: 1) that partial head (Mason 2) fractures frequently involve less than a third of the radial head surface area; 2) that partial head fractures have more small and difficult to repair fragments than whole head fractures (Mason 3); and 3) that whole head fractures with more than 3 fragments are relatively uncommon (4 patients, 23% of Mason type 3 and 8.7% of total), but some 3 fragment-fractures have small fragments. These findings may influence our conception and classification of radial head fractures. For now, this technique is primarily designed for research purposes and not for patient care, but with further development Q3D-CT might prove useful in management decisions for individual patients.

CHAPTER 4
This chapter investigated if classification and characterization of fractures of the radial head is more accurate with 3D-CT images and 3D models than 2D-CT images and radiographs, using a prospective study design with intraoperative inspection as the reference standard.

The limitations of this investigation include the fact that images were usually rated after surgery (in part due to the inherent delay in receiving the physical 3D model), so that ratings of the radiological images were in essence–retrospective; the injuries were relatively complex resulting in a spectrum bias in terms of all fractures of the radial head, although our work is representative of the types of fractures that would be studied with CT and operated on; two patients (one with addition of a capitellum/trochlea fracture and one anterior-transolecranon fracture dislocation) had non-nondisplaced fractures of the radial neck, which are relatively unusual–both fractures were seen only on operative exposure; and multiple physicians were involved in the ratings at two sites, which makes the results more generalizable, but less consistent. These data should also be interpreted in light of the fact that the first assistant was usually a resident or fellow, so that the observer variability may largely reflect differences in training and experience. The strengths of this investigation include the prospective design, the relatively large number of patients, and an intraoperative reference standard.

This study found that increasing levels of sophistication in imaging/modeling: 1) improved the sensitivity for diagnosis of numerous fracture characteristics using the surgeon’s interpretation of the intraoperative findings as the reference standard; and 2) decreased observer variation between surgeon and first assistant. This is in concordance with prior studies that have demonstrated improved agreement in characterization and classification of fractures with 3D-CT compared to 2D-CT and radiographs alone 5, 7, 10, 11, 14, 15, 28, 29. Prior studies that addressed the classification of radial head fractures specifically found substantial observer variation 5, 20, 21, 27 when fractures were evaluated by radiographs only. However, these studies differed in that they are based upon retrospective data in small groups of observers/patients and the reference standard was based upon surgeon recollection and the medical record (e.g. operative notes).

We interpret this combination of findings to indicate that fracture classification and characterization based on 3D imaging and models is more accurate and reliable, essentially helping to narrow the experience and training gap. While experienced surgeons sometimes suggest that little is added by more sophisticated imaging, science is establishing that more sophisticated imaging does improve our understanding of the injury. However, recommendations regarding the use of a new technology should be based on both diagnostic performance characteristics and clinical impact. The next steps are to investigate whether more sophisticated imaging leads to more effective treatment as measured by fewer complications with less functional impairment.

CHAPTER 5
This chapter investigated in a large web-based collaborative of experienced orthopaedic surgeons if 3D-CT improve the interobserver reliability of the classification of radial head fractures according to the Broberg and Morrey modification of the Mason classification.

The collaborative, web-based approach has facilitated large international studies of inter-rater variation. Additionally, only fully trained surgeons, many with substantial clinical experience participated. Inclusion of surgeons from multiple countries and continents should increase the generalizability of the results. Using high-speed Internet connections and improved compression techniques, we were able to provide sophisticated reproduction images and movies via the Internet.
There are some weaknesses in this study. First, the quality of the radiographs was limited to what had been obtained at the time of injury, which reflects usual practice, but not what might be achieved with specific protocols. In addition, we provided limited information about the patient and the injury. There was also a spectrum bias by selecting cases to represent the known variety of injuries, with the result that less common complex fractures were over represented compared to the more common minimally or slightly displaced fractures. Our study reflects what would be expected with relatively complex fractures of the radial head—the reliability would be expected to be higher if we included more of the non-displaced or minimally displaced fractures that make up the majority of radial head fractures. Another shortcoming is the fact that a small number of observers either uncommonly or never treat radial head fractures, but we did not plan for exclusions on this basis and therefore did not do so after the fact to avoid introducing bias. Finally, this is an artificial research situation given that in clinical practice clinicians would have both the 2D and 3D reconstructions available to them.

Three-dimensional CT images led to small but significant decreases in variation between observers for fracture classification and some fracture characteristics compared to 2D-CT, but a notable amount of variation remains even with more sophisticated imaging. Our belief that 3D-CT images are easier for surgeons to interpret is supported by the observation that 3D-CT produced a higher agreement for Broberg and Morrey’s modification of the Mason classification than previously reported in the literature 20, 21 and 3D-CT was associated with less disagreement in classification than 2D-CT across various cultures, training, subspecialty and levels of experience. Nonetheless agreement was only fair or moderate at best even with 3D-CT. Furthermore, some might interpret this data as showing much less influence on interobserver variation than one might guess.

Other potential sources of interobserver variation include unfamiliar or unclear definitions, and differences in culture, training, and exposure. In our opinion, the fact that well-trained, experienced observers disagree indicates that there are variations in these factors that lead different experts to see different things in sophisticated images. In other words, reducing interobserver variation seems to depend on something more than better imaging. Additional research to identify and reduce sources of observer variation in the interpretation of diagnostic images is merited.

CHAPTER 6
This chapter investigated the psychosocial aspects of radial head fractures. More specifically, if agreement with the idea that “stretching of the elbow beyond the point were it becomes painful is important in recovery” leads to greater elbow range of motion one month after injury.

The strengths of this study included the prospective design and enrollment of patients from 6 different surgeons’ practices. Limitations include: 1) Enrollment after diagnosis, reassurance, and coaching with motion exercises, all of which were therapeutic interventions that may have affected attitudes towards pain (and may explain why the majority of patients agreed with the importance of pain for recovery); 2) Ceiling effects since most patients with minimally displaced radial head fractures regained near normal motion regardless of their paradigm; 3) Meaningless variation (or “noise”) added to the data by virtue of the fact that the measurement error of a hand-held goniometer was comparable to the small differences in elbow flexion contractures observed; 4) The measure of agreement with a statement regarding the role of pain in recovery was an indirect measure of confidence with exercises—a more direct and objective measure would be preferable; patients may state agreement on a questionnaire, but still have a hard time performing stretches beyond pain; 5) Wide range in the time that people returned for the “one-month” follow-up (although this did not correlate with any of the outcome measures); and 6) Limited power due to unequal distribution of patients among agreement groups.

In spite of these shortcomings, we did find that a patient’s paradigm with respect to the role of pain in recovery predicted motion one month after injury and that a patient’s paradigm had small but significant correlation with pain catastrophizing. The lack of correlation between attitude and disability might be due to the small number of patients in the neutral (9) and disagree (6) categories versus the agree category (55). There was a nearly 11 point difference in the mean DASH score in patients that agree (17.4) or were neutral (17.3) about the role of pain and those that disagree (28.0), which seems clinically important. Of note is that the mean DASH for patients that disagree was higher than what had been reported in patients with fractures, while the mean DASH for the other categories was lower (21).

This line of research should be pursued. If additional studies corroborate the role of automatic thoughts and beliefs (intuition, “gut feelings”) in recovery from injury, as well as the correlation of these thoughts with depressive symptoms and maladaptive responses to nociception, then there is room for improvement in our teaching and coaching of post-injury exercises. As Paul Brand noted in his book “The Gift of Pain”, nociception exists for our protection. It is no surprise that pain after injury may make us feel vulnerable and protective. The key may be to help our patients change their mindset from vulnerability to recovery, seeing a painful exercise more as a useful stretch exercise and the post-exercise pain more as that rewarding ache after a great work out.
This chapter assessed the risk factors for posttraumatic elbow arthrosis on radiographs after elbow injury in the long term. The limitations of this investigation included the fact that we have only cross-sectional (rather than longitudinal) data and that we did not address symptoms and dysfunction. We based assessment of arthrosis on radiographs alone, and we acknowledge the known limited relationships among radiographic evidence of arthrosis and symptoms, impairment, and disability. Interobserver variability for the radiographic arthrosis rating was not measured. Unfortunately, available reproductions of the initial injury radiographs and initial postoperative radiographs were inadequate to quantify articular incongruity, intra-articular comminution, or fracture severity, and we did not have sufficient numbers to analyze the influence of subclassification of each injury type (eg, most of the injuries in each category were of a single AO type). For instance, nearly all of the columnar distal humerus fractures were type C according to the AO classification, and we did not feel confident about measures of articular incongruity. In addition, there were a large number of surgeons involved and fixation was often performed with older techniques that would be considered nonstandard at this time.

Injury type was the only significant independent predictor of moderate or severe radiographic arthrosis. Different injury types may lead to more severe degrees of articular surface injury and realignment. Distal humerus fractures and capitellum/trochlea fractures created the greatest articular injury and were associated with the greatest risk of radiographic arthrosis. Radial head fractures and proximal ulna/olecranon fractures were associated with lower incidence of radiographic arthrosis. Unfortunately, we could not accurately or reliably measure intra-articular displacement and comminution from records available decades after treatment of these injuries. These findings are all consistent with the previous literature on post-traumatic elbow radiographic arthrosis, which notes that intra-articular distal humerus fractures are a common source of posttraumatic elbow radiographic arthrosis.

Radiographic arthrosis was not related to follow-up time, age, hand dominance, occupation, gender, or mechanism of injury. This suggests that post-injury activities and occupation are not important risk factors for the development or advancement of radiographic arthrosis. This finding is reassuring and enabling, although counterintuitive.

Consequently, this study looked broadly at general types of injuries rather than at the influence of articular incongruity or fracture pattern and concludes that isolated fractures of the radial head and olecranon are less prone to moderate or severe radiographic arthrosis in the long term than fractures of the distal humerus and fracture-dislocations. This finding is expected; nevertheless, the data objectively document and quantify the differences using long-term evaluations that are hard to come by.

**Conclusion**

Throughout the various chapters in this thesis, our results showed that advancements in technological, imaging, psychosocial and long-term outcome can help improve classification, treatment and outcome after radial head fracture. First, we validated our new Q3D-CT modeling technique and successfully applied this technique to radial head fractures. Measurement of proximal articular surface area and radial head volume has not been attempted before and it will improve our analysis and characterization of radial head fracture patterns. We demonstrated prospectively and in a multi-rater study that 3D images led to increased agreement in classification of radial head fractures. We also demonstrated that patients who agree that pain is a necessary part of recovery have improved outcomes after radial head fractures. Additionally, we identified predictors for arthrosis after elbow trauma in the long term. In general, these advancements can help gain more insight in the classification, treatment and outcome of fractures in orthopedic trauma surgery.

As shown in this thesis, advancements in technical analysis, imaging modalities, increased interest in psychosocial aspects of treatment and the availability of long-term outcome data can help improve classification, treatment and outcome in fractures of the radial head. Implementation and application of new technologies as they emerge in medicine are needed to allow further improvement of our current treatments. Dogmas in orthopedics on the psychosocial aspects of treatment should be set aside. With all these new technologies and advancements widely available, it is our duty to carefully evaluate them and—if proven beneficial—to use them in the treatments of our patients. It is science that created these advancements and through adequate scientific evaluation of these advancements we can continue creating more effective treatments for our patients.
References


Part VI: Summary

Summary
INTRODUCTION
The advancements in analyzing techniques, 3D imaging and modeling, increased interest in psychosocial aspects of treatment and the recent availability of multiple long-term outcome studies give us the opportunity to further investigate the classification, treatment and outcome of radial head fractures. This all could lead to improved treatment and possible better outcomes for patients. The aim of this thesis was to apply these advancements to the radial head in order to: 1) gain further insight in classification, treatment and outcome of radial head fractures and 2) function as a model for general improvements in orthopedic trauma surgery.

CHAPTER 2
QUANTITATIVE MEASUREMENTS OF THE VOLUME AND SURFACE AREA OF THE RADIAL HEAD
This chapter investigated if quantitative Q3D-CT modeling technique based on anatomical and demographic data that can measure size, shape, and proximal articular surface area could be used to develop formulas that could predict the volume and proximal surface area of the intact radial head in patients with fractures of the radial head. To our knowledge, measurement of proximal articular surface area and radial head volume has not been attempted. We produced equations capable of estimating the volume and proximal articular surface area of the intact radial head–on the basis of parameters usually available in fractured radial heads–with an average relative percent difference of 0.5%. The ability to estimate the volume and surface area of the bone prior to fracture provides useful information when we analyze a fractured radial head. For instance, it allows us to measure the percentage of the surface area involved in the fracture, which is one criterion in Broberg and Morrey’s modification of Mason’s classification. We will be using this technique to study fracture fragment size and injury pattern.

CHAPTER 3
QUANTITATIVE THREE-DIMENSIONAL COMPUTED TOMOGRAPHY MEASUREMENT OF RADIAL HEAD FRACTURES
This chapter analyzed radial head fracture fragment morphology on Q3D-CT images in terms of size, shape, and articular surface area. Quantitative analysis of 3D-CT scans proved to be a useful technique for analyzing articular fracture pattern and morphology. Using this technology we identified that partial head (Mason 2) fractures frequently involve less than a third of the radial head surface area; that partial head fractures have more small and difficult to repair fragments than whole head fractures (Mason 3); and that whole head fractures with more than 3 fragments are relatively uncommon, but some 3 fragment-fractures have small fragments. These findings may influence our conception and classification of radial head fractures.

CHAPTER 4
DIAGNOSTIC ACCURACY OF TWO-DIMENSIONAL AND THREE-DIMENSIONAL IMAGING AND MODELING OF RADIAL HEAD FRACTURES
This chapter investigated if classification and characterization of fractures of the radial head is more accurate with 3D-CT and 3D models than 2D-CT and radiographs, using a prospective study design with intraoperative inspection as the reference standard. We found that increasing levels of sophistication in imaging/modeling: 1) improved the sensitivity for diagnosis of numerous fracture characteristics; and 2) decreased observer variation between surgeon and first assistant. We found that fracture classification and characterization based on three-dimensional imaging and models is more accurate and reliable, essentially helping to narrow the experience and training gap.

CHAPTER 5
INTEROBSERVER RELIABILITY OF RADIAL HEAD FRACTURE CLASSIFICATION: TWO-DIMENSIONAL VS. THREE-DIMENSIONAL COMPUTED TOMOGRAPHY
This chapter investigated in a large web-based collaborative of experienced orthopaedic surgeons if 3D reconstructions of CT scans improved the interobserver reliability of the classification of radial head fractures according to the Broberg and Morrey modification of the Mason classification. Three-dimensional CT images led to small but significant decreases in variation between observers for fracture classification and some fracture characteristics compared to 2D-CT, but a notable amount of variation remained even with more sophisticated imaging. We believe that 3D-CT images are easier for surgeons to interpret. Nonetheless agreement was only fair or moderate at best even with 3D-CT. Furthermore, some might interpret this data as showing much less influence on interobserver variation than one might guess. Reducing interobserver variation seems to depend on something more than better imaging.

CHAPTER 6
ATTITUDE TOWARDS STRETCH PAIN OF THE ELBOW AFTER RADIAL HEAD
This chapter investigated if agreement with the idea that “stretching of the elbow beyond the point were it becomes painful is important in recovery” leads to greater elbow range of motion one month after injury. We found that a negative attitude towards stretch pain during recovery from fracture of the radial head is associated with less elbow motion one month after injury.
CHAPTER 7
INCIDENCE AND RISK FACTORS FOR THE DEVELOPMENT OF
RADIOGRAPHIC ARTHROSIS AFTER TRAUMATIC ELBOW INJURIES
This chapter assessed the risk factors for posttraumatic elbow arthrosis on radiographs after elbow injury in the long-term. We found that injury type was the only significant independent predictor of moderate or severe radiographic arthrosis. Radiographic arthrosis was not related to follow-up time, age, hand dominance, occupation, gender, or mechanism of injury. This suggests that post-injury activities and occupation are not important risk factors for the development or advancement of radiographic arthrosis. Fractures of the radial head and olecranon are less prone to moderate or severe radiographic arthrosis in the long term than fractures of the distal humerus (both columnar and capitellum/trochlea) and elbow fracture-dislocations.

Conclusions
This thesis shows that advancements in technical analysis, imaging modalities, increased interest in psychosocial aspects of treatment and the availability of long-term outcome data can help improve classification, treatment and outcome in fractures of the radial head. It is science that created these advancements and through adequate scientific evaluation of these advancements we can continue creating more effective treatments for patients.
Samenvatting
Introductie

De nieuwe ontwikkelingen in analyse technieken, driedimensionale (3D) beeldvorming en modellering, toegenomen belangstelling voor psychosociale aspecten van de behandeling en de recente beschikbaarheid van meerdere lange termijn studies biedt ons de gelegenheid om verder onderzoek te doen naar de classificatie, de behandeling en uitkomst van radiuskop fracturen. Dit alles kan leiden tot een betere behandeling en eventueel betere resultaten voor patiënten. Het doel van dit proefschrift was om deze nieuwe ontwikkelingen toe te passen op de radiuskop om: 1) meer inzicht te verkrijgen in de classificatie, de behandeling en de uitkomst van radiuskop fracturen en 2) te functioneren als een model voor algemene verbeteringen in de orthopedische traumatologie.

HOOFDSTUK 2
KWANTITATIEVE METINGEN VAN DE INHOUD EN DE OPPERVLAKTE VAN DE RADIUS KOP

In dit hoofdstuk werd onderzocht of de kwantitatieve 3D computertomografie (Q3D-CT) techniek, die grootte, vorm en proximale articulaire oppervlakte meet, kan worden toegepast op de intacte radiuskop om zo formules, gebaseerd op anatomische en demografische gegevens, te creëren die het volume en de proximale oppervlakte kunnen voorspellen bij patiënten met fracturen van de radiuskop. Voor zover onze kennis reikt, is de meting van proximale articulaire oppervlakte en radiuskop volume niet eerder uitgevoerd. We produceerde vergelijkingen die kunnen berekenen wat de omvang van het proximale articulaire oppervlakte en het volume is van een intacte radiuskop, op basis van parameters die meestal beschikbaar zijn in de gebroken radiuskop met een gemiddeld relatief procentueel verschil van 0,5%. De mogelijkheid om het volume en het proximale articulaire oppervlak van het bot in te schatten voorafgaand aan de breuk, is waardevolle informatie wanneer we een gebroken radiuskop analyseren. Bijvoorbeeld, het stelt ons in staat om exact te meten welk percentage van de oppervlakte betrokken is bij de breuk. Dit is een criterium in de Broberg en Morrey’s classificatie volgens Mason. We zullen deze techniek gebruiken om fractuur fragment grootte en fractuur patronen te bestuderen.

HOOFDSTUK 3
KWANTITATIEVE DRIEDIMENSIONALE COMPUTER TOMOGRAFIE ANALYSE VAN RADIUSKOP FRACtUREN

In dit hoofdstuk werden radiuskop fracturen geanalyseerd op fragment morfologie met driedimensionale CT-beelden (Q3DCT) in termen van grootte, vorm en articulaire oppervlakte. Kwantitatieve analyse van 3D-CT scans bleek een nuttige techniek voor het analyseren van patronen en morfologie van articulaire fracturen. Met behulp van deze technologie hebben we vastgesteld dat: 1) partiële radiuskop fracturen (Mason type 2) frequent breken met minder dan een derde van de radiuskop oppervlakte; 2) partiële radiuskop fracturen meer kleiner en moeilijk te herstellen fragmenten hebben dan hele radiuskop fracturen (Mason 3); en 3) hele radiuskop fracturen met meer dan 3 fragmenten relatief zeldzaam zijn, en dat enkele 3-fragment-radiuskop fracturen kleine fragmenten hebben. Deze bevindingen kunnen onze opvatting en indeling van radiuskop fracturen beïnvloeden.

HOOFDSTUK 4
DIAGnostiSChe NAUWKeURiGeHiGhvd Van TWEEdimensiONEAls EN DriEdimENsioNaLE BEELDvORMING ENS ModelLEN Van riADUSKOP FrAcTuren

In dit hoofdstuk werd onderzocht of de classificatie en karakterisering van fracturen van de radiuskop nauwkeuriger is met 3D-CT en 3D modellen dan met 2D-CT en röntgenfoto’s, met behulp van een prospectieve studie opgetz met intraoperatieve inspectie als de referentiestandaard. We vonden dat toename van de geavanceerdheid in de beeldvorming/modellen leidde tot: 1) verbeterde sensitiviteit voor de diagnose van een groot aantal fractuur kenmerken, en 2) gedaalde waarner variatie tussen de chirurg en de eerste assistent. We vonden dat fractuur classificatie en karakterisering op basis van drie-dimensionale beeldvorming en modellen nauwkeuriger en betrouwbareder is, en zodoende helpen om de ervaring- en opleidings-kloof te dichten.

HOOFDSTUK 5
InTer-BEOORDelAars BeTroUWBAArHiGhvd Van riADUSKOP FrAcTuur ClAssifiCAtiE: TWEEdIMENSIONAAL VS. DRIEdIMENSIONAAL COMPUTER TOMOGRAFIE

In dit hoofdstuk werd in een groot online samenwerkingsverband van ervaren orthopedisch chirurgen onderzocht of 3D reconstructies van CT-scans verbeterde inter-beoordelaars betrouwbaarheid van de classificatie van radiuskop fracturen gaven met de Broberg en Morrey classificatie volgens Mason. Driedimensionale CT beelden leidden tot een kleine, maar significante afname van de variatie tussen waarnemers voor fractuur indeling en een aantal fractuur kenmerken in vergelijking met 2D-CT, maar een opmerkelijke hoeveelheid variatie bleef aanwezig, zelfs met meer geavanceerde beeldvorming. Wij geloven dat 3D-CT beelden gemakkelijker voor chirurgen te interpreteren zijn. Toch was de overeenstemming redelijk of op zijn best schappelijk, zelfs met 3D-CT. Bovendien zullen sommigen deze gegevens interpreteren als hetgeen waaruit blijkt dat 3D-CT veel minder invloed op de interobserver variatie heeft dan men zou verwachten. Het verminderen van interobserver variatie lijkt dus op meer te berusten dan alleen betere beeldvorming.
HOOFDSTUK 6
HOUDING TEN OOPZICHT VAN REK PIJN IN DE ELLEBOOG NA RADIUSKOP FRACHTUUR
Dit hoofdstuk onderzocht of instemming met het idee dat “rekken van de elleboog voorbij het punt dat het pijnlijk wordt belangrijk is in het herstel” leidt tot een groter bereik van de elleboog beweging een maand na het letsel. Wij vonden dat een negatieve houding ten opzichte van rek pijn tijdens het herstel van een fractuur van de radiuskop was geassocieerd met minder elleboog beweging een maand na letsel.

HOOFDSTUK 7
INCIDENTIE EN RISICOFACTOREN VOOR DE ONTWIKKELING VAN RADIOGRAFISCHE ARTHROSE NA TRAUMATISCHE LETSELS VAN DE ELLEBOOG
In dit hoofdstuk werden de risicofactoren voor posttraumatische elleboog arthrose op röntgenfototo’s na het doormaken van een elleboog fractuur in de lange termijn onderzocht. We vonden dat het type fractuur de enige significante onafhankelijke voor-speller van een matige of ernstige radiografische arthrose is. Radiografische arthrose was niet gerelateerd aan de tijd sinds letsel, leeftijd, dominantie, beroep, geslacht of mechanisme van de verwonding. Dit suggereert dat post-traumatische activiteiten en beroep geen belangrijke risicofactoren voor de ontwikkeling of voortgang van radiografische arthrose zijn. Fracturen van de radiuskop en olecranon zijn minder gevoelig voor matige of ernstige radiografische arthrose op de lange termijn dan fracturen van de distale humerus (zowel collum en capitellum/trochlea) en elleboog fractuur-dislocaties.

Conclusie
Dit proefschrift toont aan dat nieuwe ontwikkelingen in technische analyse, beeldvorming, interesse in de psychosociale aspecten van de behandeling en de beschikbaarheid van lange termijn studies, kunnen helpen bij het verbeteren van de classificatie, de behandeling en uitkomst van fracturen van de radiuskop. Het is de wetenschap die deze nieuwe ontwikkelingen heeft gecreëerd en door middel van adequate wetenschappelijke evaluatie van deze nieuwe ontwikkelingen kunnen we verder met het vervaardigen van meer effectieve behandelingen voor patiënten.
Glossary

2D Two-dimensional
3D Three-dimensional
AO Arbeitsgemeinschaft für Osteosynthesefragen
AP Anteroposterior
B&M Broberg and Morrey Score
CAD Computer-Aided Design
CES-D Center for Epidemiologic Studies Depression Scale
CI Confidence interval
CMM Coordinator measuring machine
CT Computed Tomography
CV Coefficient of variation
DASH Disabilities of the Arm, Shoulder, and Hand questionnaire
DICOM Digital Imaging and Communications in Medicine
GEE Generalized estimating equations
IRB Institutional Review Board
Matlab Numerical computing environment
MRI Magnetic Resonance Imaging
MVA Multi-vehicle accident
MVC Motor vehicle collision
NURBS Non-Uniform Rational B-Spline
ORIF Open reduction and internal fixation
PCS Pain Catastrophizing Scale
POFD Posterior-olecranon-fracture dislocation
Q3D-CT Quantitative Three-dimensional CT
Rhinoceros Three-dimensional modeling tool based on NURBS
ROM Range of Motion
SD Standard Deviation
Vitrea Visualization solution that creates Three-dimensional reconstructions
X-ray Röntgen radiation

The Broberg & Morrey Modification of the Mason Classification

Type I

Type II

Type III

Type IV

The Broberg-Morrey modification of the Mason classification of radial head and neck fractures
Type I = fx of the radial head or neck displaced ≤2 mm
Type II = fx of the radial head or neck displaced ≥2 mm and involving ≥90% of the joint surface
Type III = comminuted fx of the radial head or neck
Type IV = elbow dislocation with any of the above fx types
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Curriculum Vitae
Curriculum vitae

Thierry Guillaume Guitton was born on October 16th 1983 in Delft, the Netherlands. Son of a Dutch mother and French father, he was the middle child of three boys. He grew up in Delft and attended the Vrije School Den Haag where he graduated in 2003. Right after graduating, Thierry was accepted at the medical school of the University of Amsterdam.

That same year he joined a student Society, the Amsterdamsche Studenten Corps en Amsterdamsche Vrouwelijke Studenten Vereniging (ASC/AVSV). He immediately became involved with organising committees and participated on several boards and was elected president of his fraternity later on.

After finishing his nursery internship in Martinique in the French Caribbean, he completed his first year and received his Bachelor's degree in 2004. During his second year in medical school he started to work for Bio Implant Services (BIS) as part of the bone explantation team. In his fourth year of medical school, he followed courses from Dr. Peter Kloen. The synergies in their interests resulted in several research projects that he performed at the Orthopedic Research Centre Amsterdam (ORCA) from the department of orthopedics at the Academical Medical Centre (AMC) in Amsterdam under the guidance of Professor C. Niek van Dijk. After completing his Masters degree in November 2007, the driving ambition to explore the opportunities on offer made him move, with support from several scholarships including the VSB, to Boston in the United States for a PhD Research Fellowship at Harvard Medical School. Thierry continued the tradition of the MGH-AMC collaboration, which already led to three PhD degrees under supervision of Professor C. Niek van Dijk at the University of Amsterdam.

Under supervision of Professor Jesse B. Jupiter and Associate Professor David Ring from the Orthopaedic Hand and Upper Extremity Service at the Massachusetts General Hospital from the Harvard University, Thierry investigated complex trauma of the upper extremity with a focus on the radial head. Thierry presented his work at multiple national and international meetings and was rewarded with honors. Besides his PhD research projects, he became the founder and director of the Science of Variation Group and the Science of Variation Foundation. In March 2010 he returned to Amsterdam to finish and defend his thesis in the beginning of 2011.

Currently, Thierry is enrolled in his clinical rotations at the AMC to finish his medical degree in early 2012. Later that year he will start his orthopedic training at the University of Amsterdam Orthopaedic Residency Program under supervision of Professor C. Niek van Dijk.