FRACTURE MAPPING

ASSESSMENT OF FRACTURE CHARACTERISTICS FROM AP TO 3D

Jos J. Mellema

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Faculteit der Geneeskunde

Voor Anita,
pa en ma

"Heb een open oor voor onderricht, en een open geest voor kennis"
Spreuken 23:12

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CHAPTER 1

Introduction and Outline of the Thesis

The characterization of fractures has been historically based on radiographs in one or more planes. Analysis of consecutive series of patients, including evaluation and grading of "roentgenographic" studies, gave rise of fracture classification systems, such as the Schatzker classification for tibial plateau fractures and comprehensive Arbeitsgemeinschaft für Osteosynthesefragen (AO) classification[1, 2]. Specific characteristics of fractures (i.e., fracture morphology) and anatomic location have been used as the basis of most classification systems[3]. Fracture classification systems aim to categorize patients into clinical useful groups that facilitate comparison between different groups, guide treatment, and helps determine prognosis, including complication risk[4].

The onset of new imaging modalities, computed tomography (CT) in particular, has led to an increase of knowledge of fracture morphology. Computed tomography scans enable assessment of factures in axial, coronal, and sagittal planes, and rendering of Three-Dimensional (3D) reconstructions[5, 6]. Consequently, CT allows a more detailed characterization of specific fractures and is therefore used in addition to conventional radiographs[7].

More advanced CT-based techniques, such as fracture mapping and quantitative 3DCT (Q3DCT), help to further improve our understanding of fracture characteristics. Fracture mapping is a qualitative technique based on Two-Dimensional (2D) or 3DCT that enables to study fracture line location, frequency, and distribution, zones of comminution, and articular involvement[8, 9]; whereas Q3DCT is a quantitative technique based on CT that enables measurement of fracture fragment characteristics (e.g., volume, articular surface area, shape, and size)[10-15]. In other words, CT-based techniques such as fracture mapping and Q3DCT accurately characterize specific fractures.

In addition to accurate characterization of fractures (i.e., description of fracture morphology), classification systems must include reliable fracture characteristics in order to be useful[16]. Reliability, often referred to as agreement, can be measured between or within surgeons using the kappa value for categorical variables, which distinguishes the level of agreement that is observed from the level of agreement expected by chance alone[17, 18]. Without reliable fracture characteristics clinical studies are imprecise and presented results questionable.

Consequently, in orthopedic trauma research there has been a continuous effort to improve characterization of specific fractures and reliability in order to optimize classification systems used in clinical practice. This thesis contributes to this line of research by assessment of fracture characteristics, included in classification systems or not, its reliability and use in clinical practice.

The overall aim of this thesis is to improve our understanding of specific fracture characteristics (i.e., morphology and reliability); more specifically, the aims can be listed as follows:

- » First, to improve our understanding of fracture line patterns and distribution, and zones of fragmentation
- » Second, to improve the current knowledge of fracture fragment size, shape, and articular involvement
- » Third, to evaluate the reliability of fracture characteristics and efforts to improve agreement between surgeons
- » Finally, to assess factors that influence decision-making in fracture management

Following the specific aims of this thesis, the manuscript has been divided into four parts as described below.

PART I: QUALITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MAPPING OF FRACTURE LINES

Fracture mapping techniques, based on 2D- and 3DCT images, result in "frequency maps" of large series of patients by superimposing fracture lines, zones of comminution, and articular involvement. Fracture maps reveal specific fracture patterns that provide helpful data for surgical approaches, fixation techniques, and implant designs. Moreover, it has been suggested that mapping techniques can be useful for the assessment of the validity (i.e., accuracy) of existing fracture classification systems[9].

Mapping of Coronoid Fractures

Specific coronoid fracture types are associated with patterns of traumatic elbow instability. In Chapter 2, fracture mapping is used to define location, frequency, distribution and patterns of coronoid fracture lines, and to qualitatively assess the association between fracture types of the coronoid process of the ulna and patterns of elbow fracture-dislocation.

Mapping of Tibial Plateau Fractures

Tibial plateau fracture classification systems have been traditionally based on anteroposterior radiographs, which limited appreciation of fractures in the coronal plane. In Chapter 3, mapping techniques are used to evaluate patterns of tibial plateau fractures in sagittal, coronal and axial planes.

Mapping of Radial Head Fractures

The distribution of fracture lines and anatomic location of displaced partial radial head fractures and its association with patterns of elbow fracture-dislocation is unclear. In Chapter 4, qualitative, as well as quantitative, analysis of fracture maps is performed to assess the relationship between fracture line distribution and location of displaced partial radial head fractures and patterns of traumatic elbow instability.

Mapping of the Lesser Sigmoid Notch

The involvement of the lesser sigmoid notch in proximal ulnar fractures is not well described. In Chapter 5, fracture mapping and Q3DCT techniques are performed to study fracture line location and fracture fragment characteristics of coronoid fracture types that involve the lesser sigmoid joint.

PART II: QUANTITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MEASUREMENT OF SPECIFIC FRAGMENTS AND ARTICULAR INVOLVEMENT

Three-dimensional polygon mesh reconstructions of fractures can be created based on CT scans with sufficient quality. Quantitative 3DCT reconstructions (i.e., polygon meshes) allow measurement of fracture fragment size, shape and articular surface area, which provide a more detailed understanding of fracture morphology[10-15]. Improved understanding of fracture morphology using Q3DCT techniques may support decision-making and implant development.

Q3DCT- Based Analysis of Coronoid Fractures

Specific coronoid fracture types and patterns of traumatic elbow instability have been described. In Chapter 6, Q3DCT-based measurements are used to determine the difference in specific characteristics (i.e., volume, articular surface involvement, and number of fracture fragments) between coronoid fracture types and patterns of traumatic elbow instability.

Q3DCT- Based Analysis of the Posteromedial Fragment in Complex Tibial Plateau Fractures

Posteromedial fragment characteristics have been described based on 2DCT analysis. The relationship between adequate fragment fixation of the posteromedial fragment and laterally applied fixed angle screws has been considered as suboptimal. In Chapter 7, Q3DCT techniques are performed to determine 2D- and 3DCT characteristics of the posteromedial fragment in complex tibial plateau fractures and to study the association between fragment fixation using laterally applied locking screws and CT-based characteristic.

PART III: ASSESSMENT OF RELIABILITY OF FRACTURE CHARACTERISTICS: MEASUREMENT OF AGREEMENT BETWEEN SURGEONS

Reliability can be measured between or within surgeons (i.e., inter- and intraobserver agreement), and is rated from “no agreement” to “almost perfect agreement” based on kappa values for categorical variables[18]. Fracture characteristics and classification systems need to be reliable in order to be useful[16, 19]. The assessment of reliability is an important aspect of orthopedic trauma research.

Reliability for Tibial Plateau Fracture Characteristics

Fracture mapping revealed four specific tibial plateau fracture characteristics; posteromedial fracture component, lateral fracture component, tibial tubercle component, and the tibial spine (central) component. Chapter 8 includes the study of interobserver reliability and diagnostic accuracy for 2D- and 3DCT–based evaluation of tibial plateau fracture characteristics.

Reliability for the Schatzker and Luo Classification Systems

Tibial plateau fracture classification systems have limited inter-surgeon reliability and new systems have emerged. Chapter 9 includes the assessment of reliability between surgeons of the Luo classification and the Schatzker classification for 2DCT and the effect of adding 3DCT on inter-surgeon agreement.

Reliability for Proximal Humeral Fractures

Classification of proximal humeral fractures seems challenging as inter- and intraobserver reliability is low. Simplifying fracture classification systems and training observers may improve reliability. Chapter 10 includes the study of the effect of both training observers and simplifying proximal humeral fracture classifications on reliability between surgeons.

PART IV: ASSESSMENT OF THE INFLUENCE OF FRACTURE CHARACTERISTICS ON DECISION-MAKING: ANALYSIS OF TREATMENT VARIATION

Variation in treatment of common fractures is associated with surgeon and patient factors, and fracture characteristics[20]. Assessment of treatment variation helps to determine whether or not there is consensus in decision-making among surgeons and helps to identify factors associated with surgeons' decision-making and treatment preferences.

Variation in Treatment of Trochanteric Fractures

Trochanteric fractures are most commonly treated with either a sliding hip screw (SHS) or intramedullary nailing (IMN) device. Level I evidence showed similar results of SHS *versus* IMN in treatment of AO/OTA 31-A1 and 31-A2 fractures. Chapter 11 describes the study of surgeon's variation in implant choice (SHS *versus* IMN) and the influence of surgeon, fracture, and patient characteristics on decision-making in treatment for these specific fractures.

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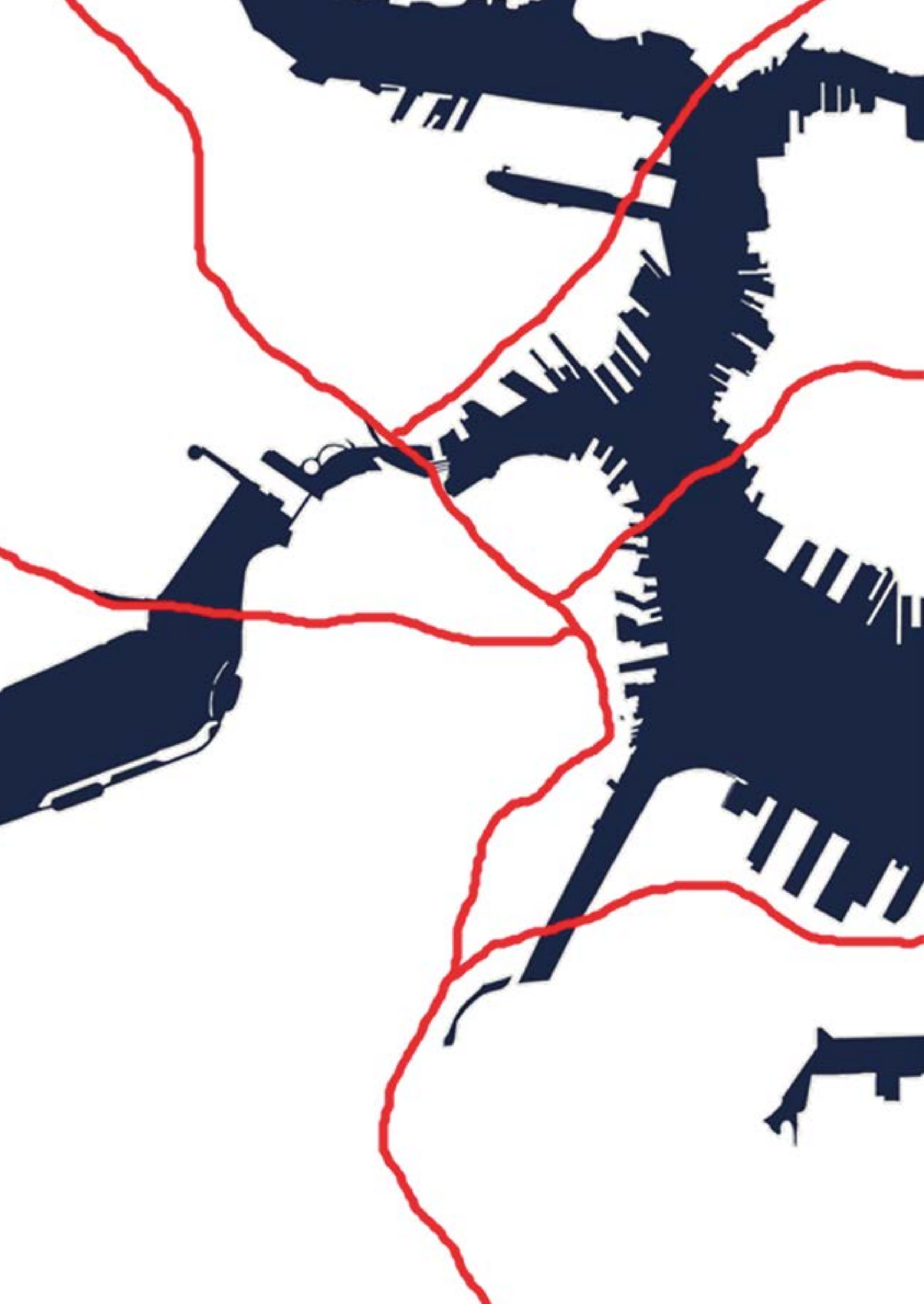

PART I
QUALITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MAPPING OF FRACTURE LINES

CHAPTER 2

Distribution of Coronoid Fracture Lines by Specific Patterns of Traumatic Elbow Instability

Jos J. Mellema, Job N. Doornberg, George S.M. Dyer, David Ring

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ABSTRACT

Purpose: By mapping fractures of the coronoid we can define the location and frequency of fracture lines of specific injury patterns of the coronoid. We tested the null hypothesis that specific coronoid fractures do not associate with specific overall traumatic elbow instability injury patterns and depicted this on fracture maps and heat maps.

Methods: We collected 110 computed tomography (CT) studies from patients identified with coronoid fractures. Fracture types and pattern of injury were characterized based on anteroposterior and lateral radiographs, 2- and 3-dimensional CT scans, and intra-operative findings, as described in operative reports. Using quantitative 3-dimensional CT techniques we were able to reconstruct the coronoid and reduce fracture fragments. Based on these reconstructions fracture lines were identified and graphically superimposed onto a standard template in order to create 2-dimensional fracture maps. To further emphasize the fracture maps, the initial diagrams were converted into fracture heat maps following arbitrary units of measure. In statistical analysis Fisher's exact test was used to evaluate the association between coronoid fracture types and elbow fracture-dislocation patterns.

Results: Forty-seven coronoid fractures were associated with a terrible triad fracture-dislocation, 30 with a varus posteromedial rotational injury, 1 with an anterior olecranon fracture-dislocation, 22 with a posterior olecranon fracture-dislocation, and 7 with a posterior Monteggia injury associated with terrible-triad fracture-dislocation of the elbow. The association between coronoid fracture types and elbow fracture-dislocation patterns, as shown on 2-dimensinonal fracture and heat maps, was strongly significant.

Conclusion: Our fracture maps and heat maps further support the observation that specific patterns of traumatic elbow instability have correspondingly specific coronoid fracture patterns. Knowledge of these patterns is useful for planning management, because it directs exposure, fixation, and associated ligament injuries and fractures that might benefit from treatment.

INTRODUCTION

Observations and studies based on patient care and computed tomography (CT) scans led to an association of specific coronoid fracture patterns[1,2] with the overall pattern of traumatic elbow instability. Knowledge of coronoid fracture types and pattern of traumatic elbow instability contributed to a useful guide to treatment[3]. Small transverse tip fractures are associated with terrible-triad injuries, anteromedial facet fractures with varus posteromedial rotational instability injuries, and larger basal fractures of the coronoid process with anterior and posterior olecranon fracture-dislocations[4-6].

This study used recently described 2-dimensional fracture mapping techniques (where a “map” of the most common fracture lines is created by superimposing fracture lines from a large number of injuries[7,8]) after creating quantitative 3-dimensional computed tomography (Q3DCT) reconstructions. We also applied heat mapping techniques whereby fracture line intensity is graphically represented in color. These techniques were used to define the location, frequency, distribution and pattern of fracture lines of the coronoid. We tested the null hypothesis that specific coronoid fractures do not associate with specific overall traumatic elbow instability injury patterns and depicted this on fracture maps and heat maps.

METHODS

Subjects

Our Institutional Review Board approved a retrospective search of our billing data for patients with a coronoid fracture between July 7th, 2001 and January 13th, 2014 at two level I trauma centers. The International Classification of Disease, 9th Revision, Clinical Modification (ICD-9-CM) (code 813.0x for closed fracture, and 813.1x for open fracture) and Current Procedural Terminology (CPT) (codes 24586-24685, including elbow dislocations, Monteggia type of fractures, radial and ulnar fractures) were used to search the billing data. Two hundred and seven patients with coronoid fractures were identified. Inclusion criteria were: patients aged 18 years or older with an acute fracture of the coronoid and a CT scan displaying the complete fracture. One hundred and twenty-one patients met the inclusion criteria. We excluded 11 patients with prior elbow injury, low quality CT images, or artifacts on CT scan. Therefore, 110 fractures were available for study.

Two-dimensional fracture mapping

Two-dimensional fracture maps represent fracture line distribution on a 2-dimensional template by superimposing fracture lines from a large number of injuries. Images of coronoid fractures needed for 2-dimensional fracture mapping were based on Q3DCT modeling techniques. The original Digital Imaging and Communications in Medicine (DICOM) files of selected CT-scans were obtained through the Picture Archiving Communications System database of the two hospitals. All CT scans had a slide thickness between 0.625mm and 3mm. The DICOM files were loaded into 3D Slicer (3D Slicer, Boston, MA). 3D Slicer is a software program used for analysis and visualization of medical images. Bony structures were manually marked on transverse, sagittal and oblique CT slides using the Paint Effect and additional Threshold Paint option available in this program. After marking all bony structures of the proximal ulna on each CT slide, 3-dimensional polygon mesh reconstructions were created in 3D Slicer. These 3-dimensional mesh reconstructions were imported in Rhinoceros (McNeel, Seattle, WA) for reduction of the fracture fragments (Figure 1).

Cole et al.[8] and Armitage et al.[7] have previously described the method of 2-dimensional fracture mapping. Using this method fracture lines were graphically superimposed onto a 2-dimensional template of an intact proximal ulna. Images of the reduced 3-dimensional mesh reconstruction were obtained in the same viewpoint as the 2-dimensional template, imported in Macromedia Fireworks MX software (Macromedia Inc, San Francisco, CA), and matched with the template by aligning anatomical landmarks. After proper alignment of the images with the 2-dimensional template, fracture lines were drawn (Figure 2).

Heat mapping

To further emphasize the 2-dimensional fracture maps, heat maps were created. In heat maps fracture line intensity is graphically represented as colors. The initial diagrams were converted into heat maps with Rhinoceros and Matlab (MathWorks, Natick, MA). All fracture lines were manually and consecutively converted into points (x, y) onto a standard 2-dimensional template of the proximal ulna in Rhinoceros. A standardized space of 0.25 units between points was applied. Subsequently, the point coordinates were exported to Excel (Microsoft Excel, Seattle, WA) and imported in Matlab. Heat maps were created based on these coordinates and by running a Data Density Matlab script file. Data density is calculated as sum of points, weighted by reciprocal squared distance from the pixel, and shown as heat map[9].

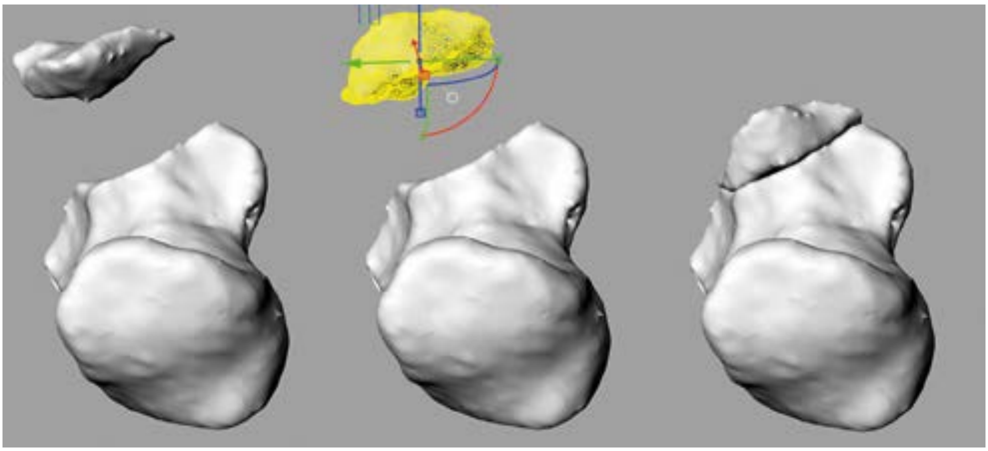

Figure 1. A series of images showing fracture fragment reduction of 3-dimensional mesh reconstructions in Rhinoceros (McNeel, Seattle, WA).

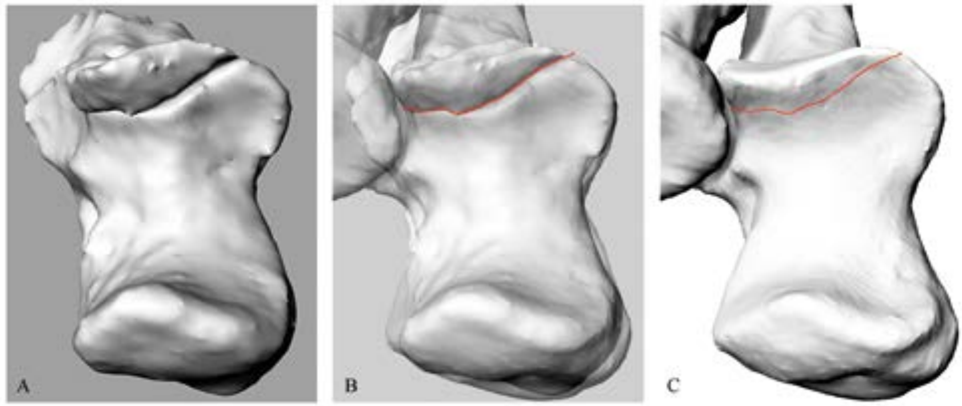

Figure 2. A series of images illustrating the 2-dimensional fracture mapping method previously described by Cole et al.[8] and Armitage et al.[7] (A) Image of reduced 3-dimensional mesh reconstruction in similar viewpoint as the template. (B) Fracture line drawn onto superimposed and matched standard 2-dimensional template of an intact proximal ulna. (C) Drawn fracture line onto the template.

Patterns of elbow fracture-dislocation

Patterns of elbow fracture-dislocation were classified based on available anteroposterior and lateral radiographs, 2- and 3-dimensional CT scans, and intra-operative findings, as described in operative reports, by two researchers. After thorough review of diagnostic imaging and medical records injuries were classified into 1 of the 4 patterns of elbow-fracture dislocation described by Doornberg and Ring[4]: (1) the terrible-triad fracture-dislocation of the elbow; (2) varus posteromedial rotational instability pattern: (3) anterior or transolecranon fracture-dislocation; (4) posterior olecranon fracture-dislocation (or type A posterior Monteggia injury according to the system of Jupiter et al.[10]). In addition to the injury patterns above, we used the pattern of elbow fracture-dislocation described by Strauss et al.[11] and further evaluated by Shore et al.[12]: posterior Monteggia injury associated with terrible-triad fracture-dislocation of the elbow, defined as a forearm fracture in association with posterior dislocation of the elbow with fractures of the radial head and the coronoid process. In case of disagreement between the researchers, consensus was obtained after discussion.

Classification of coronoid factures

The classification process was similar for coronoid fractures that were classified according to the system of O'Driscoll et al.[2], which is also known as the Mayo classification: type 1 involves fractures of the tip of the coronoid, type 2 involves a fracture of the anteromedial facet of the coronoid process, and type 3 involves a fracture of the coronoid at the base. In case a fracture type was ambiguous the type was rated based on the classified elbow fracture-dislocation and most likely associated fracture type.

Statistical Analyses

The Fisher's exact test was used to evaluate the association between elbow fracture-dislocation patterns and fracture types according to the classification of O'Driscoll et al., followed by post hoc multiple comparison with Bonferroni correction. Data was analyzed using a standard statistical software package.

RESULTS

There were 76 (69%) men and 34 (31%) women in this study, with an average age of 46 (range, 18-85 years). The majority of the patients were treated operatively. A total of 55 (50%) patients had a type 1 fracture, and 47 (43%) fractures were associated with a terrible-triad fracture-dislocation of the elbow (Table 1).

One (1%) patient presented with an isolated, minimally displaced basilar coronoid fracture and was treated non-operatively. Although this fracture pattern is unusual, this

Table 1. Demographics (n=110)

Age (mean±SD)	46 (16)
Sex, n(%)	
Male	76 (69)
Female	34 (31)
Side of Injury, n(%)	
Left	65 (59)
Right	45 (41)
Treatment, n(%)	
Non-Operatively	21 (19)
Operatively	89 (81)
O'Driscoll et al.[2], n(%)	
Type 1	55 (50)
Type 2	29 (26)
Type 3	26 (24)
Injury Patterns, n(%)	
TT	47 (43)
VPMRI	30 (27)
AOFD	1 (1)
POFD	22 (20)
PM+TT	7 (6)
Other	3 (3)

TT, terrible-triad fracture-dislocation; VPMRI, varus posteromedial rotational instability pattern; AOFD, anterior olecranon fracture-dislocation; POFD, posterior olecranon fracture-dislocation; PM+TT, posterior Monteggia injury associated with terrible-triad fracture-dislocation of the elbow.

type of fracture was classified as type 3 according to the Mayo classification. Three (3%) injury patterns involved the distal humerus and did not fit into one of our injury pattern categories. Two patients had small tip fractures of the coronoid associated with capitellum and trochlea fractures, and one patient had a coronoid tip fracture associated with lateral column fracture.

In 101 (92%) patients fracture lines entered the proximal radioulnar joint, most commonly at the upper half of the radial notch of the ulna. In terrible-triad fracture-dislocations the fracture lines predominantly exited at the tip; in varus posteromedial rotational instability injuries the fracture lines exited at the anteromedial facet; in the anterior olecranon fracture-dislocation the fracture line entered the proximal radioulnar joint and exited the coronoid at the base; in posterior olecranon fracture-dislocations 9 (41%) fractures at the base of the coronoid were fragmented and the most posterior fracture lines exited at the base; in posterior Monteggia injuries with dislocation of the elbow the fracture lines were most likely to exit at the tip, resembling coronoid fractures associated with terrible triad injuries (Figure 3).

The association between coronoid fracture types and elbow fracture-dislocation patterns, as shown on 2-dimensional fracture and heat maps, was strongly significant ($p<0.001$). Statistically significant associations were found between type 1 fractures and terrible-triad fracture-dislocations and posterior Monteggia injuries with dislocation of the elbow; between type 2 fractures and varus posteromedial rotational instability injuries; and between type 3 fractures and olecranon fracture-dislocations (Table 2).

DISCUSSION

Our fracture maps and heat maps further support the observation that specific patterns of traumatic elbow instability have correspondingly specific coronoid fracture patterns. Moreover, the maps demonstrate fracture patterns similar to coronoid fragment morphology as described by O'Driscoll et al.[2] based on experience caring for patients with these injuries. Our data emphasize that determining the pattern of elbow fracture-dislocation can be helpful for predicting the type and morphology of coronoid fractures prior to computed tomography imaging, and can therefore facilitate pre-operative planning of surgical approach, fixation techniques, and overall treatment of the injury.

The strengths of this study are the relatively large number of fractures, Q3DCT modeling techniques that allowed reduction of the fracture fragments and capturing the reduced fracture in the correct viewpoint, and new graphic methods to display coronoid fracture line patterns and distribution. However, there are also several limitations that must be considered. First, we excluded patients without CT scan. This might have influenced the distribution of elbow injury patterns and associated coronoid fractures since CT scans are more likely to be performed for some traumatic elbow instability injury patterns. Furthermore, fractures treated without CT scan may have important differences from the fractures we studied, although this seems unlikely. Second, the fracture lines were superimposed on a 2-dimensional template. Ideally, we would have used a 3-dimensional template that enables study in more than 1 viewpoint. Finally, due to great anatomical

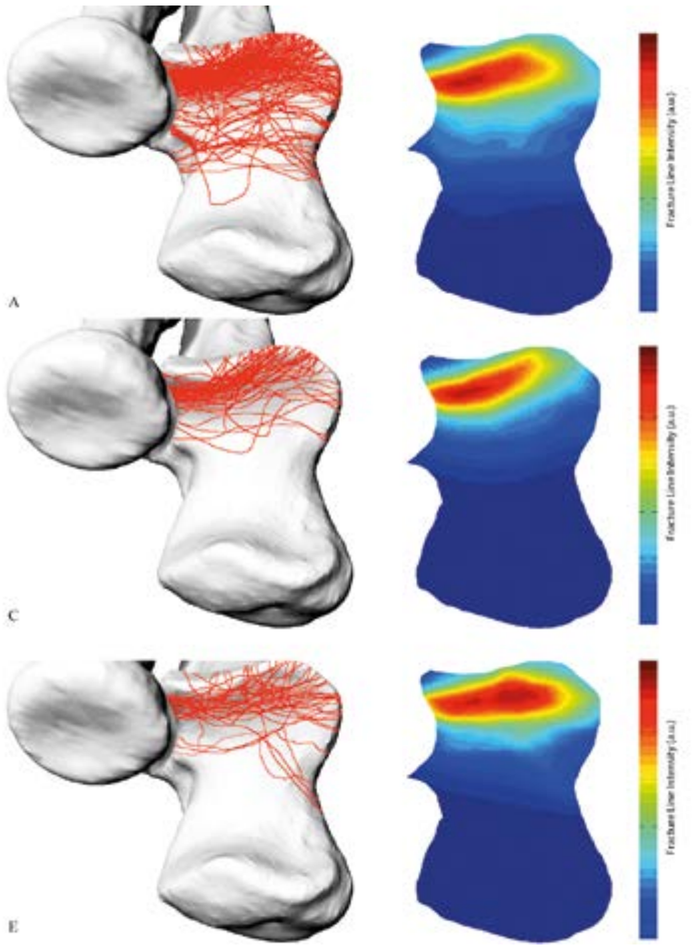

Figure 3A. Paired fracture and heat maps displaying patterns and distribution of fracture lines according to specific patterns of traumatic elbow instability. Fracture lines are shown as red lines onto the template and fracture line intensity is illustrated by heat maps following arbitrary units of measure. (A) Overall pattern (n=110). (C) Terrible-triad fracture-dislocation of the elbow (n=47). (E) Varus posteromedial rotational instability pattern (n=30).

variability of the proximal ulna and coronoid process more specifically, some images of the 3-dimensional mesh reconstructions of the coronoid did not match the 2-dimensional template perfectly. Consequently, fracture lines drawn on the 2-dimensional template could slightly differ from true fracture morphology.

Adams et al.[13] felt it was important to distinguish oblique anterolateral and anteromedial fractures of the tip of the coronoid. According to our maps, the tip fractures associated with terrible triad pattern injuries are usually above the sublime tubercle and the anteromedial facet of the coronoid. In other words, they are relatively lateral in orientation. And since the anteromedial fractures usually involve a fracture of

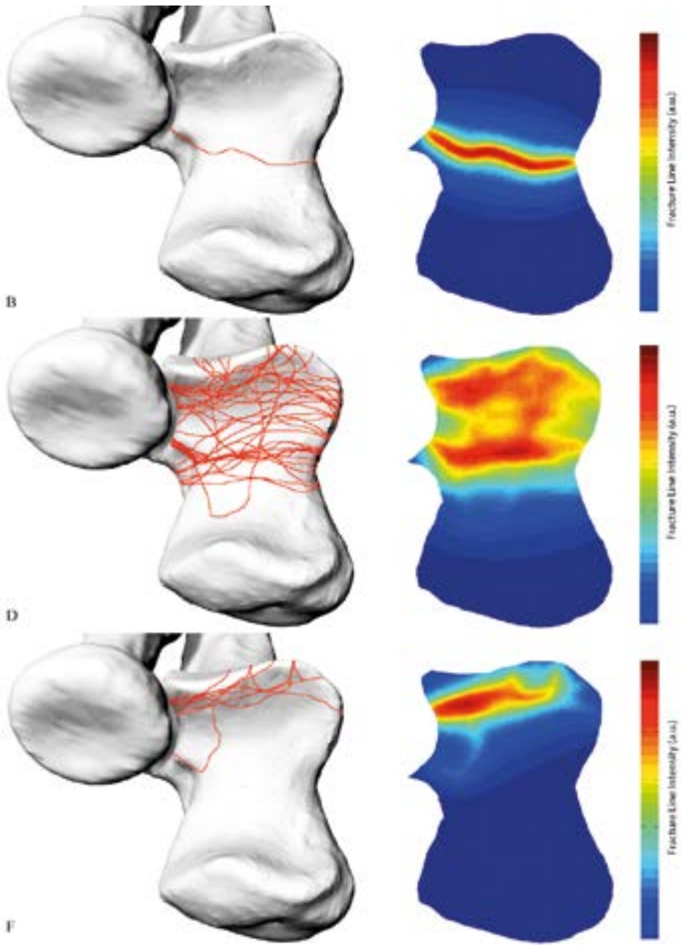

Figure 3B. Paired fracture and heat maps displaying patterns and distribution of fracture lines according to specific patterns of traumatic elbow instability. Fracture lines are shown as red lines onto the template and fracture line intensity is illustrated by heat maps following arbitrary units of measure. (B) Anterior olecranon fracture-dislocation (n=1). (D) Posterior olecranon fracture-dislocation (n=22). (F) Posterior Monteggia injury associated with terrible-triad fracture-dislocation of the elbow (n=7).

the coronoid tip as well, the map is just a bit more medial and actually very similar to that for the tip fractures.

Our findings are consistent with those of Doornberg et al.[4] based on a more qualitative study of radiographs and computed tomography. Our quantitative techniques verify the strong association of large basilar fractures of the coronoid process with posterior olecranon fracture-dislocations, small transverse fractures with terrible-triad injuries, and anteromedial facet fractures with varus posteromedial rotational instability pattern injuries. Our study also reminds us that extra- and intra-articular posterior Monteggia

Table 2. Coronoid Fracture Types and Associated Patterns of Injury

	O'Driscoll et al.[2]		
Patterns of Injury	Type 1	Type 2	Type 3
TT	42	3	2
VPMRI	3	25	2
AOFD	0	0	1
POFD	0	1	21
PM+TT	7	0	0
Other	3	0	0

TT, terrible-triad fracture-dislocation; VPMRI, varus posteromedial rotational instability pattern; AOFD, anterior olecranon fracture-dislocation; POFD, posterior olecranon fracture-dislocation; PM+TT, posterior Monteggia injury associated with terrible-triad fracture-dislocation of the elbow.

injuries associated with dislocation of the elbow[11,12] have fractures of the coronoid tip, more akin to terrible-triad fracture-dislocation of the elbow.

Mapping of fracture lines and the use of heat maps helped verify observed associations for coronoid fractures and specific injury patterns. Knowledge of these patterns is useful for planning management, because it directs exposure, fixation, and associated ligament injuries and fractures that might benefit from treatment. Determining traumatic elbow instability injury patterns may help surgeons predicting the type and morphology of coronoid fractures prior to computed tomography imaging, however, given the variability of coronoid fracture patterns determining the elbow injury pattern alone is not sufficient for predicting the overall injury pattern. The strength of these associations could help care for patients without computed tomography, which might be useful in some circumstances (e.g. low resource settings). The use of fracture mapping might be able to determine other useful patterns of injury at other anatomical sites.

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CHAPTER 3

Tibial Plateau Fracture Characteristics: Computed Tomography Mapping of Lateral, Medial, and Bicondylar Fractures

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ABSTRACT

Background: Computed tomography (CT) is seen as a useful diagnostic modality in preoperative planning for tibial plateau fractures. The purpose of this study was to characterize patterns of tibial plateau fractures with use of CT mapping. We hypothesized that CT mapping of fractures of the tibial plateau would reveal recurrent patterns of fragments and fracture lines, including patterns that do not fit into Schatzker's original classification.

Methods: One hundred and twenty-seven tibial plateau fractures were retrospectively included in this study. Fracture lines and zones of comminution were graphically superimposed onto an axial template of an intact subarticular tibial plateau to identify major patterns of fracture and comminution. This fracture map of the tibial plateau was subsequently divided into lateral (Schatzker types I, II, and III), medial (Schatzker type IV), and bicondylar (Schatzker types V and VI) fracture maps.

Results: This study included seventy-three female and fifty-four male patients (average age, forty-seven years [range, seventeen to ninety-one years]) with a tibial plateau fracture. Sixty-four of the fractures were Schatzker type I, II, or III; fifteen were Schatzker type IV; and forty-eight were Schatzker type V or VI. Analysis of the fracture maps suggested patterns in the Schatzker type-IV, V, and VI fractures beyond those described in Schatzker's original classification. The maps of the 127 fractures revealed four recurrent major fracture features: the lateral split fragment (A), found in 75%; the posteromedial fragment (B), seen in 43%; the tibial tubercle fragment (C), seen in 16%; and a zone of comminution that included the tibial spine and frequently extended to the lateral condyle (D), seen in 28%.

Conclusions: Tibial plateau fracture maps show recurrent patterns of fracture lines, revealing four major fracture characteristics. An understanding of these recurrent features of tibial plateau fractures can aid surgeons during diagnosis, preoperative planning, and execution of surgical strategies.

INTRODUCTION

Tibial plateau fractures are among the most challenging intra-articular fractures to treat[1-2]. Fracture characteristics range from simple to complex, with little or extensive articular involvement[3-5], and treatment with open reduction and internal fixation can be difficult[6-11]. The classification of tibial plateau fractures has been historically based on anteroposterior radiographs[5,12], without consideration of bicondylar coronal fracture lines and resulting sagittal plane deformity[3-5, 13-15]. While, as our understanding of the morphologic characteristics of tibial plateau fractures has evolved substantially[3,4], current classification systems have not yet been revised with use of computed tomography (CT) and magnetic resonance imaging (MRI)[13,16].

Cole and colleagues were the first to describe an imaging technique to characterize (articular) fractures with three- dimensional CT[17,18]. This "fracture mapping" improves our understanding of fracture patterns and morphology in two[18] and three[17] dimensions. With use of axial plane CT images, fracture lines and zones of comminution are superimposed to create a visual map of major and minor fracture lines. The major fracture lines are defined by the constancy of the pattern.

Insight into recurrent elements of tibial plateau fractures may contribute to our understanding of this complex fracture and may augment "classic" classification systems to guide treatment, surgical approaches, and the development of fracture-specific fixation. To the best of our knowledge, fracture mapping has not previously been performed on tibial plateau fractures.

The purpose of this study was to characterize the patterns of a large series of tibial plateau fractures with use of fracture mapping. We hypothesized that mapping of fractures of the tibial plateau would reveal recurrent patterns of fragments and fracture lines, including patterns that do not fit into the classification described by Schatzker and colleagues[12]. Recognition and understanding of these recurrent features of tibial plateau fractures can aid surgeons during diagnosis, preoperative planning, and execution of surgical strategies.

MATERIALS AND METHODS

Subjects

A retrospective search was performed for CT imaging data of patients treated for a tibial plateau fracture in a level-I or III trauma center (Academic Medical Center and Sint Lucas Andreas Hospital, Amsterdam, the Netherlands). International Classification of Diseases, Ninth Revision (ICD-9) codes for orthopaedic tibial plateau surgery performed between 2000 and 2013 were used to search the surgery database of the level-I trauma center. The key phrase "CT Lower Extremity" was used to search the picture archiving and communication system (PACS) database of the level-III trauma center for patients treated for a tibial plateau fracture. CT images of insufficient quality or an image thickness of <3.0 mm were excluded. Good-quality CT scans of 127 tibial plateau fractures were available for this study. The included tibial plateau fractures were assigned a Schatzker classification with use of radiographs and CT imaging. Classification was based on the consensus of two authors (R.J.M. and J.N.D.), with disagreements resolved by discussion with the senior author (P.K.).

Fracture Mapping

Cole and colleagues previously described the method of two-dimensional (2D) fracture mapping[17,18]. In the current study, the fracture mapping methodology was modified for tibial plateau fractures (Figure 1). Because of the frequent presence of comminution and displaced, depressed, and impacted fragments, the classic method of fracture mapping, in which one axial CT slice of standardized height is chosen[18], is not applicable to more complex tibial plateau fractures. In our analysis of these fractures, we first estimated the origin of respective fragments by reviewing the axial, sagittal, and transversal CT images. Subsequently, fracture lines of the "virtually" reduced fragments were drawn onto the subarticular axial tibial plateau template. Because the modified fracture-mapping technique corrects for fragment displacement, the results are considered unaffected by application of an external fixator prior to CT scanning.

We defined the resulting axial fracture map 3 mm below the articular surface[18], essentially representing the fracture lines at the articular surface. Comminution was defined as fragments smaller than 1.0 cm^2 in size[18]. At the end of the mapping process, lines and zones of each respective case were graphically superimposed onto a standard template of a subarticular axial CT image of an intact left tibial plateau (Figure 2). Rotation and normalization were guided by aligning specific tibial plateau landmarks: the medial and lateral tibial plateau, the tibial tubercle, and the fibula. The overlap of fracture lines and zones of comminution resulted in a frequency diagram based on the density of fracture lines and zones of comminution.

Data Analysis

The analysis of the fracture maps was descriptive[17,18]. Fracture patterns and zones of comminution were qualitatively analyzed. The complete fracture map (n = 127, Schatzker types I through VI) was divided into a lateral fracture map (Schatzker types I, II, and III), a medial fracture map (Schatzker type IV), and a bicondylar fracture map (Schatzker types V and VI) for visual comparison. The fracture maps were assessed for recurrent patterns of fracture lines and zones of comminution.

Associations between the major fracture features and the Schatzker fracture types were assessed in a post-hoc analysis with use of phi coefficients (ϕ). The phi coefficient is a measure of correlation between two binary variables and is similar to the Pearson correlation coefficient in terms of interpretation. Phi coefficients and corresponding p values were calculated with use of MATLAB 7.9 (R2009b) and Statistics Toolbox 7.2 (MathWorks, Natick, Massachusetts).

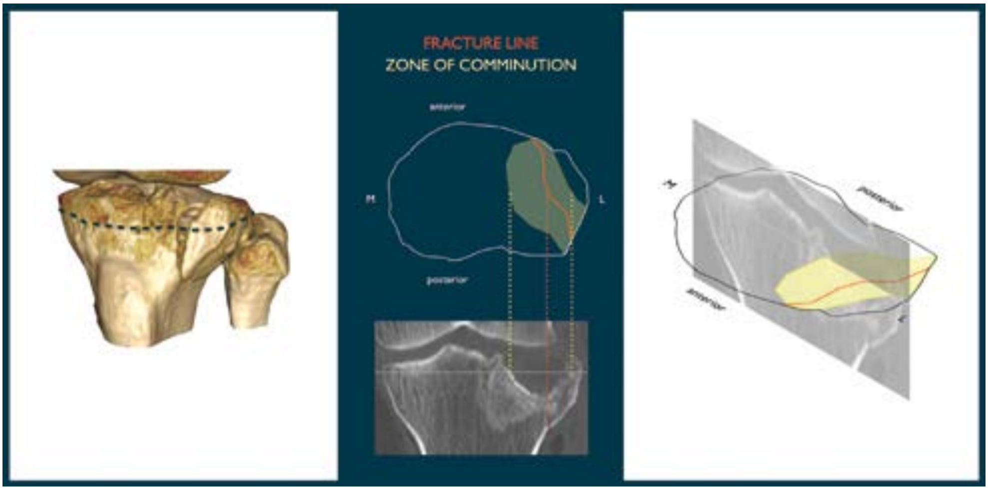

Figure 1. Fracture mapping of tibial plateau fractures is performed by (1) selecting the most proximal subarticular axial CT image as a reference; (2) dynamically scrolling through the axial, sagittal, and coronal CT images to define the origin and subsequent (virtual) reduction of respective fragments; and (3) drawing fracture lines and marking zones of comminution on the tibial plateau template. The fracture lines are red, and the zones of comminution are yellow. M = medial, and L = lateral.

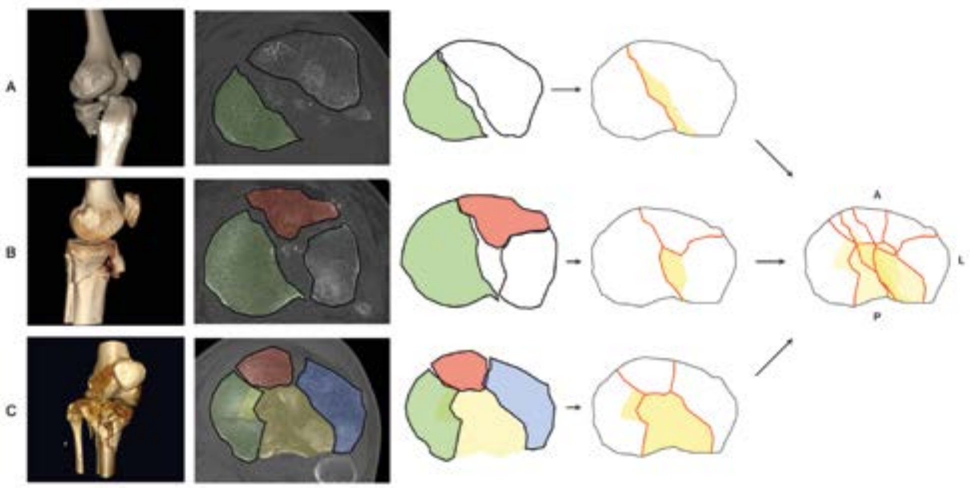

Figure 2. Application of the fracture-mapping technique to a Schatzker type-IV fracture (Fig. 2-A), a Schatzker type-V fracture (Fig. 2-B), and a Schatzker type-VI fracture (Fig. 2-C). The individual maps were then superimposed to create a fracture map. A = anterior, L = lateral, and P = posterior.

RESULTS

Subjects

We reviewed 127 CT scans: sixty-four showing a Schatzker type-I (six), II (forty-eight), or III (ten) tibial plateau fracture; fifteen showing a Schatzker type-IV tibial plateau fracture; and forty-eight showing a Schatzker type-V (twenty- six) or VI (twenty-two) tibial plateau fracture. There were seventy-three female and fifty-four male patients, with an average age of forty-seven years (range, seventeen to ninety-one years). Patient demographics are summarized in Table 1.

Fracture Maps

Mapping of the 127 tibial plateau fractures resulted in a diverse diagram of fracture lines and zones of comminution (Figure 3). The complete fracture map was divided into lateral, medial, and bicondylar fracture maps for visual comparison and analysis.

Lateral Fracture Map (Figure 4A)

The fracture lines and zones of comminution of Schatzker types-I, II, and III fractures have a predictable pattern con- forming to Schatzker's original description: fracturing of the lateral condyle with (Schatzker type II) or without (Schatzker type I) comminution or impaction of the lateral side of the plateau, or isolated lateral impaction (Schatzker type III). The lateral-sided, anteroposterior oval pattern of comminution suggests an etiology of valgus-directed trauma resulting in direct compression of the lateral femoral condyle into the lateral tibial condyle in these fractures. Although most fracture lines are located at the lateral rim of the comminution zone (split fragments), there are multiple fracture lines directly crossing the lateral condyle, with three fractures even extending into the medial side of the tibial plateau.

Medial Fracture Map (Figure 4B)

A pattern of posteromedially oriented oblique fracture lines is present in Schatzker type-IV fractures. Interestingly, a number of these fracture lines exit the posterior cortex on the lateral side of the plateau. Furthermore, an oblique zone of comminution or impaction (directed from anteromedial to posterolateral) extending into the lateral condyle frequently accompanies these posteromedial fragments. In general, Schatzker type-IV fractures are considered unicondylar (and defined accordingly), but the medial fracture map suggested that this assumption is arguable.

Bicondylar Fracture Map (Figure 4C)

Fracture mapping of the Schatzker type-V and VI fractures showed a diverse diagram of fracture lines. One observable pattern consists of a range of oblique fracture lines, representing posteromedial fragments, comparable with the pattern observed in the medial fracture map. The orientation of the fracture lines of these fragments is variable and ranges from anterior to posterior, to anteromedial to posterolateral, to completely

Table 1. Patient Demographics (N = 127)

Variable	
Sex (no.)	
Male	54
Female	73
Mean age (range) (yr)	47 (17-91)
Trauma center (no.)	
Level I	86
Level III	41
Side of injury (no.)	
Left	77
Right	50
Fracture distribution (no. [%])	
Lateral	64 (50)
I	6 (5)
II	48 (38)
III	10 (8)
Medial (IV)	15 (12)
Bicondylar	48 (38)
V	26 (20)
IV	22 (17)

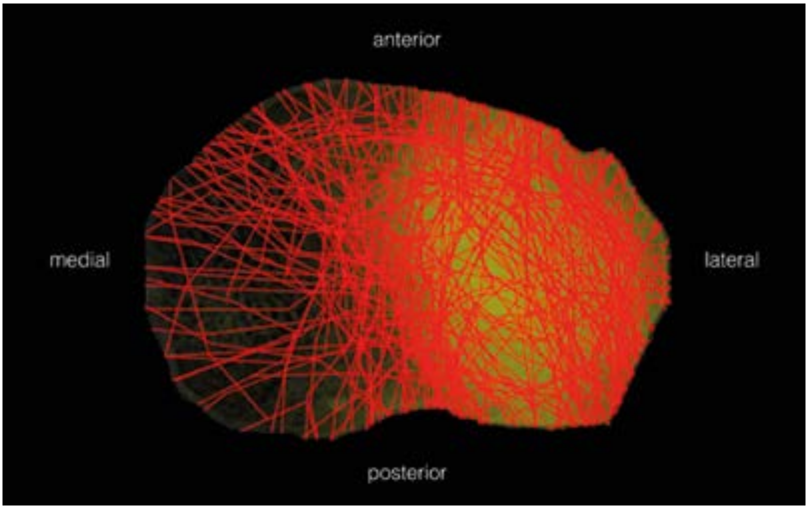

Figure 3. A complete fracture map of the 127 tibial plateau fractures in the series.

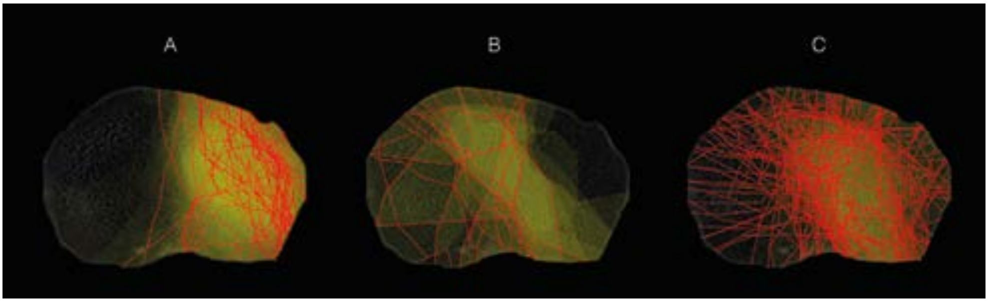

Figure 4. Fracture maps of the sixty-four lateral fractures (Fig. 4-A), fifteen medial fractures (Fig. 4-B), and forty-eight bicondylar fractures (Fig. 4-C). The orientation is similar to that in Figure 3.

medial to lateral (i.e., coronal). In coronal split fragments (present in 17% of the bicondylar fractures), the percentage of the fragment surface originating from the medial plateau averaged 78% (range, 64% to 95%), suggesting that coronal fragments are more medially than laterally located. Furthermore, the bicondylar fracture map showed anteroposterior oriented fracture lines at the lateral side of the plateau, and a U-shaped clustering of fracture lines on the anterior side of the plateau, representing tibial tubercle fragments. The zone of comminution is mainly located at the level of the tibial spine and the lateral condyle (posterocentrolateral), again in an anteromedial to posterolateral direction. Comminution or impaction at the medial side of the plateau appears to be nonexistent in Schatzker type-V and VI fractures.

Main Features of Tibial Plateau Fractures

Four consistent features were identified on the fracture maps of the tibial plateau fractures (Figure 5, Table 2): a lateral split fragment with or without comminution (A) was seen in 75% (ninety-five) of the 127 fractures, a posteromedial fragment that often extended from the (antero)medial to the (postero)lateral side of the plateau (B) was seen in 43% (fifty-five), an anterior tibial tubercle fragment (C) was found in 16% (twenty), and a zone of comminution that included the tibial spine and often extended into the lateral condyle (D) was observed in 28% (thirty-six). It seems that tibial plateau fractures can be characterized by the presence and/or absence of any of these four features, in a variety of combinations.

Feature Combinations

Almost ninety percent (89%) of the tibial plateau fractures had one of eight unique combinations of the above-mentioned fracture features (Table 3). Of note, the features were not constrained by Schatzker type. For example, a Schatzker type- IV fracture could be characterized by a posteromedial fragment and a zone of comminution extending into the lateral condyle (Figure 2A) and a Schatzker type-V fracture, by a posteromedial fragment, a central zone of comminution, and an additional tibial tubercle fragment (Figure 2B). The Schatzker type-VI fractures showed the full spectrum of fracture features:

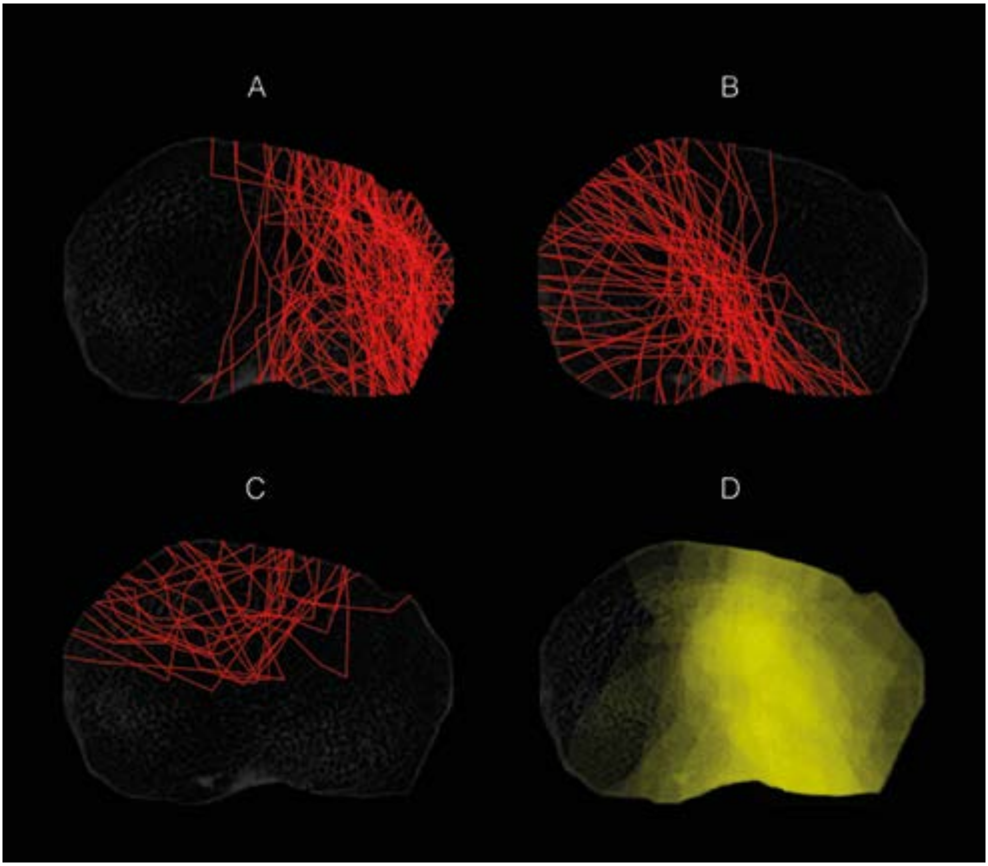

Figure 5. The main features of tibial plateau fractures are a lateral split fragment with or without depression (Fig. 5-A), a posteromedial fragment (Fig. 5-B), a tibial tubercle fragment (Fig. 5-C), and zones of comminution including the tibial spine (Fig. 5-D). The orientation is similar to that in Figure 3.

a posteromedial fragment, a central zone of comminution, a tibial tubercle fragment, and a lateral fragment (Figure 2C).

Associations Among Fracture Features and Schatzker Types

The post-hoc analysis with use of phi coefficients (ϕ) showed significant positive associations between the lateral split fragment and Schatzker type-II fractures ($\varphi = 0.45$, $p < 0.001$); the posteromedial fragment and Schatzker type-IV ($\varphi = 0.32$, $p < 0.001$), V ($\varphi = 0.38$, $p < 0.001$), and VI ($\varphi = 0.48$, $p < 0.001$) fractures; and between Schatzker type-VI fractures and a zone of comminution including the tibial spine ($\varphi = 0.22$, $p < 0.05$) and a tibial tubercle fragment ($\varphi = 0.43$, $p < 0.001$). Significant negative correlations were found between the lateral split fragment and Schatzker type-IV fractures ($\varphi = -0.63$, $p < 0.001$); the posteromedial fragment and Schatzker type-I ($\varphi = -0.19$, $p < 0.05$), II ($\varphi = -0.68$, $p < 0.001$), and III fractures ($\varphi = -0.26$,

Table 2. Feature Distribution (N = 127)

Feature	No.	Percentage
Lateral split fragment	95/127	75
Lateral map	64/64	100
Schatzker type I	6/6	100
Schatzker type II	48/48	100
Schatzker type III	10/10	100
Medial map (Schatzker type IV)	0/15	0
Bicondylar map	31/48	65
Schatzker type V	17/26	65
Schatzker type VI	14/22	64
Posteromedial fragment	55/127	43
Lateral map	0/64	0
Schatzker type I	0/6	0
Schatzker type II	0/48	0
Schatzker type III	0/10	0
Medial map (Schatzker type IV)	13/15	87
Bicondylar map	42/48	88
Schatzker type V	21/26	81
Schatzker type VI	21/22	95
Tibial tubercle fragment	20/127	16
Lateral map	0/64	0
Schatzker type I	0/6	0
Schatzker type II	0/48	0
Schatzker type III	0/10	0
Medial map (Schatzker type IV)	2/15	13
Bicondylar map	18/48	38
Schatzker type V	7/26	27
Schatzker type VI	11/22	50
Central zone of comminution	36/127	28
Lateral map	14/64	22
Schatzker type I	1/6	17
Schatzker type II	12/48	25
Schatzker type III	1/10	10
Medial map (Schatzker type IV)	3/15	20
Bicondylar map	19/48	40
Schatzker type V	8/26	31
Schatzker type VI	11/22	50

p < 0.05); and between the zone of comminution including the tibial tubercle fragment and Schatzker type-II fractures (φ =-0.34, p < 0.001).

In addition, analysis of the correlation among the four identified main fracture features demonstrated one significant negative correlation between the posteromedial fragment and the lateral split fragment (φ = -0.44, p < 0.001), suggesting that these features are most commonly mutually exclusive. Furthermore, a positive association between the posteromedial fragment and the tibial tubercle fragment was found (φ = 0.41, p < 0.001). All associations between main fracture features and Schatzker types, and among main fracture features, are summarized in Figure 6.

Table 3. Feature Combinations (N = 127)

Feature*	No.	Percentage
LF	51	40
PMF	15	12
LF + CF	15	12
LF + PMF	11	9
LF + PMF + TF	6	5
LF + PMF + CF + TF	6	5
LF + PMF + CF	5	4
PMF + CF	4	3
Other	14	11

*LF = lateral split fragment with or without comminution, PMF = posteromedial fragment, CF = comminution zone including the tibial spine, TF = tibial tubercle fragment, and other = feature combinations present in <3% of cases.

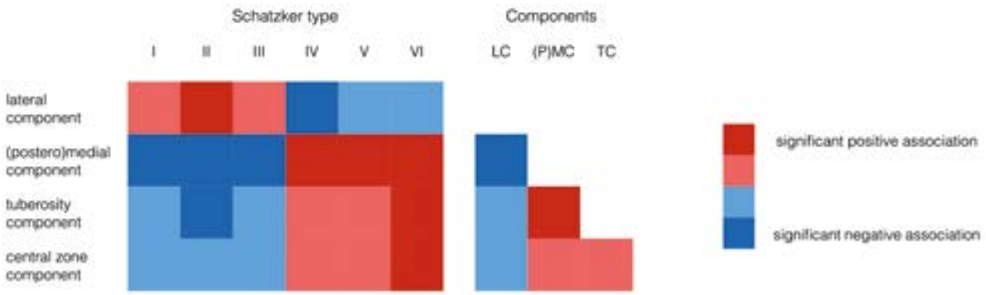

Figure 6. Positive (red) and negative (blue) associations between the main fracture features and Schatzker types, and among the main fracture features, with the dark colors indicating significant correlations. LF = lateral split fragment, PMF = posteromedial fragment, and TF = tibial tubercle fragment.

DISCUSSION

In this study, the fracture mapping developed by Cole and colleagues[17,18] was applied to a large series of tibial plateau fractures to improve our understanding of this challenging injury. Visual analysis identified four recurrent features of tibial plateau fractures: (1) the lateral split fragment with or without comminution[11,12], (2) the posteromedial fragment[3,14,19-21], (3) the tibial tubercle fragment[22,23], and (4) a zone of comminution including the tibial spine[4,19] (Figure 7). “Classic” tibial plateau classification systems have been shown to have only fair reliability and do not guide surgical strategy[19,24,25]. Some authors have favored characterization of fractures over classification[19,26,27]. Characterization of complex tibial plateau fractures with use of the main features presented in this study may be more reliable for communication among surgeons, comparison of studies, preoperative planning[2,19,24], and guiding the surgical approach and specific fixation techniques.

According to Schatzker’s classification, types I, II, and III are unicondylar lateral fractures, type IV is a unicondylar medial fracture, and types V and VI are bicondylar fractures. To support interpretation and enable comparison, we divided the complete tibial plateau fracture map according to those locations. The lateral fracture map showed a pattern conforming with Schatzker’s original description, with involvement of the lateral condyle only, in all but three fractures. However, the medial fracture map showed frequent involvement of both the medial and the lateral condyle in Schatzker type-IV fractures, which is inconsistent with the assumption of a unicondylar medial fracture. Furthermore, the variety of fracture lines crossing the tibial spine in the bicondylar fracture map suggests that Schatzker type V,

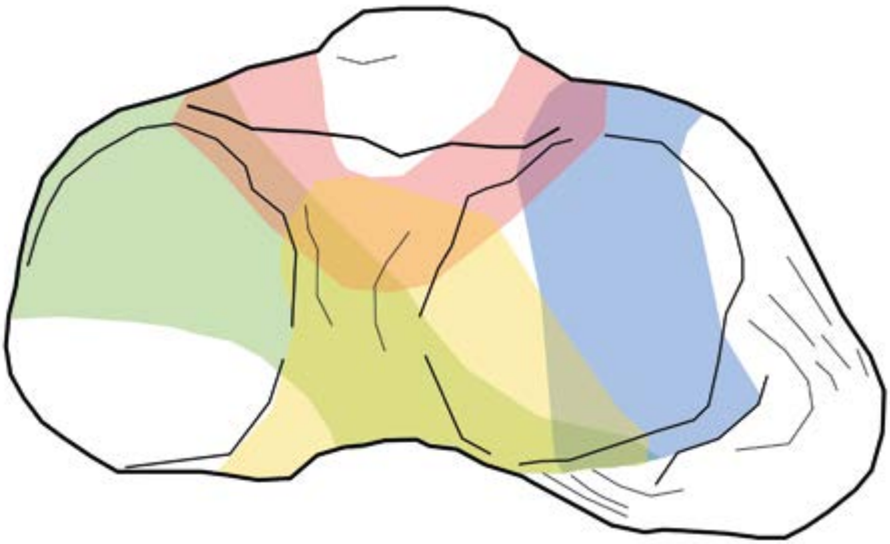

Figure 7. Schematic representation of the four main features of tibial plateau fractures in a right tibial plateau (cranial view). Blue = lateral split fragment, green = posteromedial fragment, red = tibial tubercle fragment, and yellow = zone of comminution including the tibial spine.

generally described as a medial and lateral fracture with continuity through the eminence, is in fact rare. We recognize that fracture line orientations are continuous variables and that designating groups of these patterns as dichotomous variables in the form of classification systems will never result in completely consistent designations.

The four main features of tibial plateau fractures observed in the current study may be further subdivided on the basis of minor fracture lines of each feature. The posteromedial fragment, for example, is a spectrum of fracture lines ranging from a parallel (Figure 8A), to an oblique, to an anteroposterior line orientation (Figure 8B) with respect to the posterior femoral condylar axis, as described by Barei and colleagues[3]. An arbitrary cutoff between parallel and oblique fractures lines would distinguish the “classic” posteromedial shear fracture (a coronal fracture line exiting on the medial side from a bicondylar tibial plateau fracture) from the posterior shear-type fracture (involving the posterior aspect of the medial and lateral condyles) (Figure 8A). Previous studies have shown that these bicondylar posterior shear-type fractures[3,19-21] do not fit into the type-IV, V, or VI category in the Schatzker

Figure 8. Two examples of the continuous spectrum of posteromedial fracture lines ranging from parallel (star in Fig. 8-A) to anteroposterior (star in Fig. 8-B) with respect to the posterior femoral condylar axis. Fig. 8-A Anteroposterior radiograph made after open reduction and internal fixation of a Schatzker type-V fracture in the left knee of a forty-five-year-old woman as well as a postoperative CT scan illustrating an unfixed large posterior bicondylar fragment (star). This particular fracture component might have warranted an additional posteromedial or posterior approach. Fig. 8-B Preoperative CT scans and postoperative radiographs of a Schatzker type-IV fracture in the right knee of a forty-seven-year-old woman treated through a single medial approach. The impacted posterocentrolateral fragments were reduced through the medial plateau fracture opening.

classification. Weil and colleagues classified isolated posteromedial shear fractures as Schatzker type IV (Figure 8B) and a bicondylar shear-type fracture in the sagittal plane as Schatzker type V or VI[28].

The clinical relevance of this academic discussion and the concomitant surgical pitfalls of this range of fracture types are illustrated in Figure 8. On the plain anteroposterior radiograph, the lateral-split-depression seems properly reduced and fixed (Figure 8A). However, the large posterior bicondylar fragment was not surgically stabilized through the chosen lateral approach as clearly depicted on the postoperative axial CT scan. Although this patient did well, this particular fracture component might have warranted an additional posteromedial or posterior approach. Figure 8B represents another fracture configuration in the spectrum of posteromedial fragments, treated with a single medial approach. The impacted posterocentrolateral fragments were reduced through the medial plateau fracture opening, according to the method described by Potocnik and colleagues[14]. Being aware of the full range of possible fracture elements and the variety in fragment morphology helps the surgeon to choose the best surgical approach or combination of approaches. This will allow optimal access to and reduction and fixation of this complex injury, potentially leading to a better outcome.

In 2010, Luo and colleagues described a CT-based classification system characterizing the involvement of the medial, lateral, and posterior "column" that was based on the authors' experience rather than mapping of their series of tibial plateau fractures[13]. The Luo classification system is limited as it does not account for the posteromedially oriented medial fractures that extend into the lateral plateau[14]. In our previous study comparing 2D and 3D CT for examining fracture characteristics and classification, none of the observers categorized any of the posterior shear fractures as unicondylar but they consistently characterized posteromedial fractures as bicondylar[19]. This finding is in accordance with the study by Barei and colleagues[3] and the depicted posteromedial fracture lines in the tibial plateau fracture map in the current study (Figure 5B).

In addition, the tibial plateau fracture maps depicted mainly central and lateral-sided zones of comminution, separating medial and lateral components of injuries in a fashion similar to the patterns observed by Eggli and colleagues in their prospective series[29]; in bicondylar fractures, posteromedial split fragments are combined with various amounts of multifragment lateral compartment depression. In these fractures, axial load transmission results in a split fracture without comminution or impaction on the concave medial side. In contrast, the axial loading on the convex lateral side results in multifragment depression with widening of the lateral compartment[29].

Sohn and colleagues recently identified the posterolateral fragment as part of the lateral component of injury, in the spectrum of lateral-sided split-depression-type fractures with an associated zone of lateral-sided comminution[15]. Mapping the lateral split fragment revealed the classic anteroposterior major fracture lines as well as the oblique posterolateral minor fracture lines described by Sohn and colleagues (Figure 5A).

Some shortcomings of this study have to be considered. First, only operatively treated tibial plateau fractures were included. Second, the methods and results were descriptive in nature, and one may argue that the interpretation of fracture maps is subjective[18]. Third, we used a one-dimensional simplification of complex intra-articular fractures without accounting for specific 3D fracture characteristics and patterns. Fourth, we used a subjective simplification in depicting zones of comminution when major fracture fragments and lines were incongruent. Finally, because of the frequent presence of comminution, dislocated fragments, and depressed and impacted fragments in particular, the classic method of fracture mapping, in which one static axial CT slice of standardized height is chosen[18], was amended to evaluate complex tibial plateau fractures.

However, our study also had important strengths. To our knowledge, we are the first to apply the fracture mapping technique[17] to tibial plateau fractures, and we validated this novel imaging technique for Schatzker type-I, II, and III fractures, reproducing fracture characteristics according to Schatzker's original description[12]. We also applied fracture mapping to a wide spectrum of complex tibial plateau fractures in a large consecutive series of cases collected in level-I and III trauma centers, likely representing the full spectrum of tibial plateau fractures.

In conclusion, tibial plateau fracture classification systems have been based mainly on anteroposterior radiographs[12,30] despite the advent of CT and MRI[13,16]. Classification systems have not been revised, even though our understanding of morphologic characteristics of tibial plateau fractures, in particular of coronal fracture lines and resulting sagittal plane deformity, has continued to evolve[3,4]. In more recent studies, authors have reassessed classic classification schemes[31] or introduced new classifications based on CT[13,25]. The approach in our current study differs from that in those previous papers. Instead of assigning individual fractures to a particular class, we suggest using four common fracture features to define—or "build"—respective tibial plateau fractures. The four major features of tibial plateau fractures observed in the current study may help to improve observer agreement in clinical studies[26] and may be useful in daily practice as an augmentation to classification systems. Further research is needed to evaluate if the main tibial plateau fracture features are reliable, and whether the identification of distinct features helps to guide surgical planning, approaches, and specific fixation techniques.

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CHAPTER 4

Fracture Mapping of Displaced Partial Articular Fractures of the Radial Head

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ABSTRACT

Background: Recognition of patterns of traumatic elbow instability helps anticipate specific fracture characteristics and associated injuries. The objective of this study was to assess the association of fracture line distribution and location of displaced partial articular radial head fractures with specific patterns of traumatic elbow instability using fracture mapping techniques.

Methods: Fracture line distribution and location of 66 acute displaced partial articular radial head fractures were identified using quantitative 3-dimensional computed tomography reconstructions that allowed reduction of fracture fragments and a standardized method to divide the radial head into quadrants with forearm in neutral position. Based on qualitative and quantitative assessment of fracture maps, the association between fracture characteristics of displaced partial articular radial head fractures and specific elbow fracture patterns was determined.

Results: In partial articular radial head fractures, the highest fracture line intensity was located in the anterolateral quadrant near the center of the radial head. Fracture location corresponded with fracture line distribution; most fractures involved the anterolateral quadrant (n = 65; 98%), whereas parts of the posteromedial quadrant were involved in a minority of the fractures (n = 10; 15%). The association of fracture line distribution and location with overall fracture patterns of the elbow, as depicted on fracture maps, was not statistically significant.

Conclusion: Fracture maps demonstrated no association between fracture line distribution and location of displaced partial articular fractures of the radial head and overall specific patterns of traumatic elbow instability, suggesting a common fracture mechanism that involves the anterolateral part of the radial head in most patients.

INTRODUCTION

Fracture mapping, as initially described by Cole et al[1,6], enables evaluation of fracture characteristics, such as location and frequency, that help identify specific fracture patterns by superimposing fracture lines, zones of comminution, and articular involvement from a large number of fractures. Using a modification of this technique[24,26], fracture line distribution and location were related to specific injury patterns for coronoid fractures.[24]

Recognition of patterns of traumatic elbow instability helps anticipate specific fracture coronoid and olecranon characteristics (e.g., location and articular involvement) and associated injuries.[7-10,12,23,28,33,34] Fracture mapping and quantitative 3-dimensional computed tomography (Q3DCT) analysis of coronoid and olecranon fractures have identified specific shapes, sizes, and orientations of fracture fragments according to pattern of traumatic elbow instability.[21,24,25] It is not clear if specific patterns of traumatic elbow instability are associated with specific locations and sizes of displaced partial articular fractures of the radial head.

Based on qualitative and quantitative assessment of fracture maps, we tested the null hypothesis that there is no difference in fracture line distribution (i.e., fracture line entries and exits) and location of displaced partial articular radial head fractures between specific patterns of traumatic elbow instability (isolated radial head fracture, radial head fracture with posterior dislocation, terrible triad injury, and posterior olecranon fracture-dislocation).

MATERIALS AND METHODS

Patients

At 2 level I trauma centers, the administrative databases were searched using the International Classification of Diseases, Ninth Revision, Clinical Modification (codes 813.0x and 813.1x for fractures of upper end of radius and ulna) and Current Procedural Terminology (codes 24586-24685, including elbow dislocations, Monteggia type of fractures, radial and ulnar fractures) for patients with a radial head fracture between July 2001 and January 2014. The search identified 769 patients with a radial head fracture. Inclusion criteria were (1) age of 18 years or older, (2) acute displaced partial articular fracture of the radial head (Mason type 2), and (3) complete radiographic assessment including anteroposterior and lateral radiographs and a computed tomography (CT) scan displaying the complete fracture. Displaced partial articular radial head fractures were defined as Broberg and Morrey modified Mason type 2 fractures (more than 2 mm of displacement, involving only a part of radial head)[2]. Anteroposterior and lateral radiographs, CT scans, and surgical reports were evaluated by 2 authors (J.J.M. and D.R.) to establish the diagnosis. A total of 69 patients met the inclusion criteria. The exclusion criterion was artifacts on CT images that interfered with the 3-dimensional (3D) reconstruction of the proximal radius, including the radial head, fracture fragments, and the radial tuberosity. Three patients were excluded. The remaining 66 patients were analyzed in this study. Of these patients, the mean age was 49 years (range, 19-79). There were 38 (58%) men and 28 (42%) women, most of whom received operative treatment (83%). The most common injury was a terrible triad fracture-dislocation (47%; Table I).

Fracture mapping

According to the mapping technique as described by Cole et al.[1,6] and modified by our group[24,26], fracture line distribution and location, which was defined as the anatomic area of articular involvement, were determined using Q3DCT techniques. Q3DCT techniques allow the study of shapes, sizes, displacement, and orientations of bone structures.[3,15,21,25] To create Q3DCT reconstructions, Digital Imaging and Communications in Medicine files of the selected CT scans were retrieved and loaded in Slicer (3D Slicer, Boston, MA, USA). Slicer is a software program used for visualization and analysis of medical images. In Slicer, bone structures, including fracture fragments and the radial tuberosity of the proximal radius, were marked manually in axial, sagittal, and coronal planes using Edit Selected Label Map options available in this program. Subsequently, 3D polygon mesh reconstructions were built.

The 3D polygon mesh reconstructions were imported in Rhinoceros (McNeel, Seattle, WA, USA) to determine the most prominent point of the center of the radial tuberosity, which was used as reference point. Rhinoceros is application software designed to create, edit, analyze, and translate 3D reconstructions. By making the 3D polygon

Table 1. Patient Characteristics

	All Patients (n=66)
Age, mean(SD), years	49(15)
Sex, n(%)	
Men	38(58)
Women	28(42)
Side of injury, n(%)	
Right	39(59)
Left	27(41)
Treatment, n(%)	
Operative	55(83)
Nonoperative	11(17)
Injury patterns, n(%)	
Isolated radial head fracture	8(12)
Radial head fracture with posterior dislocation	3(4.6)
Terrible triad injury	31(47)
Varus posteromedial rotational instability	1(1.5)
Posterior olecranon fracture dislocation	12(18)
Posterior Monteggia with dislocation of the elbow	2(3.0)
Essex-Lopresti injury	1(1.5)
Unique pattern	8(12)

mesh reconstruction semitransparent, we were able to draw an x, y, and z axis through the volume centroid (i.e., geometric center of the 3D polygon mesh reconstruction); the x axis represented the axis of the proximal radius, whereas the y axis represented the width and the z axis represented the height. After the axes were drawn, the 3D reconstruction was turned around its x axis, and the most prominent point of the radial tuberosity, defined as the point of the radial tuberosity with the largest z value (ie, highest point), was determined on the z axis. After the most prominent point was determined, the fracture fragment was reduced (Figure 1).

The most prominent point of the radial tuberosity was then turned 132° clockwise to simulate the forearm in neural position, as described by van Leeuwen et al[35], assuming a maximum supination of 85° and that the radial tuberosity is located at 42.6° counterclockwise from the ulna with the forearm in full supination [18,36] Subsequently, images of reduced 3D polygon mesh reconstructions were obtained and imported in Macromedia Fireworks MX (Macromedia Inc, San Francisco, CA, USA). Macromedia Fireworks MX has been developed to edit bitmap images and enables creation of fracture maps as described by Cole et al.[6] and Armitage et al.[1], in which bitmap images are superimposed onto a standard template to form a compilation of fracture line distribution and location (Figure 2). On fracture maps, the fracture line entries and exits were determined; the first point of the fracture line clockwise from the radial

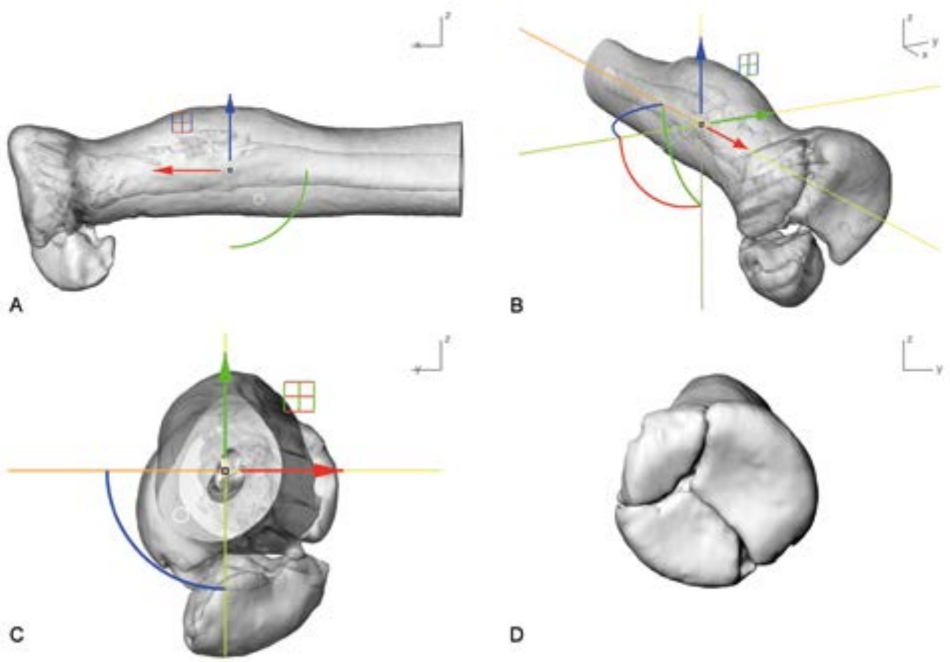

Figure 1. Determining the most prominent point of the center of the radial tuberosity. (A) Semitransparent 3D polygon mesh reconstruction of the proximal radius with volume centroid indicated as a point. (B) Drawn x, y, and z axes through the volume centroid. (C) Most prominent point of the radial tuberosity determined on the z axis. (D) Reduced 3D polygon mesh reconstruction after the most prominent point of the radial tuberosity was determined.

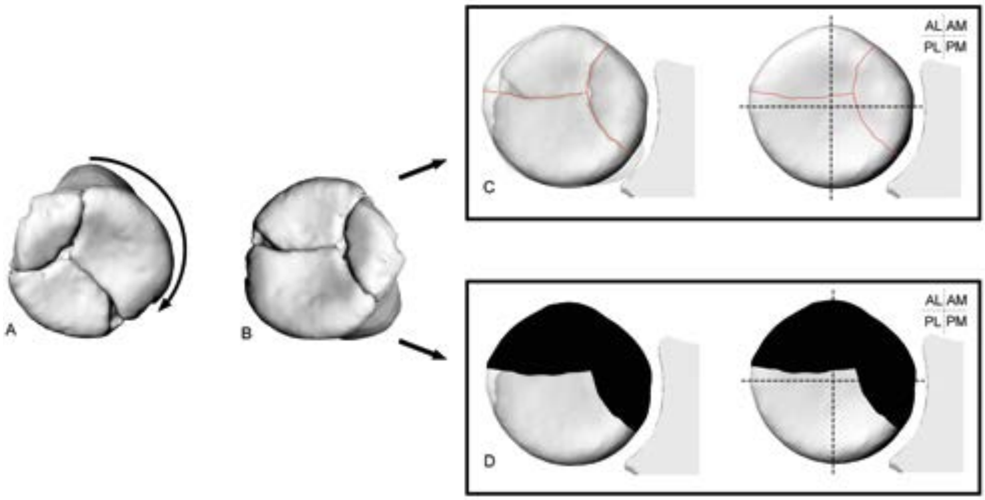

Figure 2. Method of fracture mapping. (A) The most prominent point of the radial tuberosity turned 132° clockwise to simulate forearm in neutral position. (B) Image of reduced 3D polygon mesh reconstructions. (C) Fracture line drawn onto superimposed and matched standard template of an intact radial head. (D) Fracture location marked onto the superimposed standard template. AL, anterolateral; AM, anteromedial; PL, posterolateral; PM, posteromedial.

tuberosity was considered the entry, whereas the last point of the fracture line clockwise from the tuberosity was considered the exit. In addition, heat maps were made using our previous described techniques[24], in which data density plots based on the coordinates of fracture lines are created. In heat maps, the relative fracture line distribution (i.e., fracture line intensity) is represented as color following arbitrary units of measure.

Elbow fracture patterns

The diagnosis of traumatic elbow injuries was based on anteroposterior and lateral radiographs, 2-dimensional (2D) and 3D CT scans, and surgical reports, which were evaluated by 2 authors (J.J.M. and D.R.). Elbow fracture patterns were classified into the categories as summarized by Doornberg et al.[8]: radial head fracture with posterior dislocation, terrible triad injury, posterior and anterior olecranon fracture-dislocation, and varus posteromedial rotational instability. In addition, isolated radial head fractures, Essex-Lopresti injuries, and posterior—proximal—Monteggia fractures with dislocation of the elbow were classified. All other injuries were considered unique patterns.

Statistical analysis

Patient characteristics were summarized with frequencies and percentages for categorical variables and with means and standard deviations for continuous variables.

The $\chi 2$ or Fisher exact test was used to test for differences in proportion of fracture line distribution (i.e., fracture line entries and exits) and location between elbow fracture patterns, which were grouped in case of low numbers to ensure ≥ 5 fractures in each category: isolated radial head fracture, posterior radial head and terrible triad fracture-dislocation, posterior olecranon fracture-dislocation, and “other” if these categories were not applicable.

RESULTS

Most fracture lines entered the posterolateral quadrant and exited the radial head through the anterior quadrants (77% and 98%, respectively). The highest fracture line intensity was located in the anterolateral quadrant near the center of the radial head, indicating that most fracture lines pass through the radial head through the anterolateral quadrant slightly anterolateral to the center of the radial head. Similar patterns of fracture line distribution, as depicted on fracture maps, were found between the patterns of traumatic elbow instability (Figure 3). There was no association between fracture line distribution and elbow fracture patterns, as there was no difference in proportion of fracture line entries and exits: anterolateral quadrant (P = .88 and P = .86, respectively), anteromedial quadrant (no P value and P = .56, respectively), posterolateral quadrant (P = .79 and no P value, respectively), and posteromedial quadrant (P = .19 and P = .12, respectively; Table II).

Fracture location (i.e., anatomic area of articular involvement) corresponded with fracture line distribution; most fractures involved the anterolateral quadrant (98%), whereas parts of the posteromedial quadrant were involved in a minority of the fractures (15%). Overall, the most and least involved parts of the radial head were opposite to each other. A line through these segments would result in 2 approximately symmetrical halves, indicating a symmetrical distribution. The fracture location, depicted on fracture maps, did not differ between the fracture patterns of the elbow (Figure 4). Accordingly, there was no association between fracture location and elbow fracture patterns, as the proportion of articular involvement of the anterolateral quadrant (P = .49), anteromedial quadrant (P = .79), posterolateral quadrant (P = .77), and posteromedial quadrant (P = .24) was equal between the grouped elbow fracture patterns (Table II).

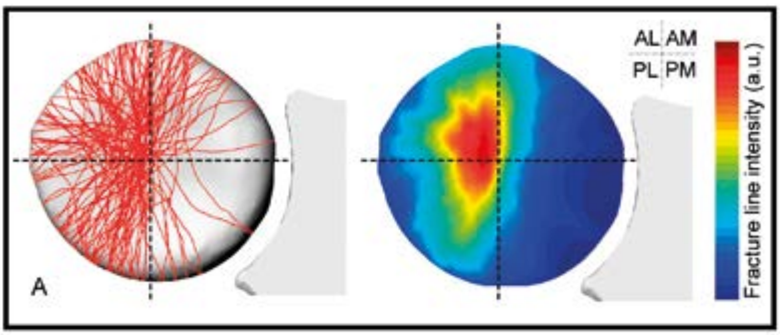

Figure 3A. Fracture and heat maps illustrating fracture line distribution. (A) Overall pattern (N = 66).

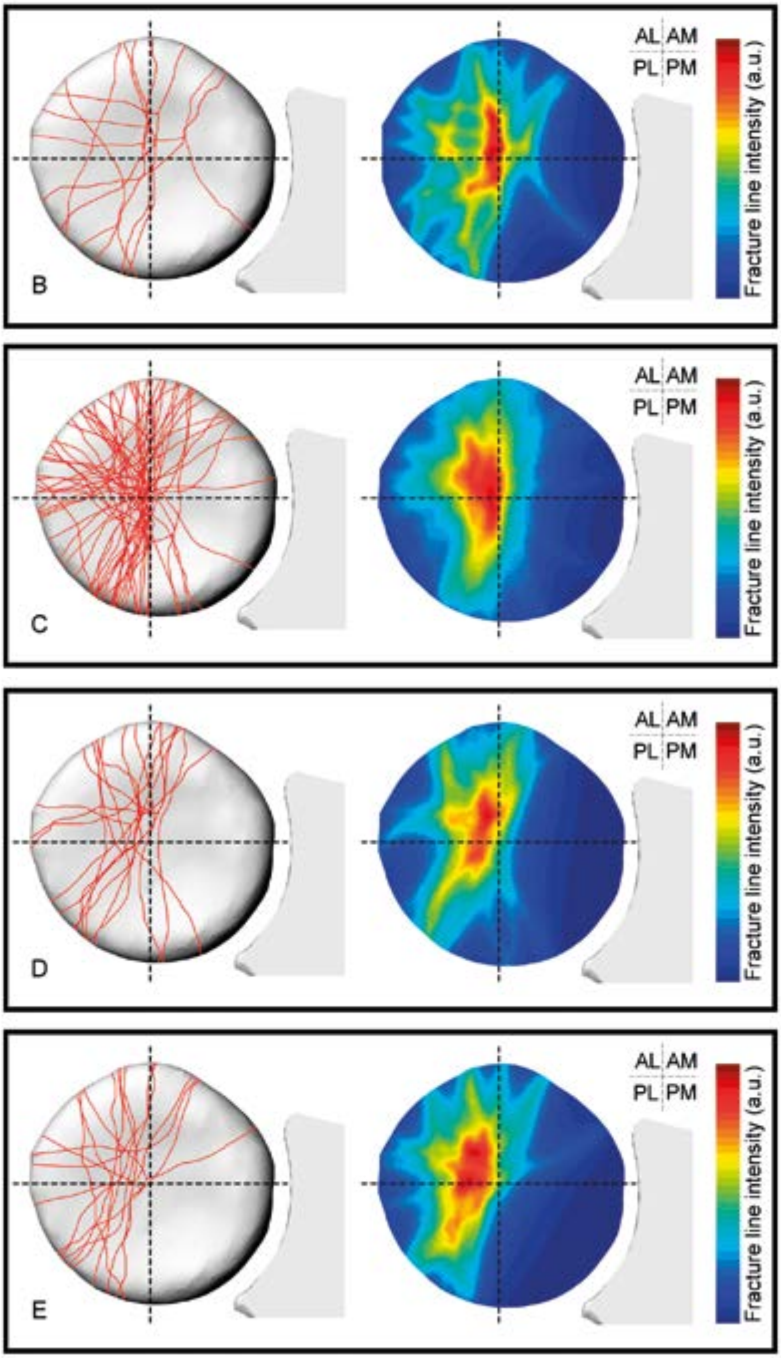

Figure 3B. Fracture and heat maps illustrating fracture line distribution. (B) Isolated injury (n = 8). (C) Posterior radial head and terrible triad fracture-dislocation (n = 34). (D) Posterior olecranon fracture-dislocation (n = 12). (E) Other fracture patterns (n = 12). AL, anterolateral; AM, anteromedial; PL, posterolateral; PM, posteromedial.

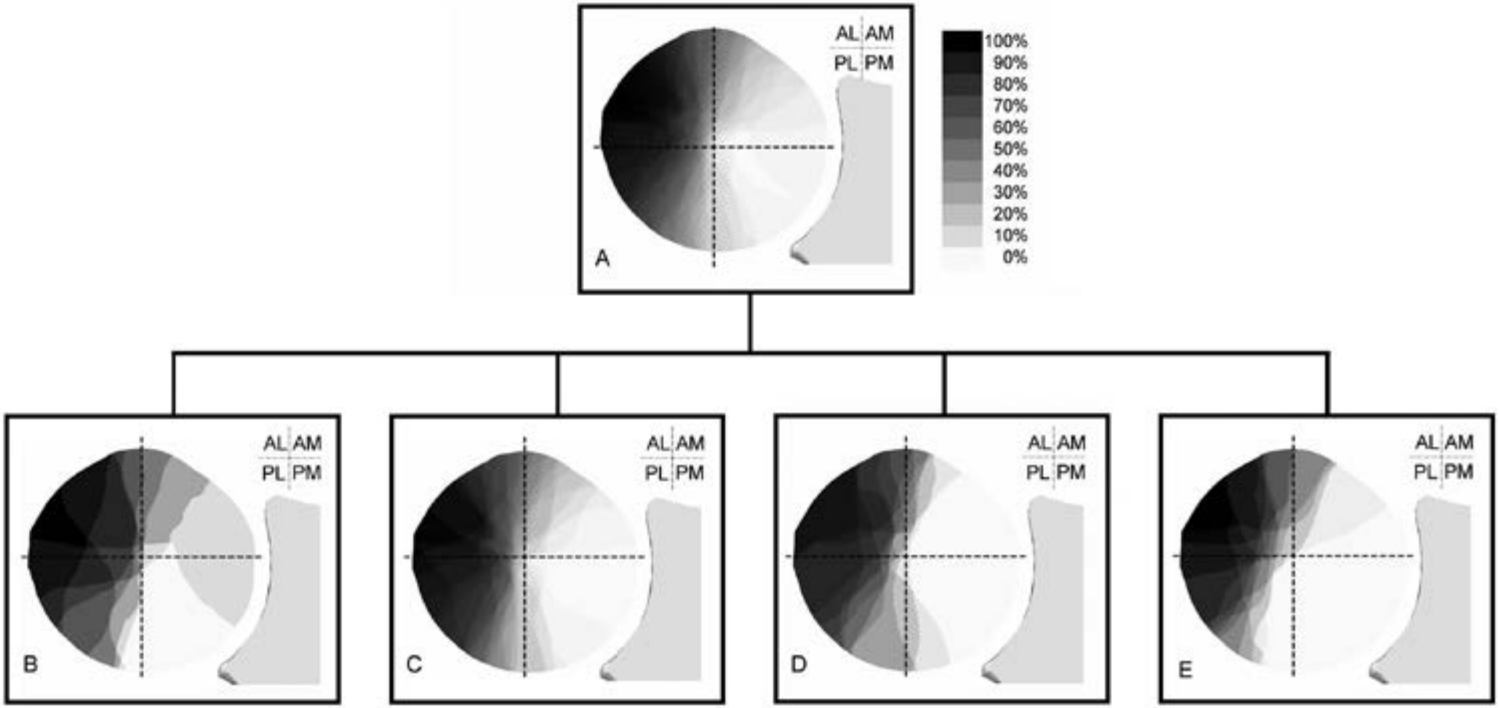

Figure 4. Fracture maps illustrating fracture location in percentage involvement. (A) Overall pattern (N = 66). (B) Isolated injury (n = 8). (C) Posterior radial head and terrible triad fracture-dislocation (n = 34). (D) Posterior olecranon fracture-dislocation (n = 12). (E) Other fracture patterns (n = 12). AL, anterolateral; AM, anteromedial; PL, posterolateral; PM, posteromedial.

Table 2. Fracture Line Distribution and Location Stratified by Elbow Fracture Patterns

	All Patients (n=66)	Elbow Fracture Patterns				P Value
		IRHF (n=8)	RHFPD and TT (n=34)	POFD (n=12)	Other (n=12)	
Fracture line distribution						
Fracture line entry, n(%)						
Anterolateral	7(11)	1(13)	3(8.8)	1(8.3)	2(17)	0.88
Anteromedial	0(0.0)	0(0.0)	0(0.0)	0(0.0)	0(0.0)	*
Posterolateral	51(77)	7(88)	26(77)	8(67)	10(83)	0.79
Posteromedial	8(12)	0(0.0)	5(15)	3(25)	0(0.0)	0.19
Fracture line exit, n(%)						
Anterolateral	35(53)	5(63)	18(53)	5(42)	7(58)	0.86
Anteromedial	30(45)	2(25)	16(47)	7(58)	5(42)	0.56
Posterolateral	0(0.0)	0(0.0)	0(0.0)	0(0.0)	0(0.0)	*
Posteromedial	1(1.5)	1(13)	0(0.0)	0(0.0)	0(0.0)	0.12
Fracture location n(%)						
Anterolateral	65(98)	8(100)	34(100)	11(92)	12(100)	0.49
Anteromedial	33(50)	3(38)	18(53)	7(58)	5(42)	0.79
Posterolateral	58(88)	7(88)	31(91)	10(83)	10(83)	0.77
Posteromedial	10(15)	2(25)	5(15)	3(25)	0(0.0)	0.24

* P value could not be calculated
IRHF, isolated radial head fracture; RHFPD, radial head fracture with posterior dislocation; TT, terrible-triad fracture-dislocation; POFD, posterior olecranon fracture-dislocation

DISCUSSION

Radial head fracture characteristics, including the amount of displacement and articular involvement—considered in the context of associated injuries—are used to determine fracture treatment.[2,11,28,30-32,37,38] Displaced partial radial head fractures have been characterized on the basis of observations in patient care and imaging techniques[2,4,17,22,35]; however, data on variation in fracture location and fracture line distribution in relationship to associated injuries (i.e., elbow fracture patterns) are scarce in comparison to association of coronoid fracture characteristics and elbow fracture patterns.[7,9,10,23-25,28] The purpose of this study was to evaluate the association between fracture line distribution and location of displaced partial radial head fractures and specific elbow fracture patterns. Based on fracture mapping techniques, which allowed both qualitative and quantitative analysis, we found that fracture line distribution and location did not differ between specific fracture patterns of the elbow: the anterolateral quadrant is the anatomic area of most frequent involvement for all injury patterns. This means that the surgical exposure for fixation of the radial head can be the same for all injury patterns.

This study was subject to several limitations that need to be considered in interpreting our findings. First, patients without a complete radiographic assessment were not included. This might have limited the generalizability of the study results, considering that patients with a CT scan are more likely to have radial head fractures with particular associated injuries. Fractures without CT scans might be different from the fractures we studied. Second, our analysis did not account for potential variability in function and anatomy and forearm rotation at the moment of injury, which were standardized for each patient. Therefore, the relative position of the radial tuberosity with respect to the ulna and maximal supination of the selected patients might have been different than assumed on the basis of prior studies.[18,36] Finally, our sample size did not allow us to stratify fracture line distribution and location by each defined elbow fracture pattern. Despite our relatively large sample size, specific elbow fracture patterns with low numbers were grouped to ensure appropriate data analysis.

We found that partial articular fractures of the radial head involve the anterolateral part of the radial head in all patterns of injury. This suggests a common mechanism of radial head fractures. Gordon et al.[14] described a mechanism in which an axial, valgus, and external rotatory loading at the radiocapitellar and proximal radioulnar joints explains shearing of the anterolateral segment of the radial head as it subluxates posterior to the capitellum.[27,29] In addition to loading transmission, distribution of fracture lines might be influenced by mechanical properties of the bone of the radial head. A recent study by Haverstock et al.[16] based on CT scan data demonstrated that radial head bone volume and density were lowest in the anterolateral quadrant, suggesting that low bone density may predispose to fractures or comminution. These findings were similar to those described by Caputo et al[5], who studied the macroscopic structure of the radial head and reported that the nonarticulating portion (i.e., the anterolateral quadrant with forearm in neutral position) was thinner and more yellow compared with the articulating part of the radial head. Koslowsky et al.[20] reported comparable findings based on subtraction densitometry and demonstrated lower subchondral bone density in the posterolateral and anterolateral part of the joint surface. Consistent with these findings, Gordon et al.[14] showed with biomechanical data that decreased bone density is correlated with decreased strength as the anterolateral portion demonstrated lower yield strength compared with the anteromedial and posteromedial quadrants. In post hoc analysis, considering that bone density is related with age and fractures of the radial head may be associated with osteoporosis[13,19] , we determined that fracture line distribution did not differ between patients older and younger than 55 years.

Furthermore, we demonstrated that the radial head fracture location did not differ between the fracture patterns of the elbow. In contrast, Capo et al.[4] reported a higher rate of elbow dislocations in fractures involving the anteromedial quadrant compared with anterolateral fractures of the radial head. However, this study had several limitations, including 2D CT–based analysis, small sample size, and assignment of fracture fragments to one of the quadrants, which could have led to inaccurate conclusions. Moreover, our findings were consistent with the findings reported by van Leeuwen et al.[35] who used quantitative analysis to confirm that the anterolateral quadrant is most commonly involved in displaced partial articular fractures of the radial head.

CONCLUSION

Fracture maps demonstrated no association between fracture line distribution and location of displaced partial articular fractures of the radial head and specific patterns of traumatic elbow instability, suggesting one common fracture mechanism that involves the anterolateral part of the radial head in most patients. In spite of the consistency in all prior studies, surgeons planning operative fixation should be aware that there is large variability in the fracture maps, and CT scans are recommended if further characterization is needed to plan surgery. Future studies evaluating the nature of load transmission through the proximal radius for specific injury patterns or particular anatomic variations, such as size of the radial head and shape, might enhance our understanding of the relationship between fractures of the radial head, anatomic variation, and associated injuries.

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CHAPTER 5

Involvement of the Lesser Sigmoid Notch in Elbow Fracture Dislocations

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ABSTRACT

Background: This study addressed the primary null hypothesis that there is no difference in the articular surface area of the lesser sigmoid notch involved among Mayo classes. Secondarily, we analyzed the fracture line location and the pattern of lesser sigmoid notch articular surface involvement among Mayo classes.

Methods: Using quantitative 3-dimensional computed tomography, we reconstructed and analyzed fractures involving the lesser sigmoid notch articular surface in 52 patients. Further, we assessed the surface area involved in the fracture, the number of fracture fragments, and the location and direction of the fracture lines. Coronoid fractures were classified according to Mayo types.

Results: There was no significant difference between Mayo types 1 and 2 in any characteristic of the involvement of the lesser sigmoid notch articular surface, whereas Mayo type 3 was significantly different from both Mayo types 1 and 2 in the area involved in the fracture (42% in Mayo type 3 vs. 9% in Mayo types 1 and 2), the number of articular fragments (>3 fragments in type 3 vs. 2 fragments in types 1 and 2), and the direction of fracture line (both horizontal and vertical lines in type 3 vs. only horizontal line in types 1 and 2).

Conclusion: Mayo type III results in a more complex fracture, which might need to be addressed directly or indirectly during open reduction with internal fixation of olecranon fracture dislocations because changes in the geometry of lesser sigmoid notch may affect the radioulnar joint if it remains incongruent.

INTRODUCTION

We have a limited understanding of how proximal ulnar fractures affect the lesser sigmoid notch. The lesser sigmoid notch articulates with the radial head[2,3] and also provides a landmark for positioning the radial head prosthesis after elbow fracture dislocations.[11] It is clear that some coronoid fractures enter the proximal radioulnar joint, but the fracture patterns of the lesser sigmoid notch are not well described. The Regan-Morrey and Mayo classifications of coronoid fractures primarily focus on the articular fracture pattern of the trochlear notch but do not consider lesser sigmoid notch involvement. The Regan-Morrey classification was based on the size of the fragment on a lateral radiograph. As computed tomography (CT) scans improved the understanding of coronoid fracture patterns, O'Driscoll introduced the Mayo classification based on shapes of coronoid fractures that are associated with specific patterns of injury.[5]

Quantitative (Q) 3-dimensional (3D) computed tomography (CT; Q3DCT) facilitates study of the morphology and articular fracture pattern of fractures.[4,6] In this study, we used Q3DCT to analyze lesser sigmoid articular involvement to address the primary null hypotheses that there is no difference in the articular surface area of the lesser sigmoid notch involved among Mayo classes. Secondarily, we hypothesized that there is no difference in the fracture line location and pattern of articular surface involvement among the Mayo classes.

METHODS

Patients

We searched the billing database of two level 1 trauma hospitals from July 2001 to January 2014 with International Classification of Diseases, 9th Revision, Clinical Modification codes 813.0x and 813.1x for closed and open elbow fractures, respectively, and Current Procedural Terminology (American Medical Association, Chicago, IL, USA) codes 24,586-24,685, which include radial and ulnar fractures, Monteggia type fractures, and elbow dislocations. We found 207 patients with coronoid fractures, of which 55 involved the lesser sigmoid notch in patients that were at least 18 years old and had a fracture completely visualized by CT with a slice thickness of 0.625 to 1.25 mm. Three patients were excluded because of low-quality CT images. The remaining 52 patients were analyzed. The most common pattern of traumatic elbow instability was the terrible triad (TT), and the second most common was posterior olecranon fracture dislocation (Table I).

Quantitative 3DCT

The original CT scans of eligible subjects were obtained as Digital Imaging and Communications in Medicine (National Electrical Manufacturers Association, Rosslyn, VA, USA) files through the picture archiving communications system at each hospital and uploaded into 3D Slicer (Boston, MA, USA), a software program used to display and analyze medical images. The 3D

Table 1. Demographics

Variables	Patients (n = 52)
Age, mean (SD), years	45 (14)
Sex, No. (%)	
Men	37 (71)
Women	15 (29)
Side of injury, No. (%)	
Right	19 (36)
Left	33 (64)
Treatment, No. (%)	
Surgical	43 (83)
Nonsurgical	9 (17)
Mayo classification, No. (%)	
Type 1	28 (54)
Type 2	8 (15)
Type 3	16 (31)
Injury patterns, No. (%)	
Terrible triad fracture-dislocation	27 (52)
Varus posteromedial rotational instability pattern	6 (12)
Olecranon fracture-dislocation	
Anterior olecranon fracture-dislocation	1 (2.0)
Posterior olecranon fracture-dislocation	11 (21)
Olecranon fracture with varus posteromedial instability	2 (4.0)
Posterior Monteggia injury associated with terrible triad fracture-dislocation	5 (9.0)

SD, standard deviation.

Slicer tools PaintEffect and Threshold Paint were used to manually mark the proximal ulna, including fracture fragments, in transverse, sagittal, and oblique images. Avoxel range of 225.00 to 1760.00 Hounsfield Units was used to identify bony structures.

Subsequently, 3D polygon mesh reconstructions were created (Figure 1) and uploaded into Rhinoceros 5.0 software (Seattle,WA, USA) for measurement of the articular surface area of the lesser sigmoid notch. The surface area of the fragment attached to the olecranon was considered as the principle fragment and referred to as the proximal (dorsolateral) fragment. A polyline was drawn on the surface of the mesh reconstruction, after which the surface area within this polyline was measured using the Area command in Rhinoceros (Figure 2). The articular surface area of each fragment was recorded and added to the area of the proximal fragment to determine the total lesser sigmoid articular surface area for each individual. The number of fracture fragments was also recorded, including the proximal fragment.

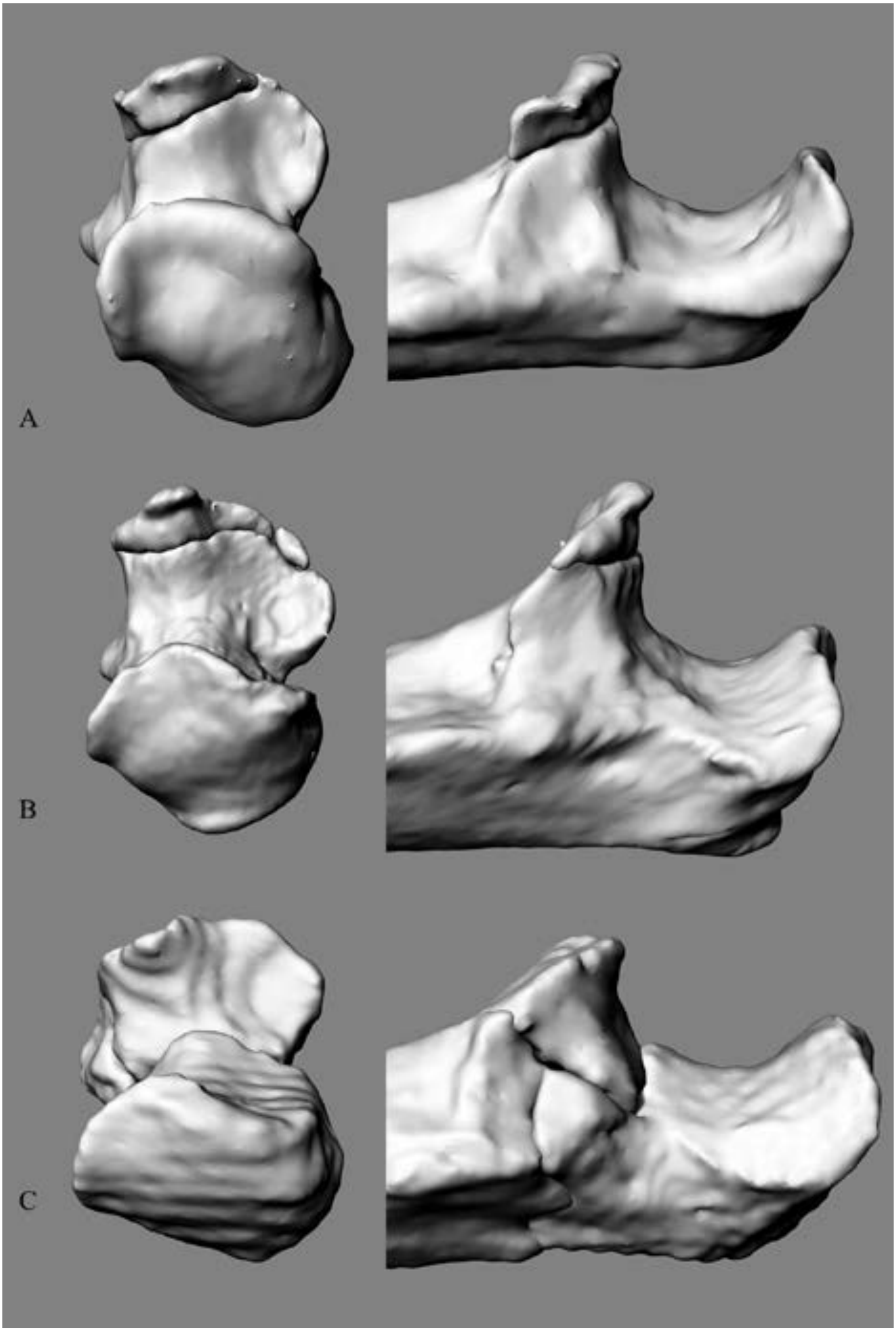

Figure 1. A 3-dimensional mesh reconstruction of elbow fractures involving the lesser sigmoid notch. The coronoid process fractures correspond to Mayo criteria (A) type 1, (B) type 2, and (C) type 3.

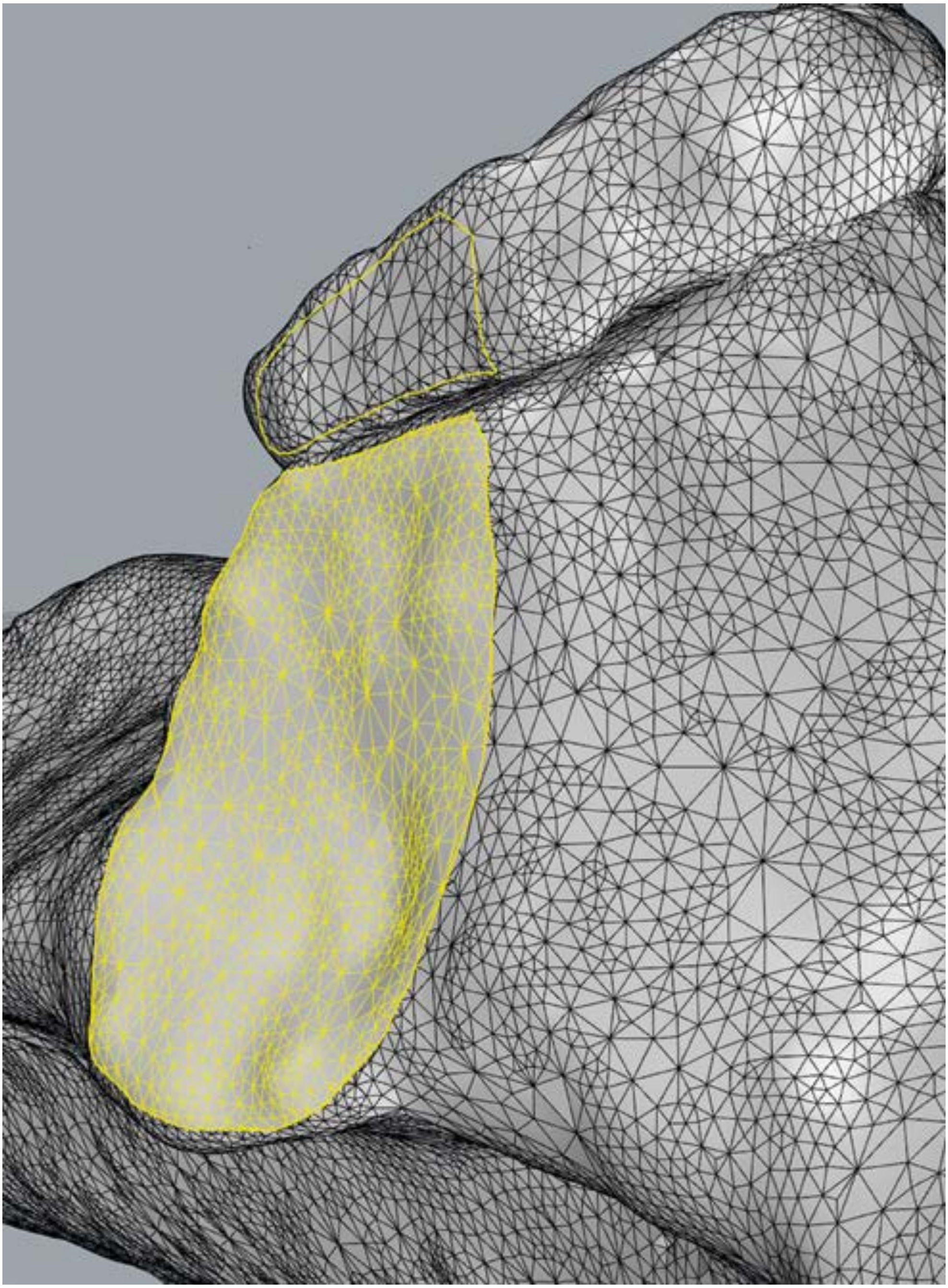

Figure 2. A 3-dimensional polygon mesh reconstruction of the lesser sigmoid notch of the ulna, with an overlying polyline (yellow) indicating the articular surface of the lesser sigmoid notch and the fracture fragment (superior).

The fracture line location was determined by measuring the 3D polygon mesh reconstruction of the lesser sigmoid notch in its longest axis in Rhinoceros 5.0. This measurement was divided by 3 to identify upper, middle, and lower thirds. The lesser sigmoid fractures were then classified according to which third the fracture line traversed. When fracture fragments contributed to the longitudinal length of the lesser sigmoid notch, the linear distance across the fragment was measured and added to the distance across the intact lesser sigmoid notch to determine the length of the long axis. A fracture line was counted once for each third traversed. For instance, a fracture line found in the upper and middle third of the sigmoid notch was counted as one in the upper and one in the middle. This was done to better characterize fractures not confined by our arbitrarily divided lesser sigmoid notch. It also adjusted all fracture lines with different traversing direction into a single model.

Coronoid fracture type

Coronoid process fractures were classified according to Mayo types: type 1, transverse fracture of the tip; type 2, fracture involving the anteromedial facet; or type 3, fracture involving the base of the coronoid process[8] (Figure 1).

Patterns of injury

Radiographs, 2D and 3D CT images, and surgical findings were used to classify each elbow fracture into 1 of 4 injury patterns: TT fracture-dislocation, varus posteromedial rotational instability (VPMRI) pattern, anterior olecranon fracture-dislocation, or posterior olecranon fracture-dislocation.[12] Some less common patterns were olecranon fracture with varus posteromedial instability and posterior Monteggia injury associated with TT fracture-dislocation.[1,5] Anterior and posterior olecranon fracture-dislocations were pooled into a group called olecranon fracture-dislocation (OFD) for statistical analysis because there was only 1 anterior olecranon fracturedislocation. In addition, 5 posterior Monteggia fractures with associated TT injury were pooled together with the TT pattern, and 2 olecranon fractures with varus posteromedial instability were pooled with VPMRI in 1 group for further analysis.[9]

Statistical analysis

Baseline demographic characteristics are provided as counts with frequencies and percentages and means with standard deviations. Continuous response variables, including the surface area, are reported in medians with interquartile ranges because the hypothesis of normal distribution of the data was rejected when tested using the 1-sample Kolmogorov-Smirnov test.

We used the Kruskal-Wallis test for continuous data and the Fisher exact test for categoric data to determine differences between the groups. When there was a significant difference ($P < .05$), a post hoc pairwise comparison was performed with adjustment for multiple testing by Bonferroni or the Dunnett-T3 correction, depending on the homogeneity of variances.

RESULTS

Mayo type 3 fractures were associated with more than 1 fracture line involving about 42% of the lesser sigmoid notch articular surface while Mayo types 1 and 2 were associated with 1 fracture line spreading out only in the upper one third of the lesser sigmoid notch with less than 9% of the surface area involved in fracture. The Mayo types 1 and 2 did not differ significantly in any characteristic of the involvement of the lesser sigmoid notch articular surface. However, Mayo type 3 was significantly different from Mayo types 1 and 2 in the area involved in the fracture, the number of articular fragments, and the pattern of the fracture involving the lesser sigmoid notch. Mayo types 1 and 2 were almost a 2-piece articular surface injury with a horizontal fracture line, whereas Mayo type 3 involved the articular surface with both horizontal and vertical fracture lines resulting in 3 or more fracture fragments (Table II , Figure 3).

The TT and VPMRI injury patterns had 1 fracture line involving only the upper one-third of the lesser sigmoid notch and less than 10% of the total surface area, whereas OFD extended to the dorsal third with more fracture lines and involvement of more than 30% of the lesser sigmoid notch surface area. There was no significant difference between TT and VPMRI in any characteristic of the involvement of the lesser sigmoid notch articular surface. However, OFD was significantly different from TT and VPMRI in location of the fracture line and the surface area involved in the fracture (Table III).

Of the 5 posterior Monteggia fractures with associated TT injury, 2 had a coronoid tip fracture (type 1) entering the top one-third of the lesser sigmoid notch as part of the TT injury component and an ulnar metaphyseal fracture affecting the lower one-third of the lesser

Table 2. Number of fragments, articular surface area, and fracture line location according to fracture type

	Mayo classification			
Variable*	Type 1 (n = 28)	Type 2 (n = 8)	Type 3 (n = 16)	P value
Fragments, No.	2 (2-2)	2 (2-2)	3 (2-3)	<.001
Articular surface area, mm2				
Proximal (dorsolateral) fragment	155 (123-185)	192 (132-233)	81 (43-144)	<.001
Fractured fragments	13 (5.7-33)	17 (5.3-22)	63 (32-94)	<.001
Total articular surface area, lesser sigmoid joint	171 (148-198)	207 (159-236)	155 (115-189)	0.09
Surface area involved in fracture,‡ %	7.3 (3.4-17)	8.7 (2.4-12)	42 (20-71)	<.001
Fracture line location				
Upper one-third	27 (96)	7 (88)	12 (75)	0.089
Middle one-third	5 (18)	1 (13)	11 (69)	0.002
Lower one-third	2 (7.1)	0 (0.0)	7 (44)	0.005

* Continuous data are shown as the median (interquartile range) and categoric data as number (%).
‡ Calculated as the percentage of the total articular surface area.

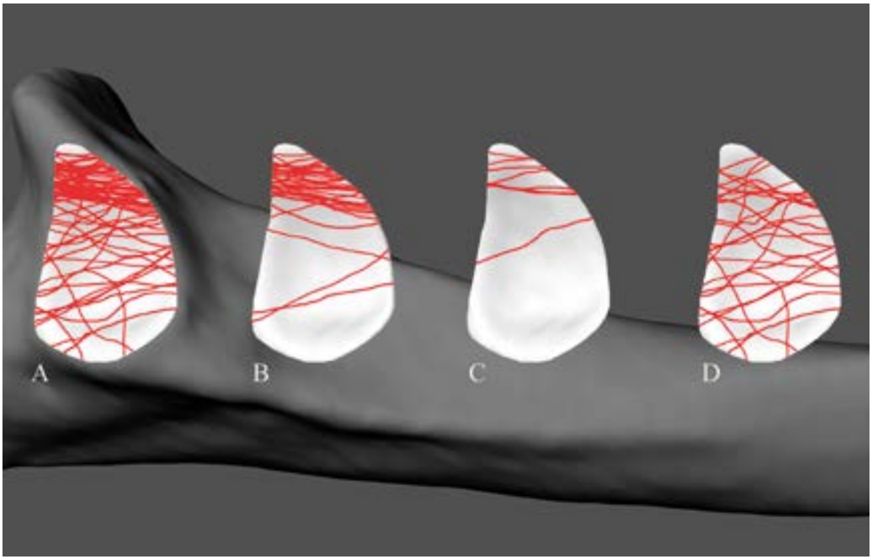

Figure 3. Sagittal view of the ulna displaying the fracture line distribution according to Mayo coronoid fractures type: (A) overall pattern, (B) type 1, (C) type 2, and (D) type 3. In the mapping of type 1, 2 had a coronoid tip fracture (type 1) entering the top one-third of the lesser sigmoid notch as part of the terrible triad injury component and an ulnar metaphyseal fracture affecting the lower one-third of the lesser sigmoid notch as part of the Monteggia injury component, which created a complex injury (posterior Monteggia/terrible triad) and a segmental fracture of the lesser sigmoid notch.

Table 3. Number of fragments, articular surface area, and fracture line location according to pattern of injury

	Injury pattern			
Variable*	TT† (n = 32)	VPMRI (n = 8)	OFD (n = 12)	P value
Fragments, No.	2 (2-2)	2 (2-2)	3 (2-3)	0.002
Articular surface area, mm2				
Proximal (dorsolateral) fragment	154 (112-185)	167 (96-228)	74 (43-144)	0.009
Fractured fragments	13 (5.7-37)	19 (11-41)	57 (29-89)	0.014
Total articular surface area, lesser sigmoid joint	179 (151-199)	185 (142-232)	138 (107-177)	0.067
Surface area involved in fracture,§ %	8.2 (3.4-19)	9.3 (5.3-30)	31 (17-71)	0.003
Fracture line location, n (%)				
Upper one-third	30 (94)	7 (88)	9 (75)	0.11
Middle one-third	8 (25)	2 (25)	7 (58)	0.12
Lower one-third	3 (9.4)	0 (0.0)	6 (50)	0.006

OFD, olecranon fracture-dislocation; TT, terrible triad; VPMRI, varus posteromedial rotational instability pattern.
* Continuous data are shown as the median (interquartile range) and categoric data as number (%).
† Includes TT fracture-dislocation and posterior Monteggia fracture with associated TT injury
§ Calculated as the percentage of the total articular surface area.

sigmoid notch as part of the Monteggia injury component, which created a complex injury (posterior Monteggia/TT) and a segmental fracture of the lesser sigmoid notch.

DISCUSSION

Our objective was to use Q3DCT to determine if coronoid process fracture type has any bearing on the fracture pattern of the lesser sigmoid notch. The Mayo type of coronoid fracture was related to the extent of articular surface involvement. Mayo type 3 generally has more complex sigmoid notch involvement.

Mayo class was associated with lesser sigmoid notch articular surface area involvement: Mayo types 1 and 2 were similar, with one horizontal fracture line and little involvement of the articular surface, whereas Mayo type 3 was significantly different, with a fracture line extending in all areas and different directions, including horizontal and vertical extension. In our data analysis, the characteristics of TT and VPMRI injuries were also similar, with little involvement of the articular surface. OFD injuries were more likely to have more than one fracture line extending in all areas of the lesser sigmoid notch in different directions.

The lesser sigmoid notch plays a role in forearm rotation.[7] Kim et al.[3] used CT scanning to study radioulnar joint articulation in forearm pronation and supination. They showed that during forearm rotation, the radial head also translates over the articular surface of the lesser sigmoid notch for a mean of 1.17 mm. Moreover, van Riet et al.[11] showed that the lesser sigmoid notch is a useful landmark for restoring radial length in radial head reconstructions after fracture dislocation of the elbow by measuring the distance from the stump of the radius to the proximal edge of the lesser sigmoid notch.

Our study had certain limitations. Patients without a CT scan with slice thickness of 0.625 to 1.25 mm were excluded, which may have affected the distribution of elbow injury patterns and coronoid fracture types but was unlikely to have affected fracture description. This study did not measure observer reliability, but we assumed that interobserver reliability was similar to that of studies with similar methods.[6] Small bony fragments (< 25 mm3) were ignored because determining articular surface area of these fragments was not feasible using our techniques.

Also, our division of the lesser sigmoid notch into 3 arbitrary regions may not be clinically significant and only suggests that different injury patterns yield fracture lines in different directions. The number of some injury patterns was too low to analyze as a separate group, and the lack of significance may represent the low power in subgroup analysis. Lastly, prior studies using the same technique have addressed radial head fractures.[3,10]

CONCLUSION

Our data suggest that coronoid fractures involved the lesser sigmoid notch. Regan-Morrey and Mayo type 3 fractures result in more complex fractures of the sigmoid notch. There is no evidence yet that fracture type, fracture alignment, and the amount of displacement in the lesser sigmoid notch has any effect on outcome and progression to osteoarthritis, but injury to this part of the coronoid might affect methods of selecting an appropriately sized radial head prosthesis.

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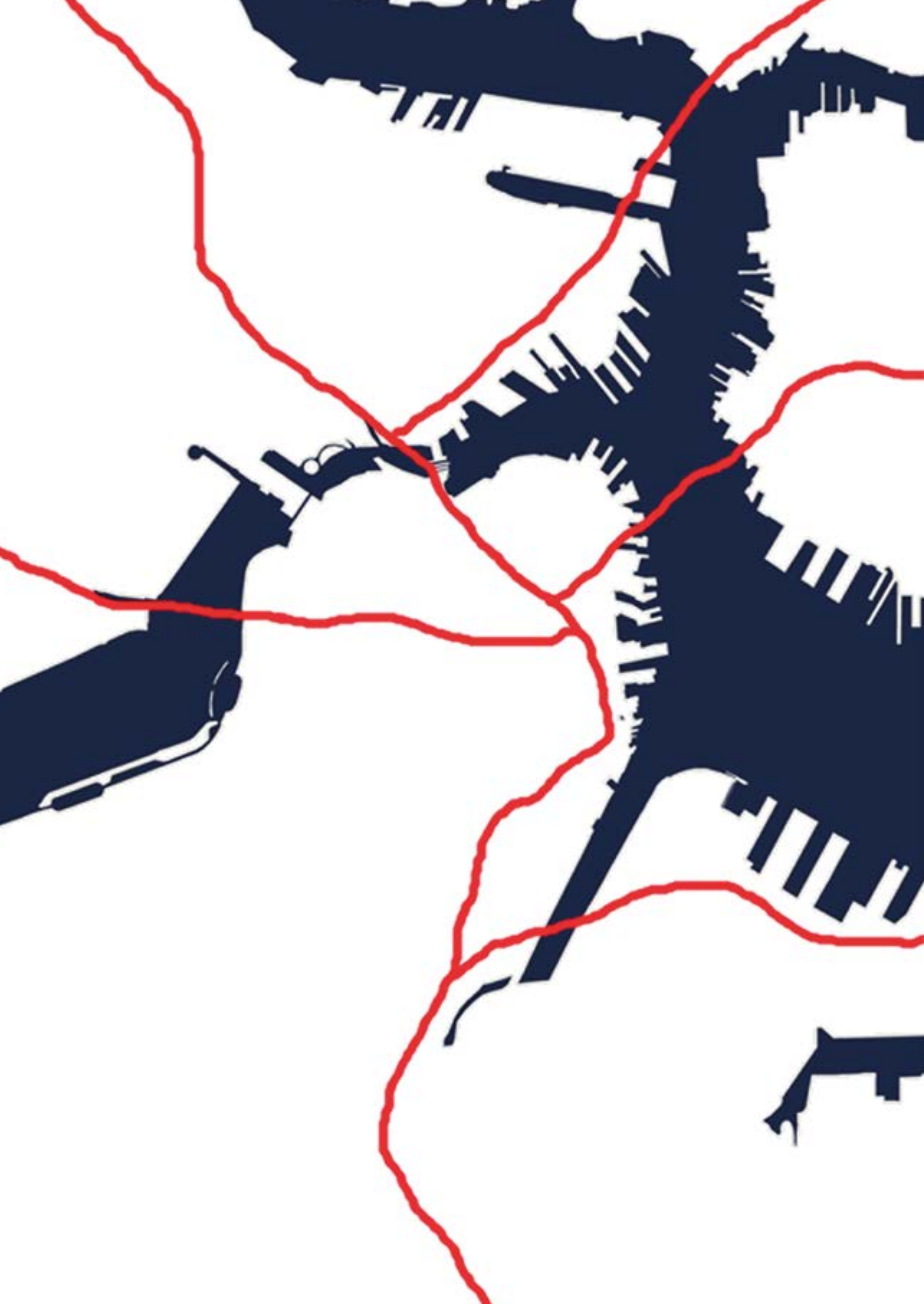

PART II
QUANTITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MEASUREMENT OF SPECIFIC FRAGMENTS AND ARTICULAR INVOLVEMENT

CHAPTER 6

Quantitative 3-Dimensional Computed Tomography Measurements of Coronoid Fractures

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42nd New England Hand Society Meeting, 4 december, 2014, Sturbridge, MA, USA.

ABSTRACT

Purpose: Using quantitative 3-dimensional computed tomography (Q3DCT) modeling, we tested the null hypothesis that there was no difference in fracture fragment volume, articular surface involvement, and number of fracture fragments between coronoid fracture types and patterns of traumatic elbow instability.

Methods: We studied 82 patients with a computed tomography scan of a coronoid fracture using Q3DCT modeling. Fracture fragments were identified and fragment volume and articular surface involvement were measured within fracture types and injury patterns. Kruskal-Wallis test was used to evaluate the Q3DCT data of the coronoid fractures.

Results: Fractures of the coronoid tip (n = 45) were less fragmented and had the smallest fragment volume and articular surface area involvement compared with anteromedial facet fractures (n = 20) and base fractures (n = 17). Anteromedial facet and base fractures were more fragmented than tip fractures, and base fractures had the largest fragment volume and articular surface area involvement compared with tip and anteromedial facet fractures. We found similar differences between fracture types described by Regan and Morrey. Furthermore, fractures associated with terrible triad fracture dislocation (n = 42) had the smallest fragment volume, and fractures associated with olecranon fracture dislocations (n = 17) had the largest fragment volume and articular surface area involvement compared with the other injury patterns.

Conclusions: Analyzing fractures of the coronoid using Q3DCT modeling demonstrated that fracture fragment characteristics differ significantly between fracture types and injury patterns. Detailed knowledge of fracture characteristics and their association with specific patterns of traumatic elbow instability may assist decision making and preoperative planning.

INTRODUCTION

Regan and Morrey [1] classified fractures by size, but the Mayo classification as described by O'Driscoll et al.[2] seems more useful because each type of coronoid fracture is associated with specific patterns of traumatic elbow instability.[3] There are associations between small transverse tip fractures and terrible triad injuries, between anteromedial facet fractures and varus posteromedial rotational instability injuries, and between larger basal fractures of the coronoid process and anterior and posterior olecranon fracture dislocations.[3-5]

Quantitative 3-dimensional computed tomography (Q3DCT) modeling technique is useful for measuring fracture fragment volume and articular surface area[6] and helps to determine articular characteristics (e.g., size, shape, articular surface area).[6-9] The Q3DCT data can provide a more detailed understanding of fracture morphology, which might guide decision making and implant development.

The purpose of this study was to analyze fractures of the coronoid using Q3DCT modeling technique. We tested the null hypothesis that (1) there was no difference in fracture fragment volume, articular surface involvement, and number of fracture fragments between different fracture types according to the Mayo classification; 2) there was no difference in fracture fragment volume, articular surface involvement, and number of fracture fragments between different fracture types according to the classification of Regan and Morrey[1]; and (3) there was no difference in fracture fragment volume, articular surface involvement, and number of fracture fragments among different injury patterns (terrible triad fracture dislocation, varus posteromedial rotational instability pattern, olecranon fracture dislocation, and posterior Monteggia injury associated with terrible triad fracture dislocation).

MATERIALS AND METHODS

Subjects

After our institutional review board approved the study, we performed a retrospective search of our billing data to identify patients with a coronoid fracture between July 2001 and January 2014 at 2 level I trauma centers. International Classification of Diseases, Ninth Revision, Clinical Modification codes (813.0x for closed fracture and 813.1x for open fracture) and Current Procedural Terminology codes (24586-24685, including elbow dislocations, Monteggia type of fractures, and radial and ulnar fractures) were used to search the billing data. We found 207 patients with coronoid fractures. Inclusion criteria were patients aged 18 years or more with an acute fracture of the coronoid and a computed tomography (CT) scan with slice thickness of 1.25 mm or less displaying the complete fracture. A total of 89 patients met the inclusion criteria. We excluded 7 patients with low-quality CT images or artifacts. There were no major differences between these patients and the 82 we included.

Quantitative 3-dimensional CT

We obtained the original Digital Imaging and Communications in Medicine files of selected CT scans through the Picture Archiving Communications System database of the 2 hospitals. All CT scans had a slide thickness between 0.625 and 1.25 mm. The Digital Imaging and Communications in Medicine files were loaded into 3D Slicer (Boston, MA), a software program used for analysis and visualization of medical images. Bony structures were manually marked on transverse, sagittal, and oblique CT slides using the PaintEffect and additional Threshold Paint option available in this program. Voxels within the predefined threshold range (225.00-1760.00 Hounsfield units) were labeled and annotated as bone. After marking all cortical bony structures, including fracture fragments, of the proximal ulna on each CT cut, we created 3-dimensional polygon mesh reconstructions (Figure 1).

The 3-dimensional mesh reconstructions were imported into Rhinoceros (McNeel, Seattle, WA) for further analyses. The volume of coronoid fracture fragments was measured using the standard volume command in Rhinoceros. Subsequently, the articular surface area was marked with a polyline on the mesh reconstructions and measured using the Area command after splitting the mesh surface with the applied polyline. To calculate the total articular surface area of the ulnohumeral joint, the articular surfaces of the fracture fragments and olecranon process were measured (Figure 2). Fragments with volumes less than 25 mm3 or no articular involvement were omitted and excluded from analyses. We used the total articular surface area of the fracture fragments and total articular surface area of the ulnohumeral joint to calculate the percentage of articular surface involvement of coronoid fractures.

To assess the interobserver reliability of measurements using 3-dimensional mesh reconstructions, 2 research fellows (J.J.M. and S.J.J.) made independent measurements of 10 reconstructions. The intra-class correlation coefficient (ICC) was substantial, with 0.97 for the articular surface area of the largest fracture fragment and 0.97 for the total articular surface area of the ulnohumeral joint. The ICC was 1.00 for the fracture fragment volume.

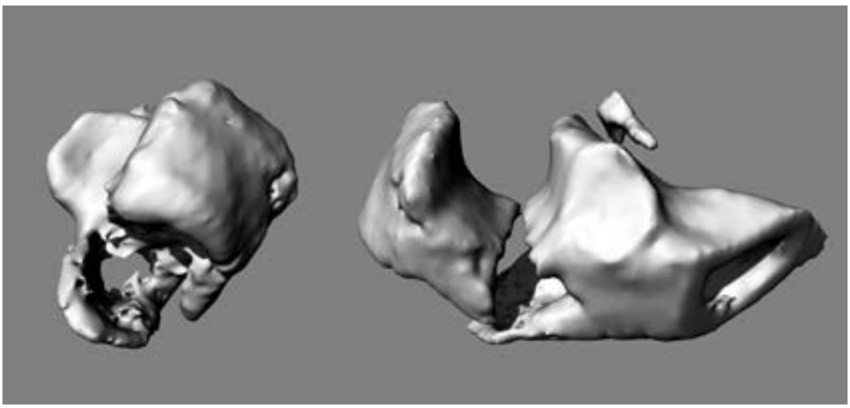

Figure 1. Three-dimensional polygon mesh reconstruction of an intra-articular posterior Monteggia injury associated with terrible triad fracture dislocation of the elbow.

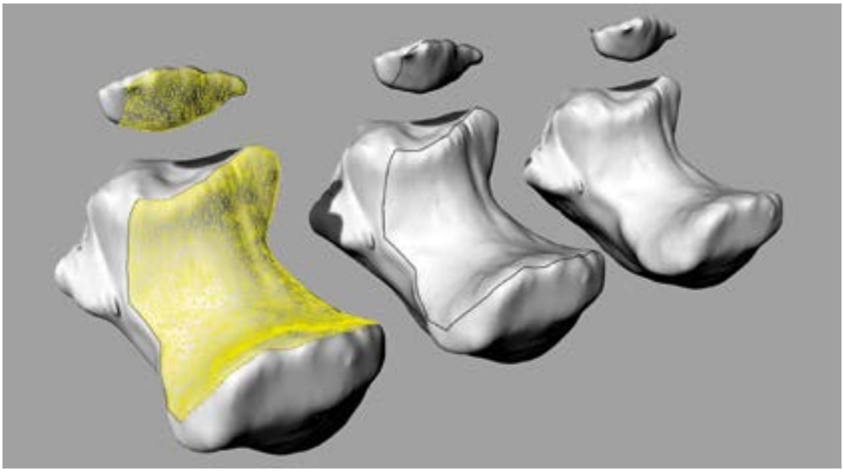

Figure 2. Series of images illustrating the method of measurement of articular surface area on 3-dimensional polygon mesh reconstructions.

Patterns of elbow fracture dislocation

Based on 2- and 3-dimensional radiographic images and surgical exposure, the injuries were classified into 1 of the 4 patterns of elbow fracture dislocation described by Doornberg and Ring[3]: (1) terrible triad fracture dislocation of the elbow, (2) varus posteromedial rotational instability pattern, (3) anterior or transolecranon fracture dislocation, and (4) posterior olecranon fracture dislocation (or type A posterior Monteggia injury according to the system described by Jupiter et al.[10]). In addition to these injury patterns, we used the pattern of elbow fracture dislocation described by Strauss et al.[11] and further evaluated by Shore et al.[12] This pattern is a posterior Monteggia injury associated with terrible triad fracture dislocation of the elbow, defined as a forearm fracture in association with posterior dislocation of the elbow with fractures of the radial head and the coronoid process.

Classification of coronoid factures

We classified coronoid fractures according to the Mayo[2] and Regan and Morrey classifications.[1]

In the Mayo classification coronoid fractures were categorized as follows: type 1, fractures of the tip of the coronoid; type 2, fractures of the anteromedial facet of the coronoid process; and type 3, fractures of the coronoid at the base. In case a fracture type was debatable, the type was rated based on the classified elbow fracture dislocation and most likely associated fracture type.

Regan and Morrey[1] classified coronoid fractures as type I, avulsion of the tip of the coronoid process; type II, a single or comminuted fragment involving more than the tip but less than 50% of the process; and type III, a single or comminuted fragment involving more than 50% of the process. Fractures were classified based on fragment size only, and associated patterns of elbow fracture dislocation were not taken into account in classifying these fractures types.

Statistical analyses

Baseline characteristics of study patients were summarized with frequencies and percentages for categorical variables and with means and standard deviations for continuous variables. We used nonparametric statistics because all response variables except one (total articular surface area ulnohumeral joint) did not meet the normality assumption as assessed with the Shapiro-Wilk test. Accordingly, the Kruskal-Wallis test was deployed to assess the differences in response variables between different injury and fracture patterns. We performed post hoc comparisons applying the Wilcoxon rank sum test for individual pairs of groups adjusted for multiple testing by Bonferroni correction.

Interobserver reliability was measured with the ICC and calculated through a 2-way mixed model with absolute agreement. Interpretation of the ICC values was carried out according to the guidelines proposed by Shrout[13] as follows: 0.00 to 0.10, virtually none; 0.11 to 0.40, slight; 0.41 to 0.60, fair; 0.61 to 0.80, moderate; and 0.81 to 1.00, substantial.

RESULTS

There were 61 men (74%) and 21 women (26%) in this study, average age 44 years (range, 18-85 y). Eighty percent of fractures were treated operatively. Half of the fractures were Mayo type 1 (tip); most were associated with terrible triad injuries (Table 1). Of the 82 fractures, 1 fit none of the common injury patterns. This was a coronoid tip fracture associated with a lateral column fracture of the distal humerus.

There was a significant difference in fracture fragment volume, articular surface involvement, and number of fracture fragments among different fracture types according to the Mayo classification (Table 2). A post hoc comparison analysis demonstrated significant differences in the median number of fracture fragments between type 1 fractures and others, in the volume of the largest fracture fragment and the total volume of fracture fragments among all fracture types, for the articular surface area of the largest fracture fragment between type 1 and type 3, and for the total articular surface area of the fracture fragments and percent articular surface involvement of the fracture among all fracture types. Similar differences in fracture fragment volume, articular surface involvement, and number of fracture fragments were found among fracture types described by Regan and Morrey[1] (Table 3).

There was also a significant difference in fracture fragment volume, articular surface involvement, and number of fracture fragments between different injury patterns (Table 4). A post hoc comparison analysis demonstrated a significant difference in the median number of fracture fragments between terrible triad and olecranon fracture dislocations; in the volume of the largest fracture fragment between olecranon fracture dislocations and all other injury patterns; in the total volume of fracture fragments between all injury patterns, except for terrible triad injuries with or without associated Monteggia injuries; in articular surface area of the largest fracture fragment between terrible triad injuries and olecranon fracture dislocations; and in the total articular surface area of the fracture fragments and percent articular surface involvement between olecranon fracture dislocations and all other injury patterns.

Table 1. Demographics (n=82)

Age in years (Mean ± SD)	44(15)
Sex, n(%)	
Men	61(74)
Women	21(26)
Side of Injury, n(%)	
Right	32(39)
Left	50(61)
Treatment, n(%)	
Surgical	66(80)
Non-Surgical	16(20)
Mayo Classification, n(%)	
Type 1	45(55)
Type 2	20(24)
Type 3	17(21)
Regan and Morrey Classification, n(%)	
Type 1	48(59)
Type 2	17(21)
Type 3	17(21)
Injury Patterns, n(%)	
Terrible-triad fracture-dislocation	36(44)
Varus posteromedial rotational instability pattern	22(27)
Olecranon fracture-dislocation	
Anterior olecranon fracture-dislocation	1(1.2)
Posterior olecranon fracture-dislocation	16(20)
Posterior Monteggia injury associated with terrible-triad fracture-dislocation	6(7.3)
Other	1(1.2)

DISCUSSION

Analyses of fractures of the coronoid using Q3DCT modeling technique demonstrated differences in fracture morphology between fracture types according to the Mayo and the Regan and Morrey [1] classifications. Fractures of the tip were less fragmented and had the smallest fragment volume and articular surface area involvement. Anteromedial facet and base fractures were more fragmented than tip fractures. Base fractures had the largest fragment volume and articular surface area involvement. Similar differences were found between fracture types described by Regan and Morrey. Comparison of the 2 classifications with Q3DCT data showed great similarities between these schemes. Furthermore, we found differences in fracture morphology between different injury types. Fractures associated with terrible triad fracture dislocations had the smallest fragment volume compared

Table 2. Volume and Articular Surface Involvement of Coronoid Fractures Types According to the Mayo Classification

	Mayo Classification			
	Type 1 (n=45)	Type 2 (n=20)	Type 3 (n=17)	P-value*
Number of fragments (median, IQR**)	1(1-2)	2(1-2)	2(1-3)	0.001
Volume in mm3 (median, IQR)				
Volume largest fragment	351(209-542)	655(479-820)	2290(1515-5726)	<0.001
Total volume fracture fragments	372(242-586)	728(571-1264)	3474(1890-6800)	<0.001
Articular surface in mm2 (median, IQR)				
Articular surface area largest fragment	74(55-101)	101(66-130)	208(179-339)	<0.001
Total articular surface area fracture fragments	86(58-103)	134(101-202)	330(266-421)	<0.001
Total articular surface area ulnohumeral joint	1085(905-1147)	1111(1040-1270)	956(885-1103)	0.14
Articular surface involvement fracture in % of total articular surface area ulnohumeral joint(median, IQR)***	8.0(5.7-10)	12(9.3-19)	35(28-43)	<0.001

*The level of significance(α) was set at 0.05
**Interquartile range (IQR)
***Calculated by dividing total articular surface area fracture fragments by total articular surface area ulnohumeral joint

with the other injury patterns. Fractures associated with olecranon fracture dislocations had the largest fragment volume and articular surface area involvement compared with the other injury patterns. Knowledge of these differences may help surgeons anticipate fracture characteristics and plan operative treatment.

The strength of this study was the relatively large number of fractures analyzed using Q3DCT modeling technique and a substantial interobserver reliability of the measuring methods. Study limitations include our exclusion of patients without a CT scan and patients with a CT scan and a slide thickness greater than 1.25 mm. This subset of patients may have had important differences from those we studied. Although this might have influenced the distribution of coronoid fracture and elbow injury patterns, we do not think that it influenced our results in terms of fracture morphology. Also, we excluded very small fragments from analyses in multi-fragmented cases. Fracture fragments with a volume of less than 25 mm3 were excluded for several reasons. For small fracture fragments it was impossible to determine whether the fragment had articular involvement, in CT scans with artifacts small fragments were hard to identify, and in comminuted fractures it was difficult to identify the donor site of fracture fragments, most especially for small fragments. This might have affected the estimates of number of fragments, the total fragment volume, and the total articular surface area to some degree. However, we believe these small fracture

Table 3. Volume and Articular Surface Involvement of Coronoid Fractures Types According to the Regan and Morrey Classification

	Regan and Morrey Classification			
	Type 1 (n=48)	Type 2 (n=17)	Type 3 (n=17)	P-value*
Number of fragments (median, IQR**)	1(1-1)	2(2-2)	2(1-3)	<0.001
Volume in mm3 (median, IQR)				
Volume largest fragment	352(211-581)	698(542-1337)	2290(1515-5726)	<0.001
Total volume fracture fragments	362(243-581)	757(667-1516)	3474(1890-6800)	<0.001
Articular surface in mm2 (median, IQR)				
Articular surface area largest fragment	72(55-99)	106(91-134)	208(179-339)	<0.001
Total articular surface area fracture fragments	82(55-102)	176(127-211)	330(266-421)	<0.001
Total articular surface area ulnohumeral joint	1084(893-1144)	1134(1046-1270)	956(885-1103)	0.07
Articular surface involvement fracture in % of total articular surface area ulnohumeral joint(median, IQR)***	7.6(5.6-9.8)	16(11-20)	35(28-43)	<0.001

*The level of significance(α) was set at 0.05
**Interquartile range (IQR)
***Calculated by dividing total articular surface area fracture fragments by total articular surface area ulnohumeral joint

fragments (< 25 mm3) were unlikely to be clinically relevant. Finally, Q3DCT technique is based on CT scan images that did not account for articular cartilage, and therefore our estimates were expected to deviate slightly from true fracture fragment volume and articular surface size.

Guitton et al.[8] used a similar Q3DCT technique to investigate the size, shape, and articular surface area of the coronoid process in healthy subjects. The volume and articular surface of the coronoid were measured after splitting 3-dimensinal mesh surface with a cutting plane at the base of the coronoid. The mean volume and articular surface of the coronoid reported by Guitton et al. were 3,059 mm3 and 378 mm2, respectively. Shin et al.[14] described similar findings and reported a mean articular surface of the coronoid process of 370 mm2, measured after marking the outline of the articular surface margin on 3- dimensional CT reconstructions of healthy subjects. According to these findings, our calculated median total articular surface area of fracture fragments of fractures at the base is almost equal to the average total surface area of the coronoid. In addition, the median total volume of fracture fragments of basal fractures measured in this study was greater than the mean total coronoid volume reported by Guitton et al.

Table 4. Volume and Articular Surface Involvement of Coronoid Fractures by Injury Pattern

	Injury Pattern				
	Terrible-triad fracture-dislocation (n=36)	Varus posteromedial rotational instability pattern (n=22)	Olecranon fracture-dislocation (n=17)	Posterior Monteggia injury associated with terrible-triad fracture-dislocation (n=6)	P-value*
Number of fragments (median, IQR)**	1(1-1.5)	1.5(1-2)	2(2-3)	1(1-2)	0.010
Volume in mm3 (median, IQR)					
Volume largest fragment	382(257-638)	604(396-803)	3825(1884-5726)	229(182-326)	<0.001
Total volume fracture fragments	424(275-638)	692(473-1191)	4913(2260-6800)	268(182-326)	<0.001
Articular surface in mm2 (median, IQR)					
Articular surface area largest fragment	83(59-106)	101(58-133)	229(101-339)	63(52-97)	0.001
Total articular surface area fracture fragments	86(64-127)	129(95-196)	345(270-422)	80(52-97)	<0.001
Total articular surface area ulnohumeral joint	1092(947-1165)	1071(883-1215)	970(885-1103)	1121(1037-1243)	0.52
Articular surface involvement fracture in % of total articular surface area ulnohumeral joint (median, IQR)* **	8.2(6.2-11)	11(8.0-19)	35(29-43)	6.8(4.6-9.1)	<0.001

*The level of significance(α) was set at 0.05.
**Interquartile range (IQR)
***Calculated by dividing total articular surface area fracture fragments by total articular surface area ulnohumeral joint

The suggestion by McKee et al.[15] that fractures of the tip are often too small for screw fixation is supported by our Q3DCT data. This is also in line with the approach suggested by Garrigues et al.[16] to use a suture lasso technique for coronoid fractures in terrible triad injuries. Ring and Doornberg[17] evaluated the management of anteromedial facet fractures and suggested sutures or buttress plating depending on the size and quality of the fracture fragments. According to our data, direct screw fixation of anteromedial facet fragments was not possible in most cases because the median volume of the largest fragment of anteromedial facet fractures was small: 655 mm3 (interquartile range, 479-820 mm3).

Adams et al.[18] described oblique anterolateral and anteromedial fractures of the coronoid after qualitative assessment of 2-dimensional CT scans obtained for elbow trauma. Oblique oriented fractures do not fit into either the Regan-Morrey or the Mayo classification, and therefore they decided to expand the Regan-Morrey classification with the oblique fractures types defined. The classifications schemes discussed are merely defined based on qualitative assessment and are most useful conceptually. Our study showed that besides qualitative assessment, quantitative analyses facilitated characterization of fracture fragments. Moreover, Q3DCT facilitated comparison between described classification schemes and helped demonstrate differences and similarities objectively.

We found that the qualitative assessment of coronoid fracture correlated with the quantitative assessment of coronoid fracture fragment volume, articular surface area, and fragmentation. The use of Q3DCT measurements after qualitative assessment of fractures should not be seen as circular, but rather as an extension and tool that helps characterize fractures. Combining qualitative and quantitative assessment may improve reliability in classification, decision making, and preoperative planning for coronoid fractures.

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CHAPTER 7

Three-Dimensional Quantitative Computed Tomography-Based (Q3DCT) Analysis of the Posteromedial Fragment in Complex Tibial Plateau Fractures: Implications for Fracture Fixation

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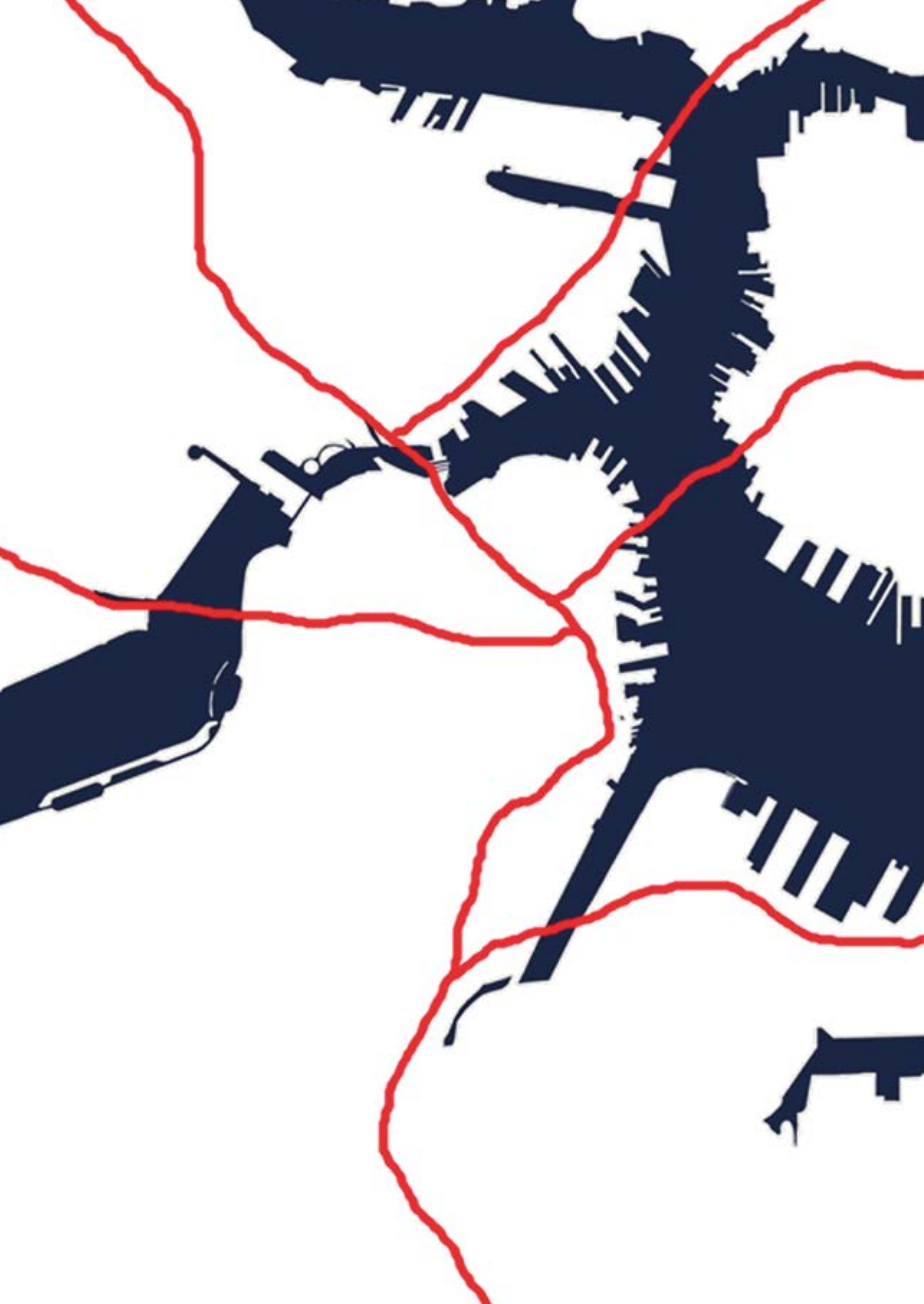

PART III
ASSESSMENT OF RELIABILITY OF FRACTURE CHARACTERISTICS: MEASUREMENT OF AGREEMENT BETWEEN SURGEONS

CHAPTER 8

Tibial Plateau Fracture Characteristics: Reliability and Diagnostic Accuracy

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In collaboration with Traumaplatform Study Collaborative & Science of Variation Group (81 Collaborators)

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ABSTRACT

Objectives: The purpose of this study was to assess the interobserver reliability and diagnostic accuracy for 2-dimensional (2D) and 3-dimensional (3D) computed tomography (CT)–based evaluation of tibial plateau fracture characteristics. We hypothesized that recognition of specific tibial plateau fracture characteristics is equally reliable and accurate in 2DCT and 2D- and 3DCT.

Methods: Eighty-one orthopedic trauma surgeons and residents were randomized to either 2DCT or 2D- and 3DCT evaluation of 15 complex tibial plateau fractures using web-based platforms to recognize 4 tibial plateau fracture characteristics: (1) a posteromedial component, (2) a lateral component, (3) a tibial tubercle component, and (4) a tibial spine (central) component. Interobserver reliability was evaluated by Siegel and Castellan's multirater kappa measure and kappa values were interpreted according to the categorical rating by Landis and Koch. Diagnostic accuracy was calculated according to standard formulas.

Results: Interobserver reliability of tibial plateau fracture characteristics ranged from "fair" to "substantial". The addition of 3DCT reconstructions did not improve agreement between observers or diagnostic accuracy, because kappa values and diagnostic accuracy were significantly better for evaluation of tibial plateau fractures using 2DCT alone. Diagnostic accuracy of fracture characteristics ranged from 70% to 89% and was better for more frequently encountered components (ie, the posteromedial and lateral component).

Conclusions: The recognition of tibial plateau fracture characteristics prove accurate and reliable on CT-based evaluation in this study and may be useful besides current classification systems, which do not account for all fracture components, in daily practice to help clinical decision making. Further research is needed to evaluate whether the use of distinct fracture components helps preoperative planning of surgical approach and specific fixation techniques.

INTRODUCTION

Experts agree that recognition of tibial plateau fracture characteristics is important to guide clinical and surgical decision making[1–7]. Commonly used classifications for tibial plateau fractures include the Arbeitsgemeinschaft für Osteosynthesefragen (AO) classification[8], the Schatzker classification[9], the Luo classification[10], and the Hohl classification [11].The reliability of these classification systems has been evaluated based on plain radiographs[12–14], computed tomography (CT)[15], and three-dimensional computed tomography (3DCT)[16–18]. These " classic" classification systems do not account for more recently recognized fracture characteristics in the axial plane [1,19,20] as they were historically based on plain radiographs. We believe that recognition of tibial plateau fracture characteristics could augment the use of fracture classification to guide surgical approach and fixation strategies.

Fracture mapping is an objective technique that enables to study fracture line location, frequency, and distribution by superimposing fracture lines, zones of comminution, and articular involvement from a large number of fractures[21–23]. For tibial plateau fractures, the Cole fracture mapping technique[22] was modified for CT-based characterization that reproduced 4 previously described fracture characteristics in 127 cases[20]: (1) a posteromedial fracture component[1,24–26], (2) a lateral fracture component[7,9], (3) a tibial tubercle component[4,5], and (4) the tibial spine (central) component[6,16]. These fracture characteristics, which are accompanied with various amount of comminution and articular impaction, are not well represented in existing two-dimensional fracture classifications[27], nor in the new Luo classification[10]. These 4 tibial plateau fracture characteristics could improve interobserver agreement in clinical studies, and may be useful besides current classification systems in daily practice to help clinical decision making[20,28]. Recognition of the posteromedial fragment, for example, is important in preoperative planning because it may require an additional posteromedial surgical approach and/or supplementary fixation methods[1–3,24–26,29]. For fracture characteristics to be useful in daily practice and for academic purposes, interobserver reliability needs to be evaluated and further research is needed to evaluate whether the identification of distinct fracture components helps guide surgical planning, approach, and specific fixation techniques.

The purpose of this study was to determine the interobserver reliability and diagnostic accuracy for the recognition of tibial plateau fracture characteristics for two-dimensional computed tomography (2DCT) and 3DCT. We tested the primary null hypothesis: (1) there is no difference in interobserver reliability between 2DCT and 2D- and 3DCT for tibial plateau fracture characteristics; and the secondary hypothesis: (2) there is no difference in diagnostic accuracy between 2DCT and 2D- and 3DCT for tibial plateau fracture characteristics with fracture mapping as the reference standard[20].

PATIENTS AND METHODS

Study Design

This study was approved by our Institutional Review Board for the use of deidentified 2D- and 3DCT scans of tibial plateau fractures. Members of the Traumaplatform Study Collaborative (http://www.traumaplatform.org) and Science of Variation Group (http://www.scienceofvariationgroup.nl), including surgeons and residents, as well as authors of studies on all peer-reviewed prospective and retrospective clinical series of tibial plateau fractures published between 2004 and 2014 and available in MEDLINE, were asked to participate in an online evaluation of tibial plateau fracture characteristics. Based on the same evaluation we assessed: (1) reliability and accuracy of tibial plateau characteristics, which is addressed in the present article, and (2) reliability of the Luo and Schatzker classification that is addressed in a separate article. All observers were approached through email and their only incentive to participate was group authorship [28,30] of the present article.

Subjects

We used Digital Imaging and Communications in Medicine (DICOM) files from our previous study[16] – evaluating the influence of CT reconstructions on the reliability of the 3 most commonly used "classic" tibial plateau fracture classification systems with selected CT scans from patients with tibia plateau fractures between 2006 and 2008 at a level III trauma center. CT scans were suitable for 3D reconstruction (slide thickness ≤1.25 mm) and demonstrated adequate quality and resolution. Based on consensus agreement of 8 senior authors regarding Schatzker Classification, a senior author of this study selected a total of 15 subjects to account for a full spectrum of complex tibial plateau fractures (Schatzker types 4–6).

The number of subjects was determined based on an appropriate balance between the expected number of observers evaluating each subject and the number of subjects [31]. With our web-based study platforms (i.e., Science of Variation Group and Traumaplatform Study Collaborative), we aim to increase the number of observers in interobserver reliability studies for maximizing power and generalizability and to allow comparison between and within subgroups. For this reason, a limited number of tibial plateau fractures were selected to decrease the burden on observers and increase participation rate (i.e., number of observers).

Observers

The observers were randomized (1:1) by computer generated random numbers (Microsoft Excel, Redmond, WA) to assess either 2DCT or 2D- and 3DCT scans.

A total of 522 participation invitations were sent, of which 261 went to the 2D group and 261 to the 2D- and 3DCT group. A total of 143 respondents started with the evaluation (completed 1 or more questions) and 81 (57%) respondents completed the evaluation. We excluded incomplete responses from analyses and therefore included these 81 responders, 42 (52%) observers in the 2DCT group and 39 (48%) in the 2D- and 3DCT group were left for further analysis. Most observers that completed the evaluation were male (95%), from Europe (57%) or United States (15%), 0– 10 years in independent practice (62%), orthopedic trauma surgeons (73%), and supervising trainees in the operating room (90%) (Table 1).

Online Evaluation

On login to the Web site, observers received a short description of the study purpose. Observers that logged in through the Science of Variation Group evaluated 2DCT scans that were converted into videos (in MPEG 4 format) and observers that logged in through the Traumaplatform evaluated 2DCT scans in a built-in DICOM viewer. All observers were able to scroll through the 2DCT scans in transverse, sagittal, and coronal planes. Three-

Table 1. Observer Demographics

	2DCT (n=42)		2D- and 3DCT (n=39)		Total (n=81)
	n	%	n	%	n
Sex					
Male	39	93	38	97	77
Female	3	7	1	3	4
Area					
United States	6	14	6	15	12
Europe	24	57	22	56	46
Asia	4	10	2	5	6
Canada	4	10	3	8	7
U.K.	1	2	2	5	3
Australia	1	2	1	3	2
Other	2	5	3	8	5
Years in independent practice					
0-5	14	33	11	28	25
6-10	10	24	15	39	25
11-20	12	29	8	21	20
21-30	6	14	5	13	11
Specialization					
General orthopaedics	6	14	7	18	13
Orthopaedic traumatology	31	74	28	72	59
Shoulder and elbow	1	2	0	0	1
Hand and wrist	0	0	1	3	1
Other	4	10	3	8	7
Supervision of trainees					
Yes	38	90	35	90	73
No	4	10	4	10	8

dimensional CT reconstructions rotated around a horizontal or vertical axis and were evaluated in a similar manner as 2DCT scans; based on created videos or using a DICOM viewer. Three-dimensional CT reconstructions were provided as presented in daily practice, for a minority of cases without subtraction of the distal femur, and observers were able to rotate in 3D.

Each observer was asked the following multiple choice questions for all selected complex tibial plateau fractures: please indicate if there is a (1) posteromedial component, (2) lateral component, (3) tibial tubercle component, and (4) tibial spine (central) component. Questions 1–4 were accompanied by figures illustrating the respective the components (Figure 1).

Statistical Analysis

A post hoc power analysis was performed as described by Guitton and Ring[32]. It was calculated for a 2-sample z-test that 81 observers provided 99% power to detect a 0.20 difference in kappa value (i.e., interobserver reliability) of the lateral component between 2DCT and 2D- and 3DCT (alfa = 0.05).

For analysis of our primary hypothesis, interobserver reliability was determined using the multirater kappa as described by Siegel and Castellan[33], which is a frequently used measure of chance-corrected agreement between multiple observers. The kappa values were interpreted according to the guidelines of Landis and Koch: a value of 0.01–0.20 indicates slight agreement; 0.21 to 0.40, fair agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and 0.81 to 0.99, almost perfect agreement. Zero indicates no agreement beyond that expected because of chance alone; –1.00, total disagreement; and 1.00, perfect agreement[34]. Kappa values were compared using the two-sample z-test and P values of <0.05 were considered significant. For a more intuitive understanding of presented data, the proportion of agreement was calculated for each fracture component (in absolute percentages, %) and defined as the proportion of observers agreeing with the most provided answer.

To test our second hypothesis, diagnostic performance characteristics (sensitivity, specificity, and accuracy) for the recognition of fracture characteristics were calculated according to standard formulas. The reference standard (disease present/absent) for fracture characteristics was based on qualitative analysis of tibial plateau fracture lines and patterns[20] using Cole' s fracture mapping techniques[21,22], which allows an objective representation of fracture lines and zones of comminution based on CT imaging. The 95% confidence intervals (95% CIs) for sensitivity, specificity, and accuracy were calculated using the formula for the standard error of a proportion, based on a binominal approximation to the normal distribution, and differences were considered significant when the CIs did not overlap[35].

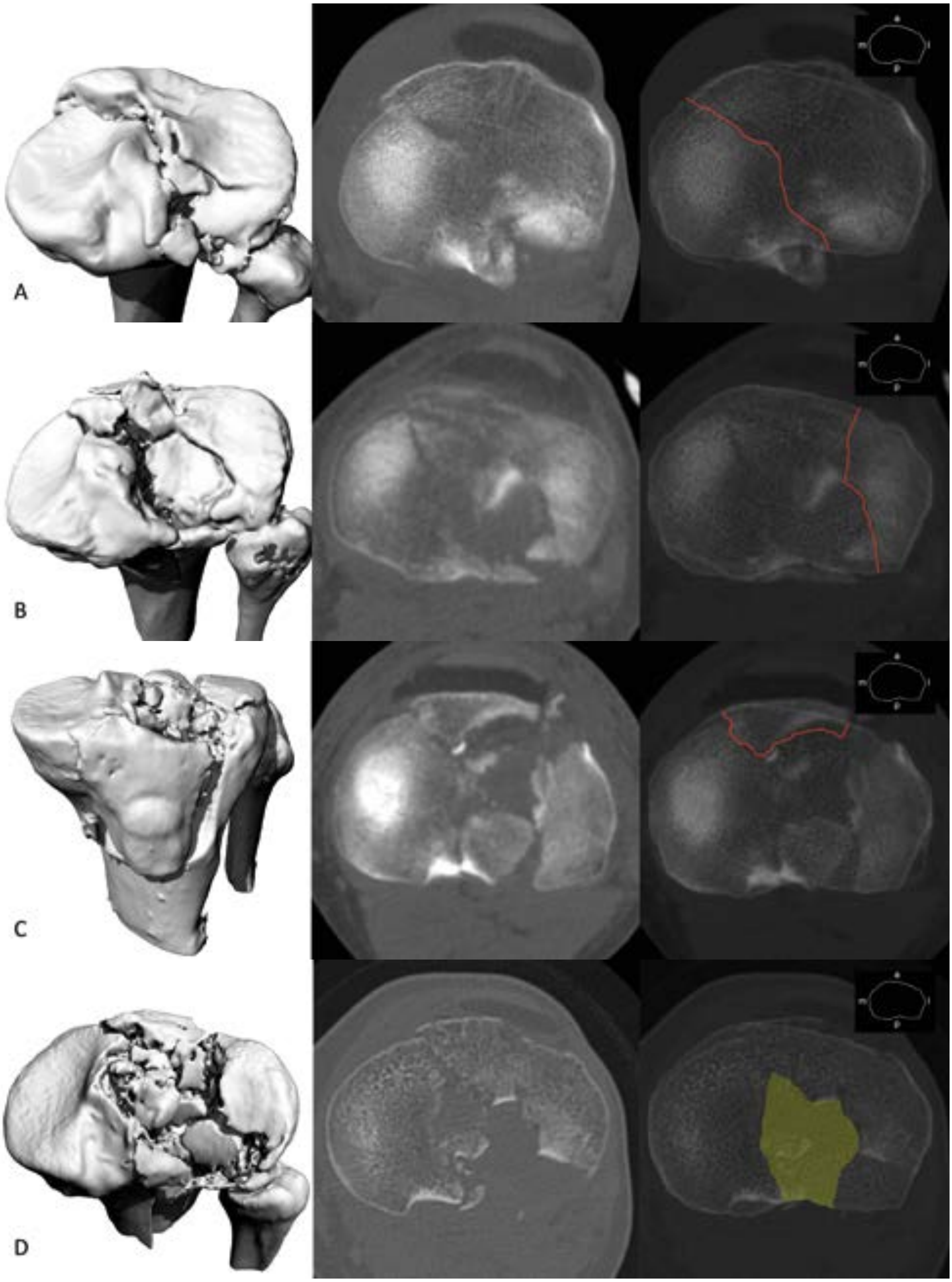

Figure 1. CT-based images, including a 3DCT reconstruction, axial 2DCT image, and fracture map, illustrating the respective tibial plateau fracture characteristics. A, The posteromedial component. B, The lateral component. C, The tibial tubercle component. D, The tibial spine (central) component.

RESULTS

Reliability of 2DCT Versus 2D- and 3DCT for Tibial Plateau Fracture Characteristics

Interobserver agreement was significantly better when observers evaluated 2DCT for recognition of all 4 respective tibial plateau fracture characteristics. Reliability for identifying (1) the posteromedial component was moderate on 2DCT (k2DCT = 0.44) versus fair on 2D- and 3DCT (k2D+3DCT = 0.27), respectively (P = 0.007); (2) the lateral component was substantial in the 2DCT group versus moderate in the 2D- and 3DCT group (k2DCT = 0.63 vs k2D+3DCT = 0.43, P < 0.001); (3) the tibial tubercle component was fair in both groups, although significantly better for 2DCT (k2DCT = 0.33 vs k2D+3DCT = 0.25, P = 0.005); and (4) the tibial spine (central) component was moderate (k2DCT = 0.53) and fair (k2D+3DCT = 0.35) on 2DCT and 2D- and 3DCT, respectively (P < 0.001) (Table 2). The average –absolute– proportion of agreement among all participating observers for identifying (1) the posteromedial component was 85% (range, 52%–98%) in the 2DCT group and 81% (range, 54%–100%) in the 2D- and 3DCT group, (2) the lateral component was 89% (range, 50%–100%) and 82% (range, 59%–100%) in the 2DCT and 2D- and 3DCT group, respectively, (3) the tibial tubercle component was 76% (range, 52%–98%) on 2DCT and 76% (range, 56%–95%) on 2D- and 3DCT, and (4) the tibial spine (central) component was 86% (range, 67%–100%) and 79% (range, 56%–95%) using 2DCT and 2D- and 3DCT, respectively (Table 3).

Diagnostic Accuracy of 2DCT Versus 2D- and 3DCT for Tibial Plateau Fracture Characteristics

Diagnostic performance characteristics for (1) posteromedial component were as follows: specificity was significantly higher for 2DCT [83% (CI95%, 80%–86%)] compared with 2D- and 3DCT [59% (CI95%, 55%–63%)], and there was no significant difference in sensitivity and accuracy between the groups; (2) lateral component were as follows: sensitivity and

Table 2. Interobserver Agreement for Fracture Characteristics by Imaging Modality

	2DCT (n=42)			2D- and 3DCT (n=39)			
	Kappa	Agreement	95% CI	Kappa	Agreement	95% CI	P Value
Fracture characteristics							
Posteromedial component	0.44	Moderate	0.36-0.52	0.27	Fair	0.17-0.37	0.007
Lateral component	0.63	Substantial	0.58-0.68	0.43	Moderate	0.38-0.48	<0.001
Tibial tubercle component	0.33	Fair	0.30-0.36	0.25	Fair	0.20-0.30	0.005
Tibial spine component	0.53	Moderate	0.51-0.55	0.35	Fair	0.33-0.37	<0.001

Table 3. Proportion of Agreement for Fracture Characteristics by Imaging Modality

	Posteromedial component				Lateral component			
	2DCT (n=42)		2D- and 3DCT (n=39)		2DCT (n=42)		2D- and 3DCT (n=39)	
Cases	Most provided answer	PA*	Most provided answer	PA	Most provided answer	PA	Most provided answer	PA
1	Present	88	Present	72	Present	93	Present	82
2	Present	91	Present	77	Present	83	Present	87
3	Absent	98	Absent	54	Absent	83	Absent	64
4	Present	69	Present	72	Absent	71	Absent	59
5	Present	95	Present	100	Present	100	Present	100
6	Absent	95	Absent	90	Absent	95	Absent	97
7	Present	81	Present	82	Absent	100	Absent	95
8	Present	98	Present	97	Present	100	Present	95
9	Present	76	Present	85	Present	98	Present	74
10	Present	55	Present	67	Present/ Absent	50	Present	59
11	Present	52	Present	67	Absent	71	Absent	77
12	Present	95	Present	95	Present	100	Present	82
13	Present	81	Present	62	Present	91	Present	85
14	Present	98	Present	100	Present	93	Present	77
15	Present	95	Present	95	Present	100	Present	97
	Tibial tubercle component				**Tibial spine component**			
	2DCT (n=42)		2D- and 3DCT (n=39)		2DCT (n=42)		2D- and 3DCT (n=39)	
Cases	Most provided answer	PA	Most provided answer	PA	Most provided answer	PA	Most provided answer	PA
1	Absent	86	Absent	92	Absent	67	Absent	77
2	Absent	60	Absent	62	Present	81	Present	80
3	Absent	69	Absent	72	Absent	81	Absent	77
4	Absent	52	Absent	56	Absent	76	Absent	72
5	Present	81	Present	59	Present	100	Present	87
6	Absent	83	Absent	77	Absent	95	Absent	82
7	Absent	95	Absent	95	Absent	86	Absent	87
8	Present	98	Present	90	Present	98	Present	95
9	Absent	55	Absent	77	Present	88	Present	67
10	Absent	83	Absent	80	Absent	81	Absent	82
11	Absent	83	Absent	87	Absent	88	Absent	82
12	Absent	60	Absent	72	Present	93	Present	72
13	Present	69	Present	62	Present	76	Present	72
14	Absent	71	Absent	74	Present	74	Present	56
15	Present	98	Present	82	Present	100	Present	92

* Proportion of agreement: the proportion of observers agreeing with the most provided answer

Table 4. Diagnostic Performance of Imaging Modalities for Fracture Characteristics

	2DCT (n=42)			2D- and 3DCT (n=39)		
	Sensitivity % (95% CI)	Specificity % (95% CI)	Accuracy % (95% CI)	Sensitivity % (95% CI)	Specificity % (95% CI)	Accuracy % (95% CI)
Fracture characteristics						
Posteromedial component	85 (82-87)	83 (80-86)*	84 (82-87)	84 (81-87)	59 (55-63)**	79 (75-82)
Lateral component	90 (87-92)*	87 (84-90)	89 (86-91)*	83 (80-86)**	81 (78-84)	82 (79-85)**
Tibial tubercle component	75 (72-79)*	71 (67-74)	73 (69-76)	63 (59-67)**	74 (71-78)	70 (66-73)
Tibial spine component	80 (77-84)	70 (67-74)	74 (70-77)	76 (72-79)	71 (67-75)	73 (69-76)

*Statistically significant compared to 2D- and 3DCT (all $P < 0.05$)
**Statistically significant compared to 2DCT (all $P < 0.05$)

accuracy were significantly higher in the 2DCT group [90% (CI95% , 87%– 92%) compared with 83% (CI95% , 80%– 86%) and 89% (CI95% , 86%– 91%) compared with 82% (CI95%, 79%– 85%), respectively], and there was no difference in specificity on 2DCT compared with 2D- and 3DCT; (3) the tibial tubercle component were as follows: sensitivity was higher in the 2DCT group (75%, CI95% , 72%– 79%) compared with the 2D- and 3DCT group (63%, CI95% , 59%– 67%), and there was no significant difference in specificity and accuracy; and (4) tibial spine (central) component were as follows: there was no difference in sensitivity, specificity, and accuracy between the evaluation on 2DCT and 2D- and 3DCT (Table 4).

DISCUSSION

Experts suggest that recognition of tibial plateau fracture characteristics is important for guiding clinical and surgical decision making[1–7]. The purpose of this study was to evaluate the interobserver reliability and diagnostic accuracy for the recognition of these tibial plateau fracture characteristics. This study showed that interobserver reliability ranged from "fair" to "substantial" for CT-based evaluation of tibial plateau fracture characteristics. Moreover, our findings support our current belief that the addition of 3DCT reconstructions does not improve reliability and diagnostic accuracy for recognition of specific fracture characteristics. In other words, orthopedic surgeons agree fair to substantial on identification of tibial plateau fracture characteristics[20], and thus in the accurate description of complex tibial plateau fractures using these 4 respective components—suggesting a reliable augmentation of currently used classification systems.

This study should be interpreted in the light of its limitations: (1) for practical purposes, we chose to limit this article to report evaluation of "contemporary" fracture characteristics only, as reliability of "classic" classification systems (i.e., those of AO, Hohl, and Schatzker) have been extensively studied[12–17]; (2) comparison of "classic" tibial plateau fracture classification versus "contemporary" fracture characteristics was not the purpose of this study because we believe that recognition of specific tibial plateau fracture characteristics, which are accompanied with various amount of comminution and articular impaction, could augment –rather than replace– the use of fracture classification to guide surgical approach and fixation strategies[28]; (3) online evaluation of CT scans was based on either converted videos or built-in DICOM viewer. Interestingly, the agreement was higher based on videos compared with DICOM viewer for some but not all fracture characteristics, and we will discuss its potential differences in a separate study[36]. Most importantly, randomization within the video (i.e., Science of Variation Group) and DICOM (ie, Traumaplatform Study Collaborative) group guaranteed well-balanced groups and therefore it is unlikely that this would have influenced our results; (4) operative treatment strategies were not part of this interobserver study; and (5) we decided not to test intraobserver reliability. We included interobserver agreement only, as interobserver agreement is the broadest and most clinically useful measure of reliability in case disagreement between observers (i.e., surgeons) is highly relevant[37]. Furthermore, we have limited our assessment to 1 evaluation because we want to limit burden on members of our collaborative to ensure high participation rates.

Strengths include: (1) a large series of observers, which allowed randomization and subgroup analysis; (2) online evaluation platform that allow techniques, which facilitate window-leveling and other features that represent clinical practice; (3) optimized case mix to account for the Kappa Paradox[38,39]; (4) selection of these complex tibial plateau fractures was based on consensus agreement of 8 senior authors regarding Schatzker classification[16]; and (5) evaluation of diagnostic performance characteristics for tibial plateau fracture characteristics using an objective reference standard[21,22].

3DCT reconstructions sometimes improve interobserver reliability and diagnostic accuracy at other anatomic areas, but not always[28,32,40–42]. Bruinsma et al.[28] studied the interobserver reliability of the classification and characterization of proximal humerus fractures among 107 observers that evaluated 15 fractures and found that observers randomized to the 2DCT group had slightly but significantly better agreement on displacement of the greater tuberosity and on the AO classification for proximal humerus fractures compared with the 3DCT group. They argue that surgeons who are used to looking at radiographs and 2DCT scans not benefit from the more intuitive 3D reconstructions. In this study of tibial plateau fractures, the 2DCT group had higher reliability and diagnostic accuracy for the recognition of specific fracture characteristics compared with the 3DCT group. This suggests that observers might be distracted by or less familiar with the 3D images, which may indicate that observers rely heavily on 2DCT and do not have similar body of experience with 3DCT. Moreover, instead of decreasing interobserver variability, 3DCT could have been a source of variation in case findings on 3D reconstructions were not consistent with plain CT images. Other studies evaluated the use of 3DCT images for tibial plateau fractures. Hu et al.[17] presented radiographs and 2DCT or 3DCT scans of 21 cases that were evaluated by 4 observers and reported improved kappa values for the AO (k_{2DCT} = 0.71 and k_{3DCT} = 0.83) and Schatzker classification systems (k_{2DCT} = 0.74 and k_{3DCT} = 0.85) based on 3DCT; however, the authors did not perform any statistical analyses to signify these differences. A similar study by our group[16], in which radiographs and 2DCT or 2D- and 3DCT scans of 45 cases were evaluated by 6 observers, did not show an additional value of 3DCT after 2DCT because moderate to substantial kappa values did not significantly improve (k2DCT range, 0.54 to 0.79 and k3DCT ranged, 0.55– 0.75).

Observers in this study had substantial to fair agreement on recognition of tibial plateau fracture characteristics, with interobserver agreement again significantly better when observers evaluated only 2DCT. Accuracy of 2DCT ranged from 73% (tibial tubercle component), through 74% (tibial spine component) and 84% (posteromedial component), to 89% for identifying the lateral component suggesting that recognition of the more commonly encountered tibial plateau fractures characteristics is most accurate. To the best of our knowledge, this is the first study to evaluate diagnostic accuracy for tibial plateau fracture characteristics. McEnery et al.[43] did evaluate accuracy of CT to detect depression of tibial plateau fractures, but did not study accuracy for any of the other fracture characteristics.

In our previous study[20], we suggested that describing fractures according to fracture characteristics together with the amount of comminution and articular impaction might augment the use of fracture classifications, because the " classic" Schatzker classification does not account for fractures involving the sagittal plane and the recent Luo classification is limited because it does not account for tibial spine and tibial tubercle fractures specifically[4–6,16]. Considering that tibial plateau fracture characteristics prove accurate and reliable in this study, we encourage its use in daily practice.

In conclusion, recognition of tibial plateau fracture characteristics demonstrated moderate reliability and accuracy on CT-based evaluation on average. Furthermore, the addition of 3DCT to 2DCT did not improve interobserver reliability or diagnostic accuracy for the evaluation of tibial plateau fracture characteristics. Further clinical studies are needed to evaluate if the recognition of tibial plateau fracture components (1) facilitates surgical decision making, (2) predicts clinical outcome; and (3) facilitates comparison of clinical studies from different institutions and investigators[44].

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CHAPTER 9

Interobserver Reliability of the Schatzker and Luo Classification Systems for Tibial Plateau Fractures

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ABSTRACT

Introduction: Tibial plateau fracture classification systems have limited interobserver reliability and new systems emerge. The purpose of this study was to compare the reliability of the Luo classification and the Schatzker classification for two-dimensional computed tomography (2DCT) and to study the effect of adding three-dimensional computed tomography (3DCT).

Materials and Methods: Eighty-one observers, orthopedic surgeons and residents, were randomized to either 2DCT or 2D- and 3DCT evaluation of a spectrum of 15 complex tibial plateau fractures using web- based platforms in order to classify according to the Schatzker and according to Luo's Three Column classification. Reliability was calculated with the use of Siegel and Castellan's multirater kappa measure. Kappa values (k) were interpreted according to the categorical rating by Landis and Koch.

Results: Overall interobserver reliability of the Schatzker classification was significantly better compared to the Luo classification (kSchatzker = 0.32 and kLuo = 0.28, P = 0.021), however, 'fair' for both fracture classification systems. For the Schatzker classification observers agreed significantly better on 2DCT compared to 2D- and 3DCT (k2DCT = 0.37 and k2D+3DCT = 0.29, P < 0.001). The addition of 3DCT did not improve the overall interobserver reliability for the Luo classification as well, as kappa values were not significantly different on 2DCT and 2D- and 3DCT (k2DCT = 0.31 and k2D+3DCT = 0.25, P = 0.096).

Conclusions: The agreement between observers was significantly better for the Schatzker classification compared to Luo's Three Column classification, however agreement was fair for both classification systems. Furthermore, the addition of 3DCT reconstructions did not improve the reliability of CT-based evaluation of tibial plateau fractures. Considering that new classification systems and 3DCT do not seem to improve agreement between surgeons, other efforts are needed that lead to more reliable diagnosis of complex tibial plateau fractures.

INTRODUCTION

The AO classification [1], the Schatzker classification [2], and the Hohl classification [3] for tibia plateau fractures do not account for recently recognized fracture characteristics [4–13]. New classification systems have since emerged. In 2010, Luo et al. [14] published the 'three-column classification' based on fractures in the sagittal and coronal plane. This classification divides the tibial plateau in lateral, medial and posterior columns in order to improve surgical decision-making [14,15]. Tibial plateau fracture classifications ideally guide surgical approach and fixation strategies in daily practice [16]. The Luo classification does not include all major fracture characteristics [4–13]. For example, fractures involving the tibial spine and tubercle [13] do not fit in the 'star-shaped' three columns as described by Luo.

Fracture classification systems help orthopedic surgeons to characterize fractures, determine prognosis, plan treatment, and report and compare study results. For classifications to be useful in these domains they need to be reliable as well as accurate [17]. The reliability of commonly used tibial plateau fracture classifi- cation systems have been studied using different imaging modalities [16,18–22]. Studies that assessed the reliability of Luo's computed tomography (CT)-based classification system demonstrated higher reliability compared to the AP based Schatzker classification, however with unknown statistical- and clinical significance [15,23,24]. The results of these studies are debatable in terms of limited methodology and need confirmation by other groups because of potential bias by including only the authors as observers that coined this Three-Column classification, as well as unsatisfactory data analysis, and suboptimal study design.

The purpose of this study was to determine the reliability of the Schatzker classification and the Luo classification among a large number of surgeons on two-dimensional CT (2DCT) and to study the effect of adding three-dimensional CT (3DCT). We tested the null hypothesis that 1) there is no difference in interobserver reliability between the Luo- and the Schatzker tibial plateau fracture classification, and 2) that there is no difference in interobserver reliability between 2DCT and 2D and 3DCT based evaluation for tibial plateau fracture classification systems.

MATERIALS AND METHODS

Study design

Members of the Traumaplatform Study Collaborative (http://www.traumaplatform.org) and the Science of Variation Group (http://www.scienceofvariationgroup.nl) as well as authors of studies including tibial plateau fractures, published between 2004 and 2014 that were identified via MEDLINE, were invited to participate in an online evaluation of tibial plateau fractures [2,14] in order to answer two primary study questions addressed in two separate papers: (1) reliability and accuracy of CT-based recognition of tibial plateau characteristics and (2) reliability of the Luo- and Schatzker classification which is addressed in the present manuscript. All observers were approached via email and the only incentive to participate was group authorship [25–27]. Our institutional review board approved the use of anonymized 2D- and 3DCT scans of tibia plateau fractures.

Subjects

Digital Imaging and Communication in Medicine (DICOM) files from our previous study in this Journal [16], including CT scans from patients with tibial plateau fractures between 2006– 2008 at a level III trauma center, were obtained to identify complex tibial plateau fractures (Schatzker 4–6). Computed tomography scans demonstrated sufficient quality and resolution for 3D reconstruction (slide thickness ≤ 1.25 mm). Based on consensus agreement between the senior authors on the Schatzker classification, a total of 15 subjects were selected to account for a full spectrum of CT scans demonstrating complex tibial plateau fractures. Complex fractures were selected as complexity is a source of variation, which is the substance of interobserver reliability studies.

Observers

The members of the Traumaplatform Collaborative and Science of Variation Group as well as authors of tibial plateau fracture related papers were randomized (1:1) to assess either 2DCT or 2D- and 3DCT scans, using computer-generated random numbers (Microsoft Excel, Redmond, WA, USA).

A total of 522 participation emails were sent, of which 261 to the 2DCT group and 261 to the 2D- and 3DCT group. One hundred forty-three respondents started with the evaluation (i.e., completed one or more questions) and 81 (57%) respondents completed the evaluation. Incomplete responses were excluded from analyses and therefore 81 responders were included, 42 (52%) observers in the 2DCT group and 39 (48%) in the 2D- and 3DCT group. Observers were predominately from Europe (57%) and the United States (15%). Other observes were from Canada (8.6%), Asia (7.4%), United Kingdom (3.7), and Australia (2.4%) (Table 1).

Online evaluation

Observers were provided a short description of the study aim after logon to the website. Via the Science of Variation Group observers evaluated 2DCT scans that were converted into videos (in MPEG 4 format) and via the Traumaplatform observers evaluated 2DCT scans in a built-in DICOM viewer. Each observer was able to evaluate 2DCT scans in transverse, sagittal and coronal planes. For observers that were randomized into the 2D- and 3DCT group, 3DCT reconstructions that rotated around a horizontal or vertical axis were available in the video or DICOM set-up.

All observers were asked to classify (1) according to the Schatzker classification [2], and (2) according to the Luo classification [14]. In order to clarify these classifications, hyperlinks were used that directed to the original studies that described the respective classification systems [2,14].

Statistical analysis

Power was calculated post-hoc as described by Guitton and Ring [28]. Including fifteen cases evaluated by 81 observers yielded 100% power to detect a clinical relevant difference between the groups defined as a difference of one categorical rating according to Landis and Koch (Δ kLuo - kSchatzker = 0.20) with $\alpha = 0.05$. In addition, it was determined that

Table 1. Observer Demographics

	2DCT (n=42)	2D- and 3DCT (n=39)	Total (n=81)
Sex, n (%)			
Male	39 (93)	38 (97)	77 (95)
Female	3 (7.1)	1 (2.6)	4 (4.9)
Area, n (%)			
United States	6 (14)	6 (15)	12 (15)
Europe	24 (57)	22 (56)	46 (57)
Asia	4 (9.5)	2 (5.1)	6 (7.4)
Canada	4 (9.5)	3 (7.7)	7 (8.6)
U.K.	1 (2.4)	2 (5.1)	3 (3.7)
Australia	1 (2.4)	1 (2.6)	2 (2.4)
Other	2 (4.8)	3 (7.7)	5 (6.2)
Years in independent practice, n (%)			
0-5	14 (33)	11 (28)	25 (31)
6-10	10 (24)	15 (39)	25 (31)
11-20	12 (29)	8 (21)	20 (25)
21-30	6 (14)	5 (13)	11 (14)
Specialization, n (%)			
General orthopaedics	6 (14)	7 (18)	13 (16)
Orthopaedic traumatology	31 (74)	28 (72)	59 (73)
Shoulder and elbow	1 (2.4)	-	1 (1.2)
Hand and wrist	-	1 (2.6)	1 (1.2)
Other	4 (9.5)	3 (7.7)	7 (8.6)
Supervision of trainees, n (%)			
Yes	38 (91)	35 (90)	73 (90)
No	4 (9.5)	4 (10)	8 (9.8)

81 observers provided 32% power to detect a 0.04 difference (effect size = 0.33) in kappa value (i.e., interobserver reliability) between the Schatzker classification and the Luo classification ($\alpha = 0.05$) using a two-sample z-test.

Interobserver reliability was calculated with the use of the multirater kappa as described by Siegel and Castellan [29]. The kappa statistic is a frequently used measure of chance-corrected agreement between observers. The kappa values were interpreted according to the guidelines of Landis and Koch: a value of 0.01 to 0.20 indicates slight agreement; 0.21 to 0.40, fair agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and 0.81 to 0.99, almost perfect agreement;–1.00, total disagreement; and 1.00, perfect agreement[30]. Kappa values were compared using the two-sample z-test and P values of <0.05 were considered significant. For a better understanding of presented kappa values, the proportion of agreement was calculated for each case (in absolute percentages, %) and defined as the proportion of observers agreeing with the most provided answer.

RESULTS

Reliability of the Schatzker and Luo classification

The overall interobserver reliability of the Schatzker classification was–significantly–better compared to the Luo classification (kSchatzker = 0.32 and kLuo = 0.28; P = 0.021), however, the agreement was fair in both groups and the difference was small making the clinical relevance debatable (Table 2). The overall average– absolute–proportion of agreement was 65% (range, 46% to 95%) for the Schatzker classification and 63% (range, 33%–100%) for the Luo classification (Table 3).

Reliability of 2DCT and 2D- and 3DCT for the Schatzker and Luo Classification

Reliability of the Schatzker classification was fair in both groups, however observers agreed significantly better upon evaluating 2DCT scans (k2DCT = 0.37 and k2D+3DCT = 0.29, P < 0.001) (Table 4). The overall average–absolute–proportion of agreement for the Schatzker classification was 68% (range, 50% to 95%) in the 2DCT group and 61% (range, 36% to 95%) in the 2D- and 3DCT group (Table 5). Reliability of the Luo classification was the same on 2DCT and 2D- and 3DCT (k2DCT = 0.31 and k2D+3DCT = 0.25, respectively; P = 0.096) and fair in both groups according to Landis and Koch categorical rating (Table 4). The overall average–absolute–proportion of agreement for the Luo classification was 67% (range, 31% to 100%) in the 2DCT group and 60% (range, 33% to 100%) in the 2D-and 3DCT group (Table 5).

DISCUSSION

The Three-Column axial CT-based classification system by Luo and colleagues [14] intent to improve clinical and surgical decision-making and to improve reliability compared to the 'classic' AP based Schatzker classification. Data regarding the interobserver agreement for this Three-Column classification has not been satisfactory to date [15,23,24]. The purpose of this study was to evaluate the reliability of the Luo classification compared to the Schatzker tibial plateau fracture classification based on 2DCT evaluation and to determine the influence of imaging modalities on the interobserver agreement for tibial plateau fracture classification systems. This study showed that interobserver reliability of the Schatzker classification was significantly better compared to the Luo classification. Furthermore, 3DCT reconstructions did not improve reliability as agreement was higher on 2DCT than 2D- and 3DCT for the Schatzker and Luo tibial plateau fracture classification systems.

There were several limitations in this study: (1) for practical purposes we chose to limit this study to the mostly used classifications system [2] and a new system [14]–as reliability of the most commonly used classification systems for tibial plateau fractures (i.e. AO-, Hohl, Schatzker- systems) have been extensively studied [16,18–22,31] and comparison of all 'classic' tibial plateau fracture classification systems was not the purpose of this study and has been previously evaluated [16,18–22,31]; (2) the online evaluation

Table 2. Interobserver Agreement of the Schatzker and Luo's Three-Column Classification (n=81)

	Schatzker Classification			Luo's Three-Column Classification			
	Kappa	Agreement	95% CI	Kappa	Agreement	95% CI	P Value
Overall	0.32	Fair	0.31-0.34	0.28	Fair	0.25-0.31	0.021
Area							
United States	0.29	Fair	0.23-0.34	0.25	Fair	0.18-0.31	0.38
Europe	0.33	Fair	0.31-0.35	0.30	Fair	0.25-0.35	0.30
Other	0.34	Fair	0.31-0.37	0.27	Fair	0.20-0.34	0.069
Years in independent practice							
0-10	0.35	Fair	0.33-0.37	0.30	Fair	0.25-0.35	0.058
More than 10	0.28	Fair	0.25-0.30	0.25	Fair	0.21-0.30	0.38
Specialization							
General orthopaedics	0.32	Fair	0.27-0.37	0.32	Fair	0.23-0.42	0.98
Orthopaedic traumatology	0.33	Fair	0.31-0.35	0.28	Fair	0.24-0.31	0.015
Other	0.28	Fair	0.21-0.34	0.22	Fair	0.07-0.37	0.87

Table 3. Overall Proportion of Agreement for the Schatzker and Luo's Three-Column classification (n=81)

	Schatzker classification		Luo's Three-Column classification	
Cases	Most provided answer	PA *	Most provided answer	PA
1	Type 5	48	Two-column (lateral and posterior) fracture	42
2	Type 5	73	Three-column fracture	75
3	Type 4	46	One-column (medial column) fracture	49
4	Type 4	49	Three-column fracture	37
5	Type 6	54	Three-column fracture	96
6	Type 4	73	One-column (medial column) fracture	79
7	Type 4	78	Two-column (medial and posterior) fracture	38
8	Type 6	78	Three-column fracture	100
9	Type 5	49	Three-column fracture	51
10	Type 5	62	Three-column fracture	52
11	Type 6	51	Three-column fracture	33
12	Type 5	64	Three-column fracture	73
13	Type 6	87	Three-column fracture	72
14	Type 5	63	Three-column fracture	53
15	Type 6	95	Three-column fracture	98

* Proportion of agreement: the proportion of observers agreeing with the most provided answer

Table 4. Interobserver Agreement for the Schatzker and Luo's Three-Column Classification by Imaging Modality

	2DCT (n=42)			2D- and 3DCT (n=39)			
	Kappa	Agreement	95% CI	Kappa	Agreement	95% CI	P Value
Schatzker classification							
Overall	0.37	Fair	0.35-0.39	0.29	Fair	0.26-0.31	<0.001
Area							
United States	0.43	Moderate	0.33-0.53	0.15	Slight	0.06-0.24	<0.001
Europe	0.41	Moderate	0.38-0.44	0.27	Fair	0.24-0.30	<0.001
Other	0.29	Fair	0.24-0.34	0.43	Moderate	0.37-0.48	<0.001
Years in independent practice							
0-10	0.38	Fair	0.35-0.41	0.33	Fair	0.30-0.36	0.024
More than 10	0.35	Fair	0.31-0.38	0.21	Fair	0.17-0.26	<0.001
Specialization							
General orthopaedics	0.42	Moderate	0.32-0.51	0.29	Fair	0.22-0.37	0.044
Orthopaedic traumatology	0.36	Fair	0.33-0.39	0.30	Fair	0.27-0.33	0.002
Other	0.46	Moderate	0.33-0.58	0.23	Fair	0.10-0.35	0.011
Luo's Three-Column classification							
Overall	0.31	Fair	0.26-0.36	0.25	Fair	0.21-0.30	0.096
Area							
United States	0.26	Fair	0.16-0.37	0.20	Slight	0.09-0.31	0.40
Europe	0.36	Fair	0.28-0.44	0.26	Fair	0.19-0.33	0.059
Other	0.26	Fair	0.17-0.35	0.29	Fair	0.20-0.38	0.69
Years in independent practice							
0-10	0.34	Fair	0.26-0.42	0.28	Fair	0.21-0.34	0.21
More than 10	0.29	Fair	0.23-0.36	0.21	Fair	0.14-0.28	0.079
Specialization							
General orthopaedics	0.39	Fair	0.24-0.53	0.28	Fair	0.14-0.42	0.29
Orthopaedic traumatology	0.30	Fair	0.24-0.36	0.26	Fair	0.21-0.31	0.29
Other	0.37	Fair	0.10-0.63	0.12	Slight	-0.07-0.31	0.14

Table 5. Proportion of Agreement for the Schatzker and Luo's Three-Column classification by Imaging Modality

Schatzker classification				
	2DCT (n=42)		2D- and 3DCT (n=39)	
Cases	Most provided answer	PA *	Most provided answer	PA
1	Type 5	52	Type 5	44
2	Type 5	79	Type 5	67
3	Type 4	55	Type 4	36
4	Type 4	50	Type 4	49
5	Type 6	62	Type 5	49
6	Type 4	76	Type 4	69
7	Type 4	86	Type 4	69
8	Type 6	83	Type 6	72
9	Type 5	55	Type 5	44
10	Type 5	57	Type 5	67
11	Type 6	57	Type 6	44
12	Type 5	64	Type 5	64
13	Type 6	91	Type 6	82
14	Type 5	62	Type 5	64
15	Type 6	95	Type 6	95

Luo's Three-Column classification				
	2DCT (n=42)		2D- and 3DCT (n=39)	
Cases	Most provided answer	PA	Most provided answer	PA
1	Two-column (lateral and posterior)	41	Two-column (lateral and posterior)	44
2	Three-column	79	Three-column	72
3	One-column (medial)	64	One-column (medial)	33
4	One-column (medial)	36	Three-column	39
5	Three-column	98	Three-column	95
6	One-column (medial)	83	One-column (medial)	74
7	Two-column (medial and posterior)	43	Two-column (medial and posterior)	33
8	Three-column	100	Three-column	100
9	Three-column	64	Three-column	36
10	Three-column	50	Three-column	54
11	Two-column (medial and posterior)	31	Three-column	36
12	Three-column	79	Three-column	67
13	Three-column	71	Three-column	72
14	Three-column	60	Three-column	46
15	Three-column	100	Three-column	95

* Proportion of agreement: the proportion of observers agreeing with the most provided answer

of 2D- and 3DCT scans was based on either converted videos or built-in DICOM viewer, however, randomization within the video (i.e., Science of Variation Group) and DICOM viewer (i.e., Traumaplatform Study Collaborative) group guaranteed well-balanced groups and therefore it is unlikely that this would have influenced our results; and (3) although the Schatzker classification was initially based on AP radiographs, radiographs were not included in the evaluation of tibial plateau fractures as we were interested in CT-based assessment of tibial plateau fractures only. One may argue whether or not the Schatzker classification can be used for assessing tibial plateau fractures based on CT images, however, this is beyond the scope of our study. Strengths includes: (1) a large series of observers allowed randomization and subgroup analysis; (2) innovative web-based techniques facilitated window-leveling and other features that represents clinical practice; (3) cases were selected from a large consecutive series patients with tibial plateau fractures in order to optimize casemix and answer distribution to account for the Kappa Paradox [32,33]; and (4) selection of these cases was based on consensus agreement of multiple senior authors regarding the Schatzker classification [16].

The interobserver reliability for the Luo classification has been previously assessed by authors from the same institution that coined this classification. Zhu and colleagues [15,23] presented radiographs and CT scans of 50 patients with tibial plateau fractures to 4 observers and found better interobserver agreement for the Luo classification (kLuo = 0.77) as compared to the Schatzker classification (kSchatzker = 0.57). The authors did not included a two-sample z-test to account for statistical significance in their study, although a difference of one categorical rating according to Landis and Koch (Δ kLuo - kSchatzker = 0.20) seems clinically relevant. Pantage Subba Rao and colleagues [24] evaluated the reliability of the Luo classification versus the Schatzker classification by presenting radiographs, 2D- and 3DCT of 52 patients with tibial plateau fractures to 5 observers and reported a better interobserver agreement for the Luo classification (kLuo = 0.72 on 2DCT and kLuo = 0.87 on 2D- and 3DCT) compared to the Schatzker classification (kSchatzker = 0.54 on 2DCT and kSchatzker = 0.55 on 2D- and 3DCT) as well. Again, these studies do not provide satisfactory data due to potential bias by the authors that described this Three-Column classification, unsatisfactory data analysis, and suboptimal statistical approach limiting generalizability of results to daily clinical practice.

Using a different methodology (i.e., large number of observers from multiple countries with different training backgrounds evaluating a sufficient amount of cases using innovative web-based techniques), performed by our independent research group, which follows the GRRAS guidelines for reliability studies [34], we could not support previously reported findings that the interobserver agreement for the Luo classification is better than the Schatzker classification.

Furthermore, interobserver reliability for the Schatzker classification and Luo classification systems as reported in this study are worse than previously reported [16,21,22,31]. The relatively low agreement between observers in our study may be explained by our very large (i.e., 81 observers) and heterogeneous group of observers treating complex tibial plateau fractures in multiple countries with different training backgrounds [25–28,35–39]. It has been shown that such groups are more likely to disagree. Except for fair agreement among observers, our findings were consistent with our previous study surveying 6 observers from a single institution in that 3DCT did not show any significant benefit as compared to the use of 2DCT alone [16]. Three-dimensional CT reconstructions did not increase the reliability as adding 3DCT reconstructions might have increased complexity and observers might have been distracted by or not familiar with the 3DCT images, indicating that observers rely more on 2DCT than 3DCT for the characterization of tibial plateau fractures, which is consistent with a recent study that showed that the addition of 3DCT did not change management plans when compared to 2DCT [40]. Furthermore, classification systems may be too complex and therefore unreliable, despite advanced imaging. Although 3DCT intuitively adds to our understanding of complex fractures, from an academic point of view we have to realize that reliability studies fail to show substantial and significant differences [26,28,41–45]. One may also conclude that observer agreement is intrinsically limited by classification systems, rather than imaging techniques.

CONCLUSIONS

We found that the interobserver reliability of the Schatzker classification was significantly better compared to the Luo classification with a difference in kappa value too small to be clinically relevant. Furthermore, adding 3DCT reconstructions to the CT-based evaluation of tibial plateau fractures did not improve reliability as agreement was higher on 2DCT than 2D- and 3DCT for the Schatzker and Luo tibial plateau fracture classification systems. Considering that the Luo classification has the same limitations in terms of reliability as the 'classic' Schatzker classification and 3DCT does not seem to improve agreement between surgeons, other efforts are needed that lead to more reliable and accurate diagnosis of complex tibial plateau fractures. Training observers in tibial plateau fracture classification systems and the use of simple (i.e., few and important) tibial plateau fracture characteristics besides classification systems might improve interobserver agreement in clinical studies.

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CHAPTER 10

The Effect of Two Factors on Interobserver Reliability for Proximal Humeral Fractures

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ABSTRACT

Introduction: The purpose of this study was to assess whether training observers and simplifying proximal humeral fracture classifications improve interobserver reliability among a large number of orthopaedic surgeons.

Methods: One hundred eighty-five observers were randomized to receive training or no training in a simple classification for proximal humeral fractures before evaluating preoperative radiographs of a consecutive series of 30 patients who were treated with open reduction and internal fixation.

Results: The overall interobserver reliability of the simple proximal humeral fracture classification system was low and not significantly different between the training and the no training group (k = 0.20 and k = 0.18, respectively; P = 0.10). Subgroup analyses showed that training improved the agreement among surgeons who have been in independent practice ≤5 years (k = 0.23 versus k = 0.14; P , 0.001), surgeons from the United States (k = 0.23 versus k = 0.16; P = 0.002), and general orthopaedic surgeons (k =0.42 versus k = 0.15; P = 0.021).

Discussion: Simplifying classifications and training observers did not improve the interobserver reliability for the diagnosis of proximal humeral fractures. However, training observers improved interobserver reliability of a simple proximal humeral fracture classification system among surgeons from the United States and, in particular, younger and less specialized surgeons. This finding may suggest that our interpretations of radiographic information might become more fixed and immutable with experience.

INTRODUCTION

Fracture classification systems for the proximal humerus aim to categorize fracture patterns into clinically useful groups that predict outcomes, guide treatment, and facilitate comparison of functional and radiographic outcomes between groups in the literature[1]. The Neer and AO (Arbeitsgemeinschaft für Osteosynthesefragen) classification systems are most commonly used to characterize proximal humeral fractures in both clinical and research settings[2,3]. Classification according to these systems remains difficult because intraobserver and interobserver reliability is low on radiographs[4-7] and does not improve with the use of two-dimensional[8,9] or three-dimensional CT[10-14].

Training observers may help to increase interobserver reliability. Brorson et al.[15] and Shrader et al.[16] demonstrated that interobserver reliability of the classification according to Neer improved after training sessions. Although training observers before evaluating proximal humeral fractures is promising, its effect has been demonstrated only for the Neer classification and among a small number of observers from the same institution. Therefore, results may be less generalizable to other surgeons and classification systems. Results may also be biased because observers were aware of the intervention and were not blinded to the hypotheses of the study. To our knowledge, the effect of training in proximal humeral fracture classifications on interobserver reliability among a sample of orthopaedic surgeons from multiple countries with different educational backgrounds and for classification systems other than the Neer classification has not been reported.

The most crucial distinction among proximal humeral fractures is between surgical neck and anatomic neck fractures; therefore, simplifying fracture classification systems may lead to better agreement [12,17]. The aim of this study was to assess whether training observers and simplifying proximal humeral fracture classifications (i.e., the distinction between surgical neck versus anatomic neck fractures) improve interobserver reliability among a large number of orthopaedic surgeons. More specifically, we tested the primary null hypotheses that there is no difference in interobserver reliability between observers that had training and observers that had no training in a simple classification system for proximal humeral fractures. We also tested the secondary null hypothesis that there is no difference in proportion of agreement with the reference standard (i.e., the rating of the trainer/principal investigator) between observers in the group that received training and those in the group that did not receive training.

METHODS

Study Design

Orthopaedic surgeons affiliated with the Science of Variation Group (SOVG), a web-based collaborative that aims to study the variation in interpretation and classification of musculoskeletal injuries, were invited to evaluate radiographs of proximal humeral fractures in an online survey in October and November 2014. Before evaluation of the radiographs, all observers invited to participate were randomly allocated to receive training or no training in a simple classification for proximal humeral fractures. Our Institutional Review Board approved this study.

Subjects

In a retrospective search of our billing data using the Current Procedural Terminology, 4th Edition code 23615 for open treatment of proximal humeral fractures, we selected preoperative radiographs of a consecutive series of 30 patients, aged ≥18 years, diagnosed with a proximal humeral fracture, and treated with open reduction and internal fixation between August 2012 and July 2013. Cases with fracture-dislocation, open physes, and poor quality radiographs as determined by the principal investigator were excluded.

The number of subjects was determined to have an adequate balance between the number of subjects and the number of observers evaluating each subject[18]. Because the SOVG study platform aims to facilitate the participation of a large number of observers to improve statistical power and to allow more complex study design, the number of subjects was limited to reduce the burden on observers and increase the completion rate of the online evaluation.

Observers

Based on computer-generated random numbers (Microsoft Excel), observers were randomized (1:1) to either receive training or not receive training in a simple classification for proximal humeral fractures.

A total of 351 observers were asked to participate via email. One hundred seventy-three invitation emails (49%) were sent to observers allocated to the training group and 178 emails (51%) were sent to observers allocated to the no training group. In the group that received training, 90 observers (52%) responded, of which 89 (99%) completed the online survey. In the group that did not receive training, 97 observers (54%) responded, of which 96 (99%) completed the same online survey. Incomplete responses were excluded from analyses, resulting in 89 observers (48%) in the training group and 96 (52%) in the no training group (Table 1). These numbers do not represent a true response or participation rate because we do not know how many of the email addresses were inaccurate and some surgeons with working emails are not active participants in the SOVG. However, the size of the group and the randomization increase the internal and external validity of the data.

Training Module

The training group received an online training module before evaluating the radiographs of the selected consecutive series of patients. The module was designed to illustrate the differences between anatomic neck and surgical neck proximal humeral fractures and to calibrate observers' definitions of these respective fracture types. The first part of the module consisted of 10 different schematic examples of anatomic neck fractures versus surgical neck fractures. In the second part of the module, observers were provided 10 radiographic examples of anatomic neck fractures versus surgical neck fractures (Figure 1).

Table 1. Observer Demographics

	Training (n=89)		No Training (n=96)		Total (n=185)
	n	%	n	%	n
Sex					
Male	84	94	89	93	173
Female	5	6	7	7	12
Area					
United States	48	54	39	41	87
Europe	30	34	35	37	65
Other	11	12	22	23	33
Years in independent practice					
0-5	33	37	35	37	68
6-10	18	20	19	20	37
11-20	31	35	28	29	59
21-30	7	8	14	15	21
Specialization					
General orthopaedics	3	3	8	8	11
Orthopaedic traumatology	39	44	45	47	84
Hand and wrist	32	36	35	37	67
Other	15	17	8	8	23
Supervision of trainees					
Yes	72	81	83	87	155
No	17	19	13	14	30

Online Evaluation

The SOVG provided a link for a survey (SurveyMonkey). Using DICOM viewer software, radiographs were deidentified and converted into JPEG files. The JPEG files were uploaded into SurveyMonkey and displayed using a syntax that allowed proper relative position of the radiographs. Observers were asked to evaluate all radiographs of the selected proximal humeral fractures and to classify the fractures as an anatomic neck fracture or a surgical neck fracture.

Statistical Analysis

A post-hoc power calculation, as described by Guitton and Ring[19], showed that 185 observers provided 37% power to detect a 0.02 difference (effect size = 0.23) in kappa value between the training group and the no training group (a = 0.05). In addition, 185 observers yielded 100% power to detect a clinical meaningful difference ($\Delta = 0.20$) in kappa value defined as the difference between categorical rating scales as defined by Landis and Koch[20].

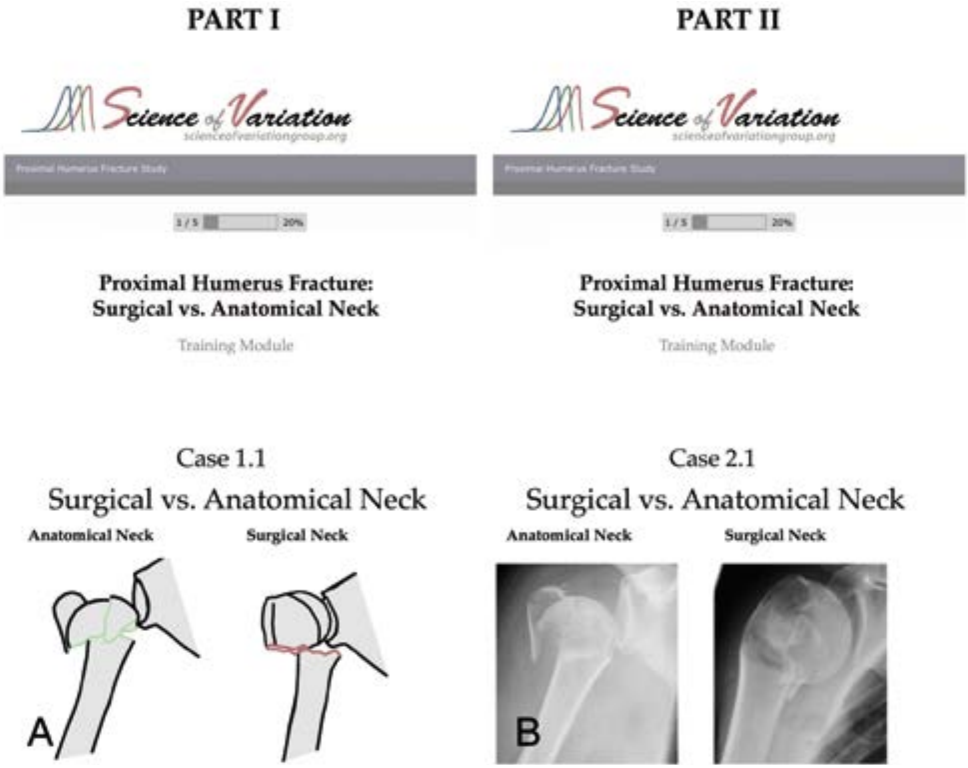

Figure 1. A, Schematic example of an anatomic neck fracture versus a surgical neck fracture as provided in the first part of the training module. B, Radiographic example of an anatomic neck fracture versus a surgical neck fracture as provided in the second part of the training module.

For analysis of our primary hypothesis, interobserver reliability was calculated with the use of the multirater kappa as described by Siegel and Castellan[21], which is a frequently used measure of chance corrected agreement between multiple observers. According to the guidelines of Landis and Koch[20], the kappa values were interpreted as follows: a value of 0.01 to 0.20 indicates slight agreement; 0.21 to 0.40, fair agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and 0.81 to 0.99, almost perfect agreement. Kappa values were compared using the two-sample z-test. P values of <0.05 were considered statistically significant.

For analysis of our secondary hypothesis, proportion of agreement with the reference standard was compared between the training group and the no training group using the two-sample test of proportions. The reference standard was based on the ratings of the principal investigator (D.R.), who was also considered the “trainer” because he shaped the training module. Accordingly, a higher proportion of agreement with the reference standard reflects a higher agreement with the “trainer.”

RESULTS

Interobserver Reliability for a Simple Proximal Humeral Fracture Classification

The overall interobserver agreement was not significantly different between the training and the no training group (k Training = 0.20 and k NoTraining = 0.18; P = 0.10) and the categorical rating of agreement was slight in both groups. In subgroup analyses, the chance corrected interobserver agreement was significantly higher in the training group for US surgeons (k Training = 0.23 and k NoTraining = 0.16; P = 0.002), surgeons in independent practice for ≤5 years (k Training = 0.23 and k NoTraining = 0.14; P , 0.001), and general orthopaedic surgeons (k Training = 0.42 and k NoTraining = 0.15; P = 0.021). There were no significant differences between observers that had training and observers that had no training in the other subgroups (Table 2).

Proportion of Agreement With the Reference Standard of a Simple Proximal Humeral Fracture Classification

The overall proportion of agreement with the reference standard was significantly higher in the training group compared with the no training group (67% and 62%, respectively; P < 0.001). In subgroup analyses, the proportion of agreement with the "trainer" was significantly higher in the training group compared with the no training group for US surgeons (69% and 62%, respectively; P < 0.001), surgeons in independent practice for ≤5 years (67% and 62%, respectively; P = 0.015), surgeons in practice >5 years (67% and 62%, respectively; P = 0.004), hand and wrist surgeons (68% and 62%, respectively; P = 0.003), surgeons that supervise trainees (67% and 63%, respectively; P = 0.001), and surgeons who do not supervise trainees (65% and 57%, respectively; P = 0.014). There were no significant differences between observers that had training and observers that had no training in the other subgroups (Table 3).

DISCUSSION

Fracture patterns of the proximal humerus are difficult to define because of their extreme variability and potential complexity[16]. Categorizing these fractures according to current classification systems is difficult and results in low reliability between and among observers on different imaging modalities[4-14]. The purpose of this study was to assess the influence of training observers and simplifying proximal humeral classification systems on interobserver reliability among a large number of musculoskeletal surgeons. We found that the overall chance corrected interobserver agreement was low with no substantially different agreement between the training group and the no training group. However, the interobserver reliability was significantly higher in the training group for surgeons in independent practice for ≤5 years, US surgeons, and general orthopaedic surgeons. In addition, the overall proportion of agreement with the reference standard was significantly higher in the training group than in the no training

Table 2. Interobserver Agreement in the Training and No Training Group for a Simple Proximal Humeral Fracture Classification

	Training (n=89)			No Training (n=96)			
	Kappa	Agreement	95% CI	Kappa	Agreement	95% CI	P value
Overall	0.20	Slight	0.19-0.21	0.18	Slight	0.16-0.20	0.10
Area							
United States	0.23	Fair	0.21-0.25	0.16	Slight	0.12-0.20	0.002
Europe	0.15	Slight	0.13-0.17	0.19	Slight	0.15-0.23	0.085
Other	0.26	Fair	0.21-0.31	0.20	Slight	0.15-0.25	0.086
Years in independent practice							
0-5	0.23	Fair	0.21-0.25	0.14	Slight	0.09-0.19	<0.001
More than 5 years	0.18	Slight	0.17-0.20	0.20	Slight	0.18-0.23	0.17
Specialization							
General orthopaedics	0.42	Moderate	0.21-0.63	0.15	Slight	0.06-0.24	0.021
Orthopaedic traumatology	0.18	Slight	0.16-0.20	0.18	Slight	0.15-0.21	0.83
Hand and wrist	0.20	Slight	0.18-0.22	0.19	Slight	0.15-0.23	0.70
Other	0.21	Fair	0.18-0.25	0.17	Slight	0.03-0.31	0.58
Supervision of trainees							
Yes	0.20	Slight	0.19-0.21	0.19	Slight	0.17-0.22	0.36
No	0.20	Slight	0.16-0.24	0.14	Slight	0.06-0.22	0.21

group. These findings indicate that simplifying proximal humeral classification systems does not improve interobserver reliability and that training provides only a small but substantially improved effect in a subset of observers.

The results of our study should be interpreted in the light of its limitations. First, the training module was short, consisted of schematics and radiographic examples only, and did not facilitate discussion between observers. A more extensive training program where observers can interact with each other and the trainer may provide a larger effect on the interobserver reliability. Second, fractures were selected based on surgical treatment consisting of open reduction and internal fixation. This selection may have increased the complexity of the fractures and negatively influenced the agreement between observers. Third, there may be important differences between the web-based evaluation as provided by the SOVG and the usual method in which surgeons evaluate radiographs. Finally, training and evaluation was limited to the choice of a simplified classification system. This could have reduced the effect of training because the distinction between anatomic and surgical neck fractures is clear for most experienced and inexperienced observers. The strength of this study is that a large number of observers participated, thus maximizing power and generalizability and allowing randomization and subgroup analyses.

Table 3. Proportion of Agreement with the Reference Standard in the Training and No Training Group for a Simple Proximal Humeral Fracture Classification

	Training (n=89)			No Training (n=96)			
	Proportion of Agreement*	SE	95% CI	Proportion of Agreement	SE	95% CI	P Value
Overall	0.67	0.009	0.65-0.69	0.62	0.009	0.60-0.64	<0.001
Area							
United States	0.69	0.012	0.67-0.72	0.62	0.014	0.60-0.65	<0.001
Europe	0.62	0.016	0.59-0.65	0.60	0.015	0.57-0.63	0.37
Other	0.69	0.025	0.64-0.74	0.65	0.019	0.61-0.68	0.17
Years in independent practice							
0-5	0.67	0.015	0.64-0.70	0.62	0.015	0.59-0.65	0.015
More than 5 years	0.67	0.012	0.64-0.69	0.62	0.011	0.60-0.64	0.004
Specialization							
General orthopaedics	0.70	0.048	0.61-0.79	0.62	0.031	0.56-0.68	0.18
Orthopaedic traumatology	0.66	0.014	0.63-0.69	0.63	0.013	0.61-0.66	0.14
Hand and wrist	0.68	0.015	0.65-0.71	0.62	0.015	0.59-0.65	0.003
Other	0.66	0.022	0.61-0.70	0.56	0.032	0.50-0.62	0.010
Supervision of trainees							
Yes	0.67	0.010	0.65-0.69	0.63	0.009	0.61-0.65	0.001
No	0.65	0.021	0.61-0.70	0.57	0.025	0.53-0.62	0.014

*Proportion of agreement with the reference standard

Our findings were partially consistent with the studies conducted by Brorson et al.[15] and Shrader et al.[16]. Brorson et al.[15] randomized 14 observers to receive training or no training in the Neer classification system before evaluating 42 pairs of proximal humerus radiographs. For observers who received two 45-minute training sessions, the interobserver reliability improved (k = 0.27 to k = 0.62) and the reliability without training was significantly lower than that with training (k = 0.33 versus k = 0.62). Shrader et al.[16] selected radiographs of 113 proximal humeral fractures that were evaluated by three observers in three sessions: the initial session, the discussion session, and the final session. After the discussion session, in which observers discussed the reasons for their disagreement in the initial session, the interobserver agreement for the Neer classification improved slightly but significantly from k = 0.42 to k = 0.47 in the final session.

We found that training slightly improved the interobserver agreement in particular subgroups (i.e., US surgeons, surgeons with ≤5 years of experience, and general orthopaedic surgeons). Surgeons from the United States were less experienced than surgeons from other countries, possibly explaining an increased level of receptiveness to training from US surgeons compared with surgeons from other counties. In other words, less experienced and more generally oriented surgeons appeared to be more receptive to training than the group as a whole. The type of training intervention and the classification system used could explain—in part—this small effect. In this study, less extensive training in a simple classification system was evaluated, whereas a more extensive training in a complex classification system (i.e., the Neer classification system) was used in the other studies.

Studies conducted on other anatomic sites have demonstrated improved interobserver reliability after training in fracture classification systems. Buijze et al.[22] selected 64 observers to evaluate 20 CT scans of scaphoid fractures. Surgeons were randomized to receive training or no training before evaluating the CT scans. Surgeons in the training group had a substantially higher interobserver reliability for the classification of scaphoid fractures than did surgeons in the no training group (k = 0.60 and k = 0.52, respectively). Furthermore, Zehnder et al.[23] presented 50 CT scans of patients with cervical spine injuries to six observers who evaluated the scans before and after a teaching session. After the teaching session, the interobserver reliability improved substantially, as indicated with the intraclass correlation coefficient, from 0.928 to 0.947.

Furthermore, we found that the overall interobserver reliability was poor in both groups for the simple classification system used in our study. This is inconsistent with the study conducted by Bruinsma et al.[12] in which 107 observers evaluated CT scans of 15 proximal humeral fractures and reported higher interobserver agreement for the identification of simple fracture characteristics compared with a more complex classification system, suggesting that simple classifications systems may lead to better agreement between surgeons.

The overall proportion of agreement with the reference standard or trainer (i.e., the principal investigator in our study who designed the training module) indicated the agreement between the surgeons and the trainer. We found that observers who received the training had a substantially higher agreement with the trainer compared with those observers that did not receive training. Although interobserver agreement is of greater interest for surgeons because it affects treatment protocols, scientific experiments, and preoperative planning, the proportion of agreement with the trainer also measures the effectiveness of the training.

In conclusion, training observers and simplifying classification systems for proximal humeral fractures did not improve interobserver reliability. The finding that training observers can improve interobserver reliability of a simple proximal humeral fracture classification system among younger and less specialized surgeons suggests that interpretations of radiographic information might become more fixed and immutable with experience. Interventions to train observers appear to have led to some but minimal improvement in reliability and more experienced observers may be less responsive to new classification systems and training; therefore, future consideration should be given to pursuing methods for increasing surgeon receptiveness to training or new classifications.

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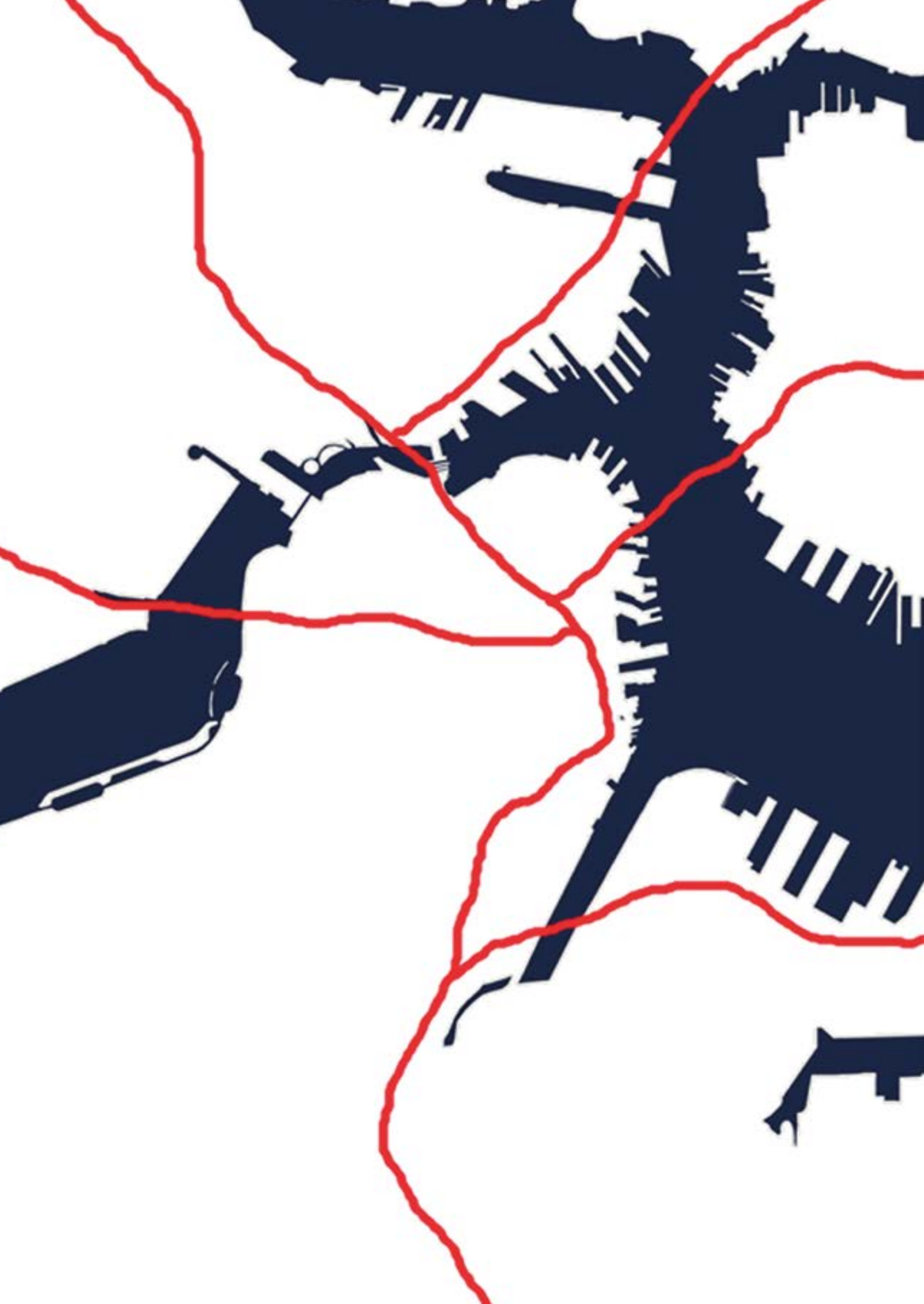

PART IV
ASSESSMENT OF THE INFLUENCE OF FRACTURE CHARACTERISTICS ON DECISION-MAKING: ANALYSIS OF TREATMENT VARIATION

CHAPTER 11

Orthopaedic Surgeons' Variation in Choice of Sliding Hip Screw versus Intramedullary Nailing for A1 and A2 Trochanteric Hip Fractures: What Factors Influence Decision-Making?

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ABSTRACT

Aims: This study: 1) evaluated variation in treatment of stable (A1) and unstable (A2) trochanteric hip fractures among an international group of orthopedic surgeons; and 2) determined the influence of patient, fracture, and surgeon characteristics on decision-making (intramedullary nailing (IMN) versus sliding hip screw (SHS)).

Patients and Methods: A total of 128 Orthopedic Surgeons of the Science of Variation Group evaluated radiographs of 30 patients with Type A Group 1 and 2 trochanteric hip fractures and indicated their preferred treatment: IMN or SHS. Agreement between surgeons was calculated using multirater kappa. Multivariable logistic regression models were used to assess whether patient, fracture, and surgeon characteristics were independently associated with choice of implant.

Results: The overall agreement between surgeons on implant choice was fair (kappa = 0.27 [95%CI 0.25-0.28]). Factors associated with preference for IMN included United States compared to Europe or the U.K. (Europe: OR, 0.56 [95%CI 0.47-0.67]; and UK: OR, 0.16 [95%CI 0.12-0.22], p<0.001); exposure to IMN only during Residency compared to surgeons that were exposed to both (only IMN during residency: OR, 2.6 [95%CI 2.0-3.4], p<0.001); and A2 compared to A1 fractures (A2 trochanteric fracture: OR, 10 [95%CI 8.4-12], p<0.001).

Conclusion: Agreement between surgeons was fair, thus reflecting large variation in implant preference for patients with A1 and A2 trochanteric fractures, which is according to our findings due to surgeon bias (country of practice and aspects of training) and fracture pattern. The observation that surgeon bias favors the more expensive implant in the absence of convincing evidence confirms that surgeon de-biasing strategies might be a useful focus for optimizing health while being a good steward of resources.

INTRODUCTION

Intramedullary nailing (IMN) devices and the sliding hip screws (SHS) – an extra-medullary device – are the two most commonly used type of implants for the treatment of trochanteric hip fractures in adults.[1] The evidence is compelling that reverse oblique fractures (AO/OTA 31-A3) are best treated with an IMN.[2-5] In contrast, the role of IMN for stable (AO/OTA 31-A1) fractures and unstable (AO/OTA 31-A2) fractures is a subject of debate with large and arguably unwarranted variation in treatment, despite equivocal- (A2) or better (A1) outcomes of less expensive extra-medullary devices and comparable operative times.[6-8] In the absence of strong supportive evidence, the rates of intramedullary nail fixation increased from 3% in 1999 to 67% in 2006, and up to 90% in 2011 in The United States of America.[9] Similar numbers have been published from Europe and the United Kingdom (U.K.).[10-12] Interestingly, this increase seems to be associated with provider factors as the increased use of IMN is not correlated to clinical superiority of nailing in recently published Level-I scientific evidence.[1, 13-25] In the era of Value-Based Health Care, one could argue that surgeons may consider SHS to effectively utilize our limited resources, thereby reducing implant related costs from €1200 to €200.[14, 26]

One decade ago, the 2010 Cochrane systematic review of randomized controlled trials (RCTs) concluded that the use of IMN may result in increased rates of intra-operative and subsequent fractures around or below the implant and higher rates of reoperation, in other words: that SHS appears superior for trochanteric fractures.[27, 28] More recently, Parker found comparable results in large prospective RCT, which involved 1000 patients treated with Targon PF(T) nail versus SHS.[1, 13, 20] Similarly, subsequent trials evaluating newer IMN devices did not report this initially reported increased risk in either operative fracture or later femur fracture[14, 15], nor showed any significant difference in terms of pain and function at one year after surgery.[16, 23-25] Authors then suggested that with the improved implant designs and surgeons' plateaued learning curves, the rate of complications is now equivocal to that of the SHS.[29]

However, results of 7643 trochanteric fractures in the Norwegian Hip Fracture Register reported by Matre et al.[30] differ: IMN results in more reoperations than SHS in A1 trochanteric fractures. In addition to presumed complication rate, the choice of implant has clear cost implications. In our hospital, IMN devices are four times more expensive (€800 - €1200) as compared to dynamic or sliding hip screws (€200).[14] In addition to implant related costs, analysis of overall cost-effectiveness showed that the use of SHS is likely more cost-effective for A1 and A2 trochanteric fractures, and IMN may be more cost-effective for A3 reverse oblique fractures, however, this analysis is highly sensitive to fixation failure rate.[26]

Thus, summarizing studies on outcomes and cost-effectiveness, surgeons' variation in decision making on implant choice (SHS versus IMN) for A1 and A2 trochanteric fractures may be explained by: surgeons' perceived clinical and biomechanical superiority of IMN that is non-Evidence-Based, professed surgical ease, and ignorance of implant costs in decision-making in a subset of surgeons.[31] As one could argue that surgeons should consider SHS in both stable A1 and unstable A2 fractures to effectively utilize our limited resources, we were curious about 1) surgeons' global variation in implant choice; and 2) those factors associated with surgeons' decision-making (IMN versus SHS) in treatment of A1 and A2 trochanteric fractures. More specifically, whether patient characteristics (e.g., age, ASA), fracture characteristics (e.g., presence fracture of the lesser trochanter), and surgeon characteristics (e.g., years in practice, country, practice type, experience, knowledge of implant costs, implants used in training) influence the decision of recommending a SHS or (short- or long) IMN.

Therefore, the purpose of this study was 1) to evaluate variation in treatment (i.e., inter-surgeon variability on implant choice) of stable (A1) and unstable (A2) trochanteric fractures among an international group of orthopedic trauma surgeons; and 2) to determine the influence of patient, fracture, and surgeon characteristics on decision-making (SHS versus IMN). We tested the null hypotheses 1) that there was no agreement between surgeons on implant choice when treating A1 and A2 trochanteric fractures; and 2) that patient characteristics (e.g., age, ASA), fracture characteristics (type A1 and A2), and surgeon characteristics (e.g., years in practice, country, practice type) were not associated with implant choice (i.e., SHS vs IMN).

PATIENTS AND METHODS

Study design

Orthopedic surgeons who treat general orthopaedic trauma –identified in both our Science of Variation Group (SOVG) (n = 340 of 800) and Ankleplatform Study Collaborative (n = 400 of 1400) – were invited via email to evaluate radiographs of selected patients with stable trochanteric AO/OTA 31-A1 and unstable AO/OTA 31-A2 fractures. Both platforms facilitate a collaborative effort to improve the study of variation in interpretation, classification, and treatment of injuries using large number of fully trained practicing orthopedic surgeons from different countries around the world, predominantly the United States and Europe, to increase external validity. Members of the SOVG and Ankleplatform have provided their areas of expertise. In this study, we have only invited surgeons that indicated orthopedic trauma surgery as their area of expertise. In addition, members of the European Federation of National Associations of Orthopaedics and Traumatology Task Force[32] were also invited to participate via the SOVG link. The study was performed under a protocol approved by the institutional research board at the principal investigator's hospital (DH and JND).

Surgeon characteristics

A total of 128 orthopedic surgeons logged onto our website and all completed the online evaluation. Surgeons were predominantly men (95%), in independent practice for less than 10 years (68%), and specialized in orthopedic trauma (92%). Most participating surgeons used both SHS and IMN devices during residency (66%). Eighty-six (67%) surgeons had knowledge of implant costs. Half of participating surgeons were from Europe (51%) (Table 1).

Table 1. Surgeon Characteristics (n=128)

Sex, n(%)	
Men	122 (95)
Women	6 (4.7)
Area, n(%)	
United States	30 (23)
Europe	65 (51)
U.K.	12 (9.4)
Other	21 (16)
Years in independent practice, n(%)	
0-10	87 (68)
> 10	41 (32)
Specialization, n(%)	
Orthopaedic traumatology	92 (72)
Other	36 (28)
Supervision of trainees, n(%)	
Yes	114 (89)
No	14 (11)
Implant used during residency, n(%)	
SHS	30 (23)
IM nail	13 (10)
Both	85 (66)
Number of hip fractures operated last year, mean(SD)	61 (70)
Knowledge of implant costs, n(%)	
Yes	86 (67)
No	42 (33)

Abbreviations: SHS, sliding hip screw; IM nail, intramedullary nail.

Patients

Patients with traumatic trochanteric hip fractures treated with either a sliding hip screw (SHS) or intramedullary (IM) nail between 2008 and 2013 were selected. Inclusion criteria were: (1) trochanteric AO/OTA 31-A1 or AO/OTA 31-A2 fracture treated with either SHS or IMN, (2) AP and lateral fracture radiographs of adequate quality and (3) patients age of 18 years and older. Patients who were previously treated with an implant on the contralateral hip were excluded from this study.

Two authors (TS and JND) selected 30 cases that met the inclusion criteria; 15 of those were in reality treated with a SHS and 15 with an IMN based on treating surgeons' preference. Also, distribution of fracture characteristics was evenly distributed between these two subgroups of 15 cases. The ratio for fracture characteristics was selected to correspond to the epidemiology of trochanteric fractures as in the randomized controlled trial conducted by Parker et al.[13] in this Journal.

There were four (27%) AO/OTA 31-A1 fractures and eleven (73%) AO/OTA 31-A2 cases in both groups. Most patients were women (67%), with a mean age of 84 years (range, 62-99 years). Sixteen (53%) were classified according to the American Society of Anesthesiologists Classification (ASA) as patients with severe systemic disease that is not life threatening (i.e., ASA 3) (Table 2).

In addition, the number of subjects was determined based on an adequate balance between the number of subjects and the expected number of observations.[33] Using our web-based study platforms we aim to increase the number of observers in interobserver agreement studies and subsequentially maximize power.

Online evaluation

All radiographs were anonymized for use in this study. The radiographs were uploaded to the online DICOM viewer of the Science of Variation Group (https://www.traumaplatform.org). Upon login to the website, observers were asked to evaluate 30 anonymized AP and lateral view radiographs of the trochanteric fractures in a random order. A short description of the patient's age, sex, side of injury, and ASA classification accompanied each set of radiographs. Observers were asked to select their preferred treatment: a) SHS;

Table 2. Patient Characteristics (n=30)

Sex, n(%)	
Men	10 (33)
Women	20 (67)
Age, mean(SD)	84 (8.0)
Fracture type (AO/OTA), n(%)	
31A1	8 (27)
31A2	22 (73)
ASA classification, n(%)	
1	2 (6.7)
2	8 (27)
3	16 (53)
4	4 (13)
Side, n(%)	
Left	17 (57)
Right	13 (43)
Implant used, n(%)	
SHS	15 (50)
IM nail	15 (50)

Abbreviations: ASA, American Society of Anesthesiologists; SHS, sliding hip screw; IM nail, intramedullary nail.

b) IMN. Observers could open a short descriptive summary of the definition of the AO/OTA 31-A1 and AO/OTA 31-A2 fractures with corresponding images, as well as figures of the other respective classification online through the website. Subsequently, observers were asked to provide the following information: (1) sex; (2) country of practice; (3) years in independent practice; (4) specialization: a) general orthopaedics, b) orthopaedic trauma, c) other; (5) caseload: number of hip fractures operated last year; (6) type of implants used during residency training for trochanteric fractures; (7) costs of SHS versus IMN in surgeons' hospital. Observers completed the survey in their own time, at their own pace, and had the possibility to use different computers at various points in time.

Statistical analysis

Patient and surgeon characteristics were summarized with frequencies and percentages for categorical variables and with mean and standard deviation for continuous variables.

Agreement between surgeons (i.e., interobserver reliability) was calculated using the multirater kappa as described by Siegel and Castellan.[34] The kappa statistic is a frequently used measure of chance-corrected agreement between observers and interpreted according to the guidelines of Landis and Koch[35]: a value of 0.01 to 0.20 indicates slight agreement; 0.21 to 0.40, fair agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and 0.81 to 0.99, almost perfect agreement. In addition, the proportion of agreement was calculated and defined as the proportion of observers agreeing with the most provided answer.

Multivariable logistic regression models were used to identify predictors (i.e., patient, fracture, and surgeon characteristics) associated with the outcome (i.e, implant choice). The sample size was sufficient based on "events per variable" for logistic regression models, resulting in stable models without overfitting.[36] We constructed separate models to assess the effect of surgeon characteristics and patient characteristics, including fracture characteristics, on implant choice, while controlling for other factors (i.e., covariate adjustment). Analyses were performed using STATA v13.0 (StataCorp, College Station, Texas) and SPSS v22 (IBM, Armonk, New York).

RESULTS

Agreement between surgeons on implant choice

To evaluate variation in treatment for stable (AO/OTA 31-A1) and unstable (AO/OTA 31-A2) trochanteric fractures among an international group of orthopedic trauma surgeons, we evaluated inter-observer agreement: The overall agreement between surgeons on implant choice when treating trochanteric fractures was fair (kappa = 0.27 [95% CI 0.25-0.28]). Subgroup analysis showed that interobserver reliability ranged from slight agreement (kappa = 0.16 [95% CI 0.055-0.26]) to fair agreement (kappa = 0.39 [95% CI 0.26-0.52]). The mean proportion of agreement was 0.75 (Table 3).

Table 3. Agreement between surgeons on implant choice (SHS vs IM nail)

	Interobserver agreement			Proportion of agreement
	Agreement	Kappa	95% CI	
Overall	Fair	0.27	0.25-0.28	0.75
Sex				
Men	Fair	0.26	0.25-0.27	0.75
Women	Fair	0.39	0.26-0.52	0.84
Area				
United States	Fair	0.32	0.27-0.38	0.81
Europe	Fair	0.27	0.26-0.29	0.76
U.K.	Slight	0.16	0.055-0.26	0.74
Other	Fair	0.29	0.26-0.32	0.76
Years in independent practice				
0-10	Fair	0.25	0.24-0.26	0.74
> 10	Fair	0.29	0.26-0.32	0.77
Specialization				
Orthopaedic traumatology	Fair	0.29	0.27-0.31	0.77
Other	Fair	0.22	0.20-0.23	0.71
Supervision of trainees				
Yes	Fair	0.28	0.26-0.29	0.76
No	Slight	0.19	0.15-0.23	0.71
Implant used during residency				
SHS	Fair	0.21	0.19-0.23	0.72
IM nail	Fair	0.30	0.18-0.42	0.82
Both	Fair	0.28	0.27-0.30	0.75
Knowledge of implant costs				
Yes	Fair	0.29	0.28-0.31	0.77
No	Fair	0.22	0.20-0.23	0.72

Abbreviations: SHS, sliding hip screw; IM nail, intramedullary nail.

Association of patient, fracture, and surgeon characteristics with implant choice

We evaluated the influence of patient, fracture, and surgeon characteristics on decision-making (SHS versus IMN): Surgeon characteristics that were independently associated with choice of implant include; 1) country of practice; 2) implant used during residency; and 3) caseload (i.e., number of hip fractures operated in a year).

The odds of recommending an IMN for their patients were 44% and 84% lower for surgeons practicing in Europe and the U.K., compared to surgeons from the U.S. (odds ratio [OR], 0.56 [95%CI 0.47-0.67] and OR, 0.16 [95%CI 0.12-0.22], p<0.001, respectively). Furthermore, the odds of using an IMN for surgeons that used only an IMN devices during residency, was 2.6 times higher compared to surgeons that used both implants during residency (OR, 2.6 [95%CI 2.0-3.4], p<0.001); whereas the odds of choosing an IMN was 28% lower for surgeons that only used SHS during residency (OR, 0.72 [95%CI 0.60-0.87], p=0.001). Surgeons with higher caseload had a higher probability of using an IMN (OR, 1.1 [95%CI 1.0-1.1], p<0.001) (Table 4).

Finally, fracture characteristics were also independently associated with implant choice, while other patient characteristics were not: the odds of surgeons to recommend an IMN device was 10 times higher for treatment of trochanteric AO/OTA 31-A2 fractures compared to AO/OTA 31-A1 fractures (OR, 10 [95%CI 8.4-12], p<0.001) (Table 5).

Table 4. Surgeon characteristics associated with implant choice (SHS vs IM nail)

	Recommending IM nail	
Characteristic	Odds ratio (95% CI)	P-value
Sex		
Men	0.79 (0.57-1.1)	0.17
Women	reference group	
Area		
United States	reference group	
Europe	0.56 (0.47-0.67)	<0.001
U.K.	0.16 (0.12-0.22)	<0.001
Other	0.59 (0.47-0.73)	<0.001
Years in independent practice		
0-10	reference group	
> 10	0.93 (0.78-1.1)	0.44
Specialization		
Orthopaedic traumatology	1.1 (0.95-1.4)	0.16
Other	reference group	
Supervision of trainees		
Yes	1.2 (0.94-1.5)	0.14
No	reference group	
Implant used during residency		
SHS	0.72 (0.60-0.87)	0.001
IM nail	2.6 (2.0-3.4)	<0.001
Both	reference group	
Number of hip fractures operated last year, per 20-unit increase	1.1 (1.0-1.1)	<0.001
Knowledge of implant costs		
Yes	1.1(0.93-1.3)	0.28
No	reference group	

Abbreviations: SHS, sliding hip screw; IM nail, intramedullary nail.

Table 5. Patient characteristics (including fracture characteristics) associated with implant choice (SHS vs IM nail)

	Recommending IM nail	
Characteristic	Odds ratio (95% CI)	P-value
Sex		
Men	0.94 (0.80-1.1)	0.46
Women	reference group	
Age, per 1-year increase	0.99 (0.98-1.0)	0.34
Fracture type (AO/OTA)		
31A1	reference group	
31A2	10 (8.4-12)	<0.001
ASA classification		
1	reference group	
2	0.79 (0.57-1.1)	0.17
3	1.3 (0.92-1.7)	0.15
4	0.99 (0.67-1.5)	0.96
Side		
Left	reference group	
Right	1.0 (0.86-1.2)	0.93

Abbreviations: SHS, sliding hip screw; IM nail, intramedullary nail; ASA, American Society of Anesthesiologists.

DISCUSSION

Intramedullary nailing (IMN) devices and sliding hip screws (SHS) are most commonly used for the treatment of trochanteric hip fractures in adults.[1] The optimal treatment of AO/OTA 31-A1 and 31-A2 fractures remain subject of ongoing debate, despite- -or due- to- similar results of SHS versus IMN in recently published high quality Level-I evidence.[1, 13-16, 20, 23-25] However, in the era of Value-Based Health Care, one could argue that surgeons should consider SHS in both stable (A1) and unstable fractures (A2) to effectively utilize our limited resources, thereby reducing implant related costs.[14, 26] In this study, we evaluated inter-surgeon agreement on implant choice as well as factors that influence decision-making between SHS versus IMN devices for treatment of A1 and A2 trochanteric fractures among an International group of fully trained Orthopedic Surgeons. We found that the overall agreement between Orthopedic Surgeons on implant choice was better than flipping a coin, yet indeed only fair according to the categorical rating by Landis and Koch which does reflect a large variation in treatment. When subsequently evaluating what factors influence decision-making, we found that 1) surgeons from the U.S. were more likely to opt for IMN compared to surgeons based in Europe or the U.K.; and that surgeons exposed to IMN only during Residency were more likely to opt for IMN compared to surgeons that were exposed to both during training; 2) the odds of recommending an

IMN for A2 fractures was higher compared to A1 fractures; and 3) that no further patient characteristics, other than fracture type, were associated with implant choice.

This study has several limitations. First, surgeons evaluated actual cases based on provided descriptions including clinical information and radiographs presented online; however, this was only a simulation of a true clinical patient encounter. Second, for practical purposes we have limited the number of predetermined factors (i.e., patient, fracture, and surgeon characteristics) in our analyses; therefore, we may not have included all factors that influence decision-making. The strengths of this study include: 1) a full spectrum of patients treated with both SHS and IMN with a similar distribution of A1 and A2 trochanteric fractures as in the randomized controlled trial conducted by Parker et al.[13] in this Journal, resulting in a representative sample; 2) a large number of fully trained practicing orthopedic surgeons from different countries around the world maximizing generalizability and allowing subgroup analyses (e.g., surgeons 0-10 years in practice and surgeons >10 years in practice). However, interpretation and treatment recommendation of our participating international group of surgeons may not reflect practice in specific regions due to geographical differences; and 3) the online evaluation via our platform (Science of Variation Group) with a built-in online DICOM viewer that mimics clinical practice by allowing to zoom in and out, adjust brightness, window level, and contrast.

The overall agreement between Orthopedic Surgeons on implant choice when treating trochanteric fractures was only fair. This reflects a large -potentially undesired- variation in treatment among surgeons for a very common fracture with a reliable fracture classification (i.e., there is substantial agreement between orthopedic surgeons for the distinction between stable/unstable trochanteric fractures).[37] In general, variation in clinical decision-making is affected by multiple factors, such as available technology, training, supply of specialists, and financial incentives.[38] Advances in clinical evidence may reduce variation, however, variation remains in practice of widely studied surgical procedures. Our results, further discussed below, suggest that the surgeons' country of practice and training, as well as fracture characteristic are the main drivers of variability in decision-making. Beyond the borders of Orthopaedic Trauma, Dr Paul Farmer, Head of Global Health Department and doctor of Internal Medicine in Brigham and Women's Hospital Boston challenges doctors throughout the world in his speech 'To Repair the World'[39]: "I doubt there is any argument that the average patient's request 'what can be done for me?' has different implications in Haiti compared with Boston". We concur that also within the borders of Orthopaedic Trauma Surgery in first world countries; one could argue that such variation in treatment is undesirable.

According to our findings, surgeon characteristics were independently associated with implant choice for treatment of A1 and A2 trochanteric hip fractures. Surgeons from the U.S. were more likely to recommend an IMN compared to surgeons based in Europe or the U.K. The geographic variation in treatment, especially the difference in practice between U.S. and non-U.S. based surgeons, may be explained by attributed superiority of nailing devices on the basis of factors other than clinical outcome (e.g., biomechanical properties, surgical ease, and payment models).[9, 17, 18, 31, 40] In addition, training (during residency) of orthopedic surgeons influenced implant choice as well. Surgeons that only used intramedullary nailing devices during residency were more likely to recommend an IMN, whereas surgeons that were only taught to use a SHS were less likely to prefer an IMN, compared to surgeons that used both devices during residency. Our results are consistent with other studies reporting that training (e.g., fellowship, specialty) of orthopedic surgeons is associated with treatment and other clinical practice patterns.[38, 41-44] Along those lines, the role of industrial suppliers in training and fellowships of orthopedic surgeons and promoting non-evidence based superiority of IMN remains unclear. However, one might speculate that the increase of the use of IMN despite lack of evidence could potentially happen if industry has been pushing its use.[45] Additionally, U.S. based surgeons may have been more receptive of IMN marketing, compared to surgeons in Europe and the U.K.: among members of the American Academy of Orthopedic Surgeons a survey reveals that implant costs (i.e., cost-effectiveness) do not seem an important factor in decision-making[31], while UK Surgeons in the National Health Service (NHS) are on a budget and according to this study seem to be more likely to use a cheaper SHS.

Furthermore, we found that the odds of recommending an IMN for A2 trochanteric hip fractures was 10 times higher compared to A1 trochanteric hip fractures. This is despite similar results of SHS versus IMN in recently published Level-I evidence studies for A2 fractures.[1, 13, 14, 20, 24, 25] In this Journal, Parker et al.[1] concluded that essentially both fixation methods produce similar outcome, although, they found a slightly better regain mobility in the intramedullary nailing group that was statistically significant. Interestingly, the authors deemed this difference not-clinically relevant at the start of this RCT in their pre-hoc power analysis. However, during intermediate analysis, the authors decided to increase their inclusion numbers from 300 to 600 patients to reach a statistically significant difference to show that pre-hoc deemed non-clinically relevant lesser difference in mobility between groups. Other recent Level-I studies did not report a difference in functional outcome at one year after surgery. Barton et al.[14] compared an IMN device with SHS in A2 trochanteric hip fractures in 210 patients and found no difference in reoperation rate, quality of life and mobility scores. Because of similar results and less expense these authors recommend SHS for these specific fracture types. In addition, Reindl et al.[24] and Sanders et al.[25] compared a traditional extramedullary hip screw with an intramedullary device in patients with A2, and A1 and A2 trochanteric fractures, respectively, and found no difference in functional outcome measures at one year postoperatively. Summarizing Evidence-Based treatment of A2 trochanteric fractures, there is scarce proof -if any- to argue that our patients do better functionally with IMN.

Finally, patient characteristics (i.e., age and ASA classification) were not associated with implant choice, in our study, although some Level-I studies reported significant increased blood loss when using a SHS compared to IMN[15, 16], and suggest that in high-risk elderly patients requiring less blood loss a nail should be considered.[21] The RCTs by Parker et al.[1] did not show difference in blood loss and units blood transfused. On the other hand, Whitehouse et al.[46] found higher 30-day mortality with use of IMN in this Journal and suggest that SHS should be the preferred choice of implant. The authors discuss that the incidence of thromboembolic events in this frail patient group may be higher with the use of IMN and suggest this as the potential cause of their findings.

In conclusion, we found that the overall agreement between orthopedic surgeons on implant choice for treatment of A1 and A2 trochanteric fractures was fair, reflecting a large variation in treatment of trochanteric hip fractures among orthopedic surgeon for these relatively common fracture types. According to our findings the choice for the most expensive-but not clinically superior- implant is influenced by: 1) by surgeons' bias- country of practice and training; and 2) fracture characteristics - non-evidence-based attributed superiority of IMN for A2 trochanteric hip fractures. Surgeons' variation on implant choice may be reduced when we take into account similar outcomes of SHS versus IMN, and then letting cost-effectiveness prevail to effectively use our scarce Health Care resources. In other words, treatment preferences based on current Value-Based Health Care principles could reduce Heath Care costs as well as unwarranted variation in treatment of trochanteric fractures.

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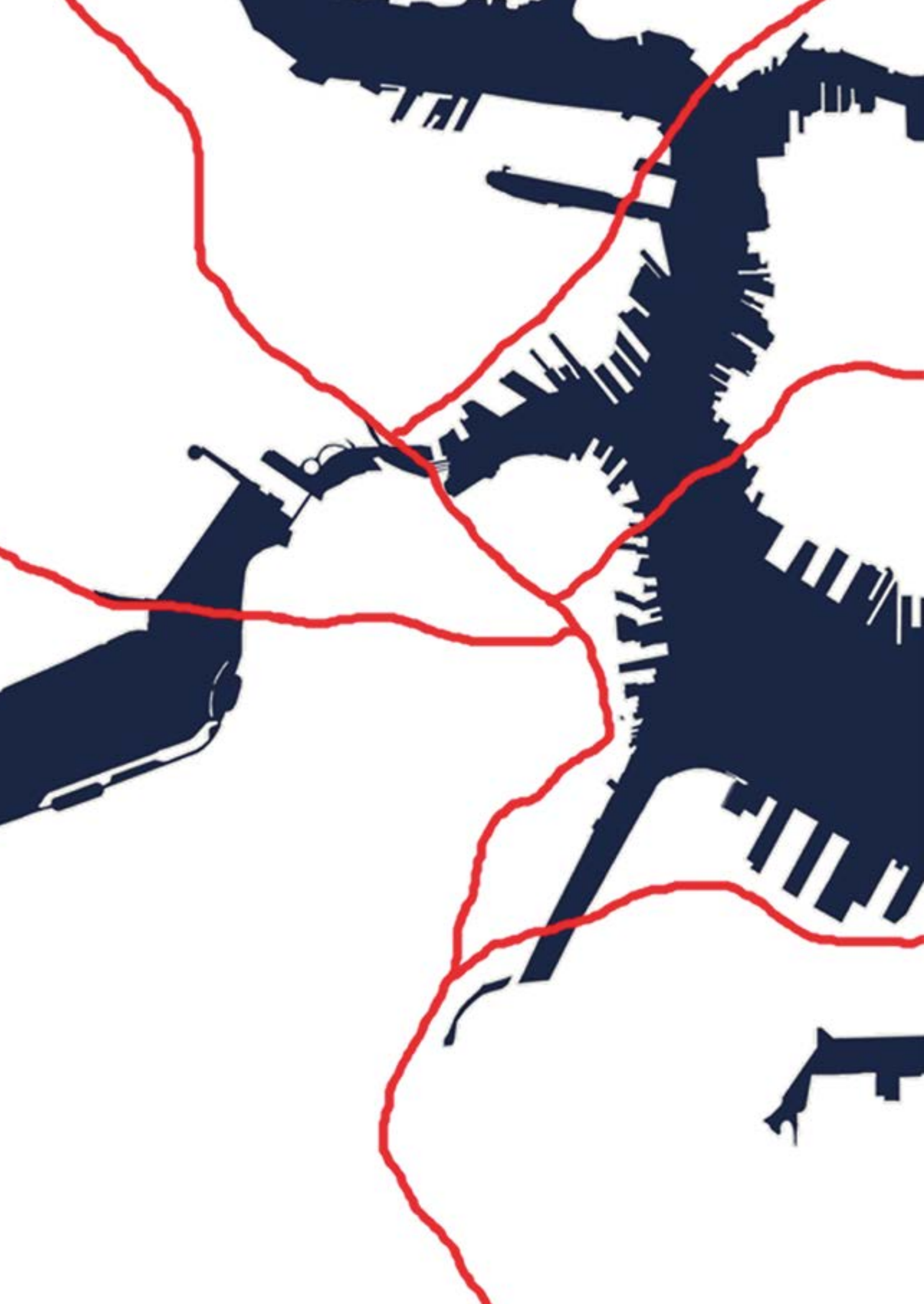

DISCUSSION AND SUMMARY

CHAPTER 12

General Discussion

The use of digital imaging techniques enables more advanced assessment (i.e., qualitative and quantitative analysis) of fracture characteristics and therefore improve our understanding of fracture morphology. In addition to accurate characterization of fractures, classification systems must include reliable fracture characteristics in order to be useful. The overall aim of this thesis is to improve characterization and reliability of the assessment of specific fractures. In this chapter, previous chapters, included in one of the four main parts of the manuscript, are discussed.

PART I: QUALITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MAPPING OF FRACTURE LINES

Mapping of Coronoid Fractures

In Chapter 2, fracture mapping techniques[1, 2] were used to define location, frequency, distribution and patterns of coronoid fracture lines, and to qualitatively assess the association between specific coronoid fracture types and patterns of elbow fracture-dislocation. A total of 110 patients with coronoid fractures were included. Fracture types and pattern of injury were characterized based on radiographs, CT scans, and intra-operative findings. Based on Q3DCT reconstructions fracture lines were identified and graphically superimposed onto a standard template in order to create 2D fracture maps. The initial diagrams were converted into fracture heat maps. Assessment of 2D fracture and heat maps showed fracture patterns similar to coronoid fragment morphology as described by O'Driscoll et al.[3]. In addition, the maps demonstrated that specific patterns of traumatic elbow instability have correspondingly specific coronoid fracture patterns.

Mapping of fracture lines helped verify fracture morphology as described by O'Driscoll et al.[3] on the basis of experience caring for patients with these injuries. Our findings were also consistent with the observations of Doornberg and Ring[4] that patterns of injury were associated with specific coronoid fracture types. Fracture mapping techniques verified the strong association of large basilar fractures of the coronoid process with posterior olecranon fracture-dislocations, small transverse fractures with terrible-triad injuries, and anteromedial facet fractures with varus posteromedial rotational instability pattern injuries. Determining traumatic elbow instability injury patterns may give surgeons a good idea of the type and morphology of coronoid fractures prior to CT imaging, however, given the variability of coronoid fracture patterns, as depicted on our fracture maps, determining the elbow injury pattern based on radiographs alone is not sufficient for accurate characterization of coronoid fractures.

Mapping of Tibial Plateau Fractures

In Chapter 3, mapping techniques[2] enabled the evaluation of tibial plateau fractures patterns in sagittal, coronal and axial planes. In this study of 127 patients treated for a tibial plateau, fracture lines and zones of comminution were graphically superimposed onto an axial template of an intact subarticular tibial plateau to identify major patterns of fracture lines and comminution. Fracture mapping techniques revealed patterns in the Schatzker type-IV, V, and VI fractures beyond those described in Schatzker's original classification[5].

The maps revealed four recurrent major fracture characteristics: 1) the lateral split fragment, found in 75%; 2) the posteromedial fragment, seen in 43%; 3) the tibial tubercle fragment, seen in 16%; and 4) a zone of comminution that included the tibial spine and frequently extended to the lateral condyle, seen in 28%.

Qualitative assessment of fracture maps demonstrated four major fracture characteristics[5-14], as mentioned above. In addition, our maps were compared to the fracture morphology as described by Schatzker et al.[5]: the lateral fracture map (Schatzker type-I, II, and III fractures) showed patterns conform with Schatzker's original description, with involvement of the lateral condyle only; the medial fracture map (Schatzker type-IV fractures) showed frequent involvement of both the medial and the lateral condyle, which is inconsistent with the assumption of a unicondylar medial fracture; and the bicondylar fracture map (Schatzker type-V and VI fractures) showed a variety of fracture lines suggesting that the Schatzker type V fracture is rare. Based on our findings, we suggest using these four common fracture features to define—or "build"—respective tibial plateau fractures. The four major features of tibial plateau fractures observed in the current study may help to improve observer agreement in clinical studies and may be useful in daily practice as an augmentation to classification systems.

Mapping of Radial Head Fractures

In Chapter 4, assessment of fracture maps is performed to study the relationship between fracture line distribution and location of displaced partial radial head fractures and patterns of traumatic elbow instability. Fracture line distribution and location of 66 acute displaced partial articular radial head fractures were identified using Q3DCT reconstructions that allowed reduction of fracture fragments and a standardized method to divide the radial head into quadrants with forearm in neutral position. The maps showed that the highest fracture line intensity was located in the anterolateral quadrant near the center of the radial head and, as fracture location correspond with fracture line distribution, most fractures involved the anterolateral quadrant. Fracture line distribution and location of partial radial head fractures were similar no matter the overall injury patterns of the elbow.

Patterns of traumatic elbow instability are associated with specific fractures of the coronoid process[3, 4, 15-17], however, the variation in fracture location and fracture line distribution of the radial head in relationship to associated injuries is incomplete. Our fracture maps demonstrated no association between fracture line distribution and location of displaced partial articular fractures of the radial head and overall patterns of injury, suggesting one common fracture mechanism that involves the anterolateral part of the radial head in most patients[18]. This suggests that the surgical exposure for fixation of the radial head can be the same for all injury patterns. However, there is large variability in the fracture maps, therefore CT scans are recommended if further characterization might help to plan surgery.

Mapping of the Lesser Sigmoid Notch

In Chapter 5, fracture mapping and Q3DCT techniques are used to study fracture line location and fracture fragment characteristics of specific coronoid fracture types that involve the lesser sigmoid joint. A total of 52 patients were analyzed. Fracture types of the coronoid were categorized according to the Mayo classification[3]. Our maps and Q3DCT data showed that type 3 coronoid fractures (i.e., large basilar fractures) have more complex involvement of the sigmoid notch: larger extent of articular surface involvement and comminution, and horizontal as well as vertical fracture line orientation.

This study improved our knowledge of how proximal ulnar fractures affect the lesser sigmoid notch; however, clinical implication of our findings remains unclear as there is no evidence yet that fracture type, fracture alignment, and the amount of displacement in the lesser sigmoid notch has any effect on outcome and progression to osteoarthritis. On the other hand, the lesser sigmoid notch provides a landmark for positioning the radial head prosthesis after elbow fracture dislocations[19], and therefore injury to this part of the coronoid might affect methods of selecting an appropriately sized radial head prosthesis.

PART II: QUANTITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MEASUREMENT OF SPECIFIC FRAGMENTS AND ARTICULAR INVOLVEMENT

Q3DCT- Based Analysis of Coronoid Fractures

In Chapter 6, specific characteristics (i.e., volume, articular surface involvement, and number of fracture fragments) of coronoid fractures were determined using Q3DCT techniques. In this study, 82 patients with a coronoid fracture were evaluated. Based on Q3DCT data, we found the following differences between coronoid fracture types: fractures of the tip were less fragmented and had the smallest fragment volume and articular surface area involvement; anteromedial facet and base fractures were more fragmented than tip fractures; and base fractures had the largest fragment volume and articular surface area involvement. Furthermore, we found differences in fracture morphology between different overall injury patterns.

Quantitative 3DCT data can provide a better understanding of fracture morphology[20-26], and might guide, for example, decision-making and implant development. For coronoid factures, Q3DCT measurements confirmed that fractures of the tip and anteromedial facet are often too small for screw fixation[27-29]. In addition, Q3DCT facilitated comparison between described classification schemes and helped demonstrate differences and similarities objectively. The implementation of quantitative (3D)CT assessment of fracture characteristics in clinical practice may improve decision-making and preoperative planning for coronoid fractures.

Q3DCT- Based Analysis of the Posteromedial Fragment in Complex Tibial Plateau Fractures

In Chapter 7, 2D- and 3DCT measurements of the posteromedial (PM) fragment in complex tibial plateau fractures were determined as well as the association between CT-based characteristics and fragment fixation using laterally applied locking screws. Quantitative 3DCT techniques[30] were used to simulate reduction and internal fixation of the PM fragment with laterally applied fixed-angle locking screws through LCP and LISS plates. Fracture fixation (i.e, better or worse fixation) was quantified by volume (mm3) and number of screws intersecting the PM fragment. Both 2D- and 3DCT characteristics were independently associated with fixation. On 2DCT, larger articular surface involvement and posterior cortical height result in better fixation (i.e., higher volume (mm3) and number of screws intersecting the fragment); and larger sagittal fracture angle results in worse fixation. Three-dimensional CT characteristics independently associated with improved fixation of the PM fragment were larger articular involvement and fragment volume.

Adequate fixation of the PM fragment using laterally applied fixed-angle screws can be challenging due to its specific fragment morphology[7, 31], however, single lateral plating may have potential advantages (e.g., less exposure in area recognized to have poor vascular supply)[32-35]. In this study, we identified that both 2DCT and 3DCT posteromedial fracture characteristics help predict fracture fixation by laterally applied fixed-angle locking screws using locking compression plates (i.e., LCP and LISS plate). In other words, specific CT-based fragment characteristics, independently associated with fixation or not, could be used in clinical setting to determine whether or not single lateral locked screw plating is sufficient to stabilize the fragment. Implementation of advanced 3D techniques, such as simulating reduction and fixation of fracture fragments, in clinical practice may help pre-operative planning and subsequently determine the most adequate fixation techniques.

PART III: ASSESSMENT OF RELIABILITY OF FRACTURE CHARACTERISTICS: MEASUREMENT OF AGREEMENT BETWEEN SURGEONS

Reliability for Tibial Plateau Fracture Characteristics

In Chapter 8, the interobserver reliability and diagnostic accuracy were determined for 2D- and 3DCT–based evaluation of tibial plateau fracture characteristics. A total of 81 orthopedic (trauma) surgeons and residents were randomized to either 2DCT or 2D- and 3DCT evaluation of 15 complex tibial plateau fractures using our web-based platforms to recognize 4 tibial plateau fracture characteristics[36]: (1) a posteromedial component, (2) a lateral component, (3) a tibial tubercle component, and (4) a tibial spine (central) component. This study showed that interobserver reliability ranged from “fair” to “substantial” for CT-based evaluation of tibial plateau fracture characteristics. Diagnostic accuracy of fracture characteristics ranged from 70% to 89% and was better for more frequently encountered components (i.e., the posteromedial and lateral component). The addition of 3DCT reconstructions did not improve agreement between observers or diagnostic accuracy.

According to our results, orthopedic surgeons agree fair to substantial on identification of tibial plateau fracture characteristics[36], and thus in the accurate description of complex tibial plateau fractures using these 4 respective components. Considering that the CT-based evaluation of tibial plateau fracture characteristics prove accurate and reliable in this study, we encourage its use in daily practice as augmentation of currently used classification systems[5, 37, 38]. Furthermore, the addition of 3DCT reconstructions did not improve the agreement between surgeons or diagnostic accuracy. This suggest that surgeons are more familiar with 2DCT scans and do not benefit from the more intuitive 3D reconstructions[39]. In addition, higher agreement using 2DCT alone, as reported in this study, indicate that 3D reconstructions may be a source of variation if not consistent with plain CT images.

Reliability for the Schatzker and Luo Classification Systems

In Chapter 9, the interobserver agreement of the Luo classification and the Schatzker classification were determined for 2D- and 3DCT-based evaluation. Eighty-one orthopedic surgeons and residents (i.e., observers) were randomized to either 2DCT or 2D- and 3DCT evaluation of 15 complex tibial plateau fractures in order to classify according to the Schatzker[5] and Luo's Three Column classification[40]. The interobserver agreement was significantly better for the Schatzker classification compared to Luo's Three Column classification and only fair according to the categorical rating by Landis and Koch for both classification systems. The addition of 3DCT reconstructions did not improve the reliability of CT-based evaluation of tibial plateau fractures.

This study, performed by our independent research group, showed that agreement between surgeons was significantly better for the Schatzker classification compared Luo's classification, in contrast to previous data from the same institution that coined this classification[41, 42]. Again, 3DCT did not increase interobserver agreement. Three-dimensional CT reconstructions might increase complexity and observers might be distracted by or not familiar with the 3DCT images, indicating that observers rely more on 2DCT than 3DCT for the classification of tibial plateau fractures.

Reliability for Proximal Humeral Fractures

In Chapter 10, the effect of training observers in a simple classification for proximal humeral fractures on interobserver reliability was evaluated. A total of 185 observers were randomized to receive training or no training in a simple classification for proximal humeral fractures before evaluating preoperative radiographs of a consecutive series of 30 patients who were treated with open reduction and internal fixation. The overall interobserver agreement of the simple proximal humeral fracture classification system was slight and not significantly different between the training and the no training group. However, subgroup analyses showed that training improved the agreement among surgeons ≤5 years in independent practice, surgeons from the United States, and general orthopedic surgeons.

Our findings indicate that simplifying proximal humeral classification systems does not improve interobserver reliability as agreement was slight in both groups, which is in contrast of a previous study that suggested that simple classifications systems may lead to better agreement between surgeons[39]. The finding that training observers can improve interobserver reliability only in a subset of observers (i.e., younger and less specialized surgeons) may suggest that interpretations of radiographic information might become more fixed and immutable with experience. In other words, more experienced observers may be less responsive to new classification systems and training. Therefore, future consideration should be given to pursuing methods for increasing surgeon receptiveness to training or new classifications.

PART IV: ASSESSMENT OF THE INFLUENCE OF FRACTURE CHARACTERISTICS ON DECISION-MAKING: ANALYSIS OF TREATMENT VARIATION

Variation in Treatment of Trochanteric Fractures

In Chapter 11, variation in treatment of stable (A1) and unstable (A2) trochanteric hip fractures among orthopedic surgeons, and the influence of patient, fracture, and surgeon characteristics on decision-making (intramedullary nailing (IMN) *versus* sliding hip screw (SHS)) were evaluated. One hundred and twenty-eight orthopedic surgeons evaluated radiographs of 30 patients with Type A Group 1 and 2 trochanteric hip fractures and indicated their preferred treatment: IMN or SHS. We found that the overall agreement between surgeons on implant choice was only fair. Furthermore, factors associated with preference for IMN included United States compared to Europe or the U.K.; exposure to IMN only during residency compared to surgeons that were exposed to both; and A2 compared to A1 fractures.

According to our findings, the interobserver reliability was fair reflecting a large variation in treatment among orthopedic surgeons for a common fracture. The implant choice was influenced by 1) surgeon bias- country of practice and training; and 2) fracture characteristics- non-evidence-based attributed superiority of IMN for A2 trochanteric hip fractures. Surgeons' variation on implant choice may be reduced when we take into account similar outcomes of SHS *versus* IMN in recent level-I studies[43-51], and then letting cost-effectiveness that favor SHS prevail to effectively use our scarce Health Care resources. We argue that according to current Value-Based Health Care principles, surgeons should consider extra-medullary devices to be the implant of choice in treatment of A1 and A2 trochanteric hip fractures.

CONCLUSIONS

- » Fracture mapping can improve our understanding of fracture line patterns and distribution, and zones of comminution. Qualitative assessment of fracture characteristics using fracture maps has proved a useful method for validating current (or new) fracture classification systems.
- » Quantitative 3DCT techniques help determine specific fracture characteristics (e.g., fragment size, shape, and articular involvement) and can be used to predict fragment fixation.
- » Interobserver reliability for tibial plateau fractures did not improve when adding 3DCT reconstructions to 2DCT-based evaluation. Furthermore, simplifying proximal humeral

classification systems did not improve interobserver reliability, however, training observers could improve reliability in a subset of observers (i.e., younger and less specialized surgeons).

» Variation in treatment of trochanteric fractures (i.e., choice of implant) is influenced by surgeon and fracture characteristics.

FUTURE PERSPECTIVES

Building on our research, fracture mapping studies have been performed by several research groups[52-57] and further developed using more sophisticated 3D imaging [58, 59]. Fracture maps, based on advanced CT techniques, help increase our knowledge of fracture morphology and enable validation of fracture characteristics included in commonly used fracture classification systems. It adds to our understanding of fracture patterns and therefore provides useful data for surgical approaches, fixation techniques (e.g., screw placement and plate position), and implant designs. Automated analysis of fracture line distribution, using Artificial Intelligence (AI) or not, may enable study of larger cohorts of patients and help identify patterns that are not found using our current qualitative assessment. However, AI is in the early stages of implementation in orthopedic trauma imaging[60]. For now, the use of current mapping techniques could be continued to study (un)known patterns in orthopedic trauma or non-fracture related conditions, for example, osteochondral defects and bone metastasis.

For quantitative analysis of fracture characteristics, Q3DCT facilitates accurate measurements of size, shape and articular involvement[21-25], and simulation of fracture fragment reduction and fixation using orthopedic implants[26]. Currently, Q3DCT techniques are time-consuming and seldom used in clinical setting. Automatic quantitative image analysis may replace manual segmentation of bone, identification of fracture lines, and reduction of fracture fragments[61]. Efforts should be made to increase the availability of Q3DCT techniques in clinical practice as this would improve pre-operative planning (e.g., surgical approach and fixation techniques). In research setting, our current Q3DCT technique can be used to continue study of specific fracture fragment characteristics and its relationship with fixation techniques until even more advanced imaging techniques become available.

As fracture characteristics need to be reliable and accurate, there has been extensive effort to improve interobserver reliability in orthopedic trauma research. Interobserver reliability studies show that 1) the effect of adding 3DCT reconstructions on agreement between surgeons is inconsistent[39, 62-67] 2), more detailed evaluation using DICOM viewers results in lower reliability[68], 3) subtraction of unfractured bones does not improve agreement for 3DCT-based evaluation[69], 4) training observers improves interobserver reliability[70-73], and 5) simpler classifications may improve reliability among surgeons[39]. Considering that more accurate imaging techniques fail to decrease disagreements, interobserver agreement may not depend on what is depicted in the images, but on interpretational differences[69]. Therefore, attention should be given to develop classification systems or conceptualizations that improve surgeons' understanding and reduce bias. In addition, alternatives for the kappa statistic in analysis of interobserver reliability may be explored. Kappa values have been frequently criticized for being unstable because of its dependence on "marginal totals"[74, 75], however, recent proposed guidelines still includes the Kappa statistic as statistical method of choice for analyzing interobserver reliability[76].

Finally, study of variation in treatment aims to better understand variation in decision-making among orthopedic surgeons[77-79]. Identifying factors (e.g., surgeon, patient, and fracture characteristics) that influence decision-making prompt discussion and efforts to reduce-undesired- variation in order to improve patient care while using our health care resources effectively. Therefore, studies need to continue to monitor variation in treatment and determine the main drivers of variability in decision-making.

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CHAPTER 13

Summary

Fracture Mapping: Assessment of Fracture Characteristics from AP to 3D

In this chapter, a summary is provided of chapters included in one of the four parts of the manuscript.

PART I: QUALITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MAPPING OF FRACTURE LINES

Mapping of Coronoid Fractures

The aim of Chapter 2 was to define location, frequency, distribution and patterns of coronoid fracture lines, and to qualitatively assess the association between patterns of elbow fracture-dislocation and specific coronoid fracture types. Fracture lines of 110 coronoid fractures were identified based on Q3DCT reconstructions. Two-dimensional fracture (heat) maps were created.

Fracture maps demonstrated similar fracture morphology as described by O'Driscoll et al.[1]. In addition, fracture mapping verified the observation by Doornberg and Ring[2] that patterns of traumatic elbow instability are associated with specific coronoid fracture types. We found an association of large basilar fractures with posterior olecranon fracture-dislocations, small transverse fractures of the tip with terrible-triad injuries, and anteromedial facet fractures with varus posteromedial rotational instability pattern.

Mapping of Tibial Plateau Fractures

In Chapter 3, the aim was to evaluate tibial plateau fracture patterns using mapping techniques. Fracture lines and zones of comminution of 127 patients treated for a tibial plateau fracture were evaluated.

Our maps showed fracture patterns beyond those described in the Schatzker classification[3]. Fracture mapping demonstrated four major fracture characteristics: 1) the lateral split fragment, 2) the posteromedial fragment, 3) the tibial tubercle fragment, and 4) a zone of comminution that included the tibial spine. Tibial plateau fractures can be "build" or defined using these specific fracture characteristics.

Mapping of Radial Head Fractures

The objective of Chapter 4 was to study the association between fracture line location and distribution of displaced partial radial head fractures and overall injury patterns of the elbow. Sixty-six displaced partial articular radial head fractures were analyzed using Q3DCT and mapping techniques.

Fracture maps showed similar fracture line location and distribution of displaced partial radial head fractures for different patterns of traumatic elbow instability. The anterolateral quadrant was involved in most fractures with the highest fracture line intensity near the center of the radial head.

Mapping of the Lesser Sigmoid Notch

In Chapter 5, the study objective was to evaluate fracture fragment characteristics and fracture line distribution of coronoid fractures that involve the lesser sigmoid joint. Fifty-two patients were analyzed using Q3DCT and fracture mapping techniques.

Quantitative 3DCT data and fracture maps showed that larger basilar coronoid fractures (type 3) have more complex involvement of the sigmoid notch compared to small transverse and anteromedial facet fractures (type 1 and 2, respectively). There was no difference in extent of articular surface involvement, comminution, and fracture line orientation between type 1 and 2 coronoid fractures.

PART II: QUANTITATIVE ASSESSMENT OF FRACTURE CHARACTERISTICS: MEASUREMENT OF SPECIFIC FRAGMENTS AND ARTICULAR INVOLVEMENT

Q3DCT- Based Analysis of Coronoid Fractures

In Chapter 6, the purpose was to determine specific characteristics (i.e., number of fracture fragments, articular surface involvement, and volume) of coronoid fractures using Q3DCT techniques. A total of 82 coronoid fractures were analyzed.

Quantitative 3DCT data showed that fractures of the tip had the smallest articular surface area involvement and fragment volume. In addition, fractures of the anteromedial facet and base of the coronoid were more fragmented than tip fractures. Furthermore, basilar coronoid fractures had the largest fragment volume and articular surface area involvement. We also found difference in coronoid fracture morphology when comparing overall injury patterns of the elbow.

Q3DCT- Based Analysis of the Posteromedial Fragment in Complex Tibial Plateau Fractures

The aim of Chapter 7 was to assess 2D- and 3DCT characteristics of the posteromedial fragment in complex tibial plateau fractures. Quantitative 3DCT analysis was preformed to assess the relationship between CT-based characteristics of the posteromedial fragment and fragment fixation using laterally applied locking screws. In total, 84 complex tibial plateau fractures were analyzed.

We found that CT-based characteristics of the posteromedial fragment help predict fixation by laterally applied fixed-angle locking screws using locking compression plates. Fracture characteristics independently associated with improved fixation of the posteromedial fragment were larger articular surface involvement and posterior cortical height on 2DCT, and larger articular involvement and fragment volume on 3DCT. On 2DCT, larger sagittal fracture angle resulted in worse fixation.

PART III: ASSESSMENT OF RELIABILITY OF FRACTURE CHARACTERISTICS: MEASUREMENT OF AGREEMENT BETWEEN SURGEONS

Reliability for Tibial Plateau Fracture Characteristics

In Chapter 8, the purpose was to determine the interobserver agreement and diagnostic accuracy for 2D- and 3DCT–based evaluation of tibial plateau fracture characteristics. Orthopedic (trauma) surgeons and residents were randomized to either 2DCT or 2D- and 3DCT evaluation of 15 complex tibial plateau fractures. In total, 81 observers completed the online evaluation.

The interobserver agreement for CT-based evaluation of tibial plateau fracture characteristics ranged from “fair” to “substantial”. Diagnostic accuracy was better for specific characteristics that are more frequently encountered (i.e., the lateral and posteromedial component) and ranged between 70% and 89%. The addition of 3DCT reconstructions did not improve interobserver agreement or diagnostic accuracy.

Reliability for the Schatzker and Luo Classification Systems

The objective of Chapter 9 was to determine the interobserver agreement of the Schatzker classification[3] and Luo’s Three Column classification[4] for 2D- and 3DCT-based evaluation. A total of 81 observers, orthopedic residents and surgeons, were randomized to assess either 2DCT or 2D- and 3DCT scans of patients with complex tibial plateau fractures.

We found that the interobserver agreement was “fair” for both classification systems. However, the agreement between observers was significantly higher for the Schatzker classification compared to the Luo classification. The addition of 3DCT did not improve interobserver agreement of CT-based assessment of tibial plateau fractures.

Reliability for Proximal Humeral Fractures

In Chapter 10, the aim was to evaluate the effect of training observers in a simple classification for proximal humeral fractures on interobserver agreement. In total, 185 observers (i.e., orthopedic surgeons) were randomized to receive training or no training before evaluating preoperative radiographs of 30 proximal humeral fractures of patient that were treated operatively.

The overall interobserver agreement was “slight” for both groups and not significantly different between surgeons in the training and no training group. However, subgroup analyses showed that training improved the agreement among general orthopedic surgeons, surgeons based in the United States, and surgeons ≤5 years in independent practice.

PART IV: ASSESSMENT OF THE INFLUENCE OF FRACTURE CHARACTERISTICS ON DECISION-MAKING: ANALYSIS OF TREATMENT VARIATION

Variation in Treatment of Trochanteric Fractures

In Chapter 11, the purpose was to evaluate the treatment variation of stable (AO/OTA 31-A1) and unstable (AO/OTA 31-A2) trochanteric fractures among orthopedic surgeons, and the influence of surgeon, patient, and fracture characteristics on implant choice (intramedullary nailing *versus* sliding hip screw). In total, 128 orthopedic surgeons assessed 30 radiographs of patients with either A1 or A2 trochanteric fractures and selected their preferred treatment: IMN or SHS.

We found that the agreement between orthopedic surgeons on implant choice was “fair”. Factors associated with preference for IMN included surgeons from the United States compared to Europe or the U.K.; exposure to IMN only during residency compared to surgeons that were exposed to both; and A2 compared to A1 trochanteric fractures.

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CHAPTER 14

Samenvatting (Dutch summary)

In kaart brengen van fracturen: analyse van fractuurkarakteristieken van AP tot 3D

In dit hoofdstuk wordt een samenvatting gegeven van deel I- IV van het manuscript.

DEEL I: ANALYSE VAN FRACTUURKARAKTERISTIEKEN (KWALITATIEF): HET IN KAART BRENGEN VAN FRACTUURLIJNEN

Kaart van fracturen van het coronoid

Het doel van hoofdstuk 2 was de locatie, frequentie, distributie en patronen van fractuurlijnen van het coronoid vast te stellen en daarnaast om het verband te onderzoeken tussen elleboog fractuur-dislocaties en specifieke coronoidfracturen. Fractuurlijnen van 110 coronoidfracturen werden geïdentificeerd op basis van Q3DCT reconstructies. Tweedimensionale fractuurkaarten werden gemaakt.

Fractuurkaarten toonden eenzelfde fractuurmorfologie zoals beschreven door O'Driscoll et al.[1]. Daarnaast werd op basis van de kaarten het verband tussen elleboog fractuur-dislocaties en specifieke coronoidfracturen, eerder geobserveerd door Doornberg en Ring[2], geverifieerd, te noemen: fractuur van de tip met "terrible-triad" letsel van de elleboog, anteromediale facet fractuur met varus posteromediale rotatie instabiliteit letsel en fractuur ter plaatse van de basis van het coronoid met posterieure olecranon fractuur-dislocatie.

Kaart van tibiaplateaufracturen

In hoofdstuk 3 was de opzet om patronen van tibiaplateaufracturen te bestuderen door middel van fractuurkaart gerelateerde technieken. Fractuurlijnen en comminutieve zones van 127 tibiaplateaufracturen werden geëvalueerd.

Kaarten van tibiaplateaufracturen lieten fractuurpatronen zien die niet zijn beschreven in de Schatzker classificatie[3]. De volgende fractuurkarakteristieken werden herkend: 1) het laterale split fragment, 2) het posteromediale fragment, 3) het tuberositas tibiae fragment, en 4) een zone van comminutie inclusief de eminentia. Tibiaplateaufracturen kunnen "gebouwd" of gedefinieerd worden met behulp van deze specifieke fractuurkarakteristieken.

Kaart van radiuskopfracturen

De opzet van hoofdstuk 4 was het evalueren van de relatie tussen letselpatronen van de elleboog en fractuurlijn distributie van verplaatste partiële radiuskopfracturen. In totaal werden 66 verplaatste partiële radiuskopfracturen geanalyseerd met Q3DCT en fractuurkaart gerelateerde technieken.

Fractuurlijn locatie en distributie van verplaatste partiële radiuskopfracturen, zoals vastgesteld op onze fractuurkaarten, waren hetzelfde voor verschillende letselpatronen van de elleboog. Het anterolaterale kwadrant was betrokken bij de meeste fracturen met de hoogste fractuurlijn intensiteit dichtbij het midden van de radiuskop.

Kaart van de incisura radialis

In hoofdstuk 5 was het doel de fractuurkarakteristieken en fractuurlijn distributie te bestuderen van coronoidfracturen waarbij de incisura radialis ulnae is betrokken. Tweeënvijftig patiënten werden geanalyseerd middels Q3DCT en fractuurkaart gerelateerde technieken.

Fractuurkaarten en Q3DCT data lieten zien dat fracturen ter plaatse van de basis van het coronoid (type 3) een meer complexe betrokkenheid hebben van de incisura radialis in vergelijking met fracturen van de tip en anteromediale facet (type 1 en 2, respectievelijk). Er was geen verschil in de mate van articulaire betrokkenheid, comminutie en fractuurlijn oriëntatie tussen type 1 en 2 coronoidfracturen.

DEEL II: ANALYSE VAN FRACTUURKARAKTERISTIEKEN (KWANTITATIEF): METING VAN SPECIFIEKE FRAGMENTEN EN ARTICULAIRE BETROKKENHEID

Q3DCT-studie van coronoidfracturen

Het doel van hoofdstuk 6 was het omschrijven van specifieke karakteristieken (i.e., aantal fractuurfragmenten, volume en articulaire betrokkenheid) van coronoidfracturen middels Q3DCT technieken. In totaal zijn 82 fracturen van het coronoid geanalyseerd.

Analyse van Q3DCT reconstructies maakte duidelijk dat de articulaire betrokkenheid en het fragment volume het kleinste waren bij fracturen van de tip. Verder waren fracturen van het anteromediale facet en de basis van het coronoid comminutiever dan tip fracturen. Het fragment volume en de articulaire betrokkenheid waren het grootste bij fracturen ter plaatse van de basis van het coronoid. Daarnaast werd verschil in coronoidfractuur morfologie vastgesteld bij het vergelijken van verschillende elleboog fractuur-dislocaties.

Q3DCT-studie van het posteromediale fragment bij complexe tibiaplateaufracturen

In hoofdstuk 7 was de doelstelling 2D- en 3DCT karakteristieken van het posteromediale fragment bij complexe tibiaplateaufracturen te analyseren. De relatie tussen karakteristieken van het posteromediale fragment en fixatie van het fragment middels lateraal geplaatste schroeven werd onderzocht met behulp van Q3DCT technieken. Vierentachtig complexe tibiaplateaufracturen werden geanalyseerd.

Karakteristieken van het posteromediale fragment, bepaald op basis van 2D- en 3DCT, helpen bij het voorspellen van fixatie door lateraal geplaatste schroeven met behulp van (hoekstabiele) plaat-schroef-systemen. Grotere articulaire betrokkenheid en posterieure corticale hoogte, zoals gemeten met 2DCT, waren geassocieerd met betere fixatie. Van de fragmentkarakteristieken bepaald middels 2DCT was grotere sagittale fractuurhoek geassocieerd met slechtere fixatie. Analyse middels 3DCT liet zien dat grotere articulaire betrokkenheid en fragment volume waren geassocieerd met betere fixatie.

DEEL III: ANALYSE VAN DE BEOORDELAARSBETROUWBAARHEID VAN FRACTUURKARAKTERISTIEKEN: BEPALEN VAN OVEREENKOMST TUSSEN CHIRURGEN

Beoordelaarsbetrouwbaarheid voor karakteristieken van tibiaplateaufracturen

De opzet van hoofdstuk 8 was het bepalen van de inter-beoordelaarsbetrouwbaarheid en diagnostische accuraatheid van 2D- en 3DCT beoordeling van fractuurkarakteristieken van het tibiaplateau. Orthopedische (trauma)chirurgen en arts-assistenten werden gerandomiseerd voor 2DCT of 2D- en 3DCT evaluatie van 15 complexe tibiaplateaufracturen. In totaal voltooiden 81 beoordelaars de online evaluatie.

De beoordelaarsbetrouwbaarheid voor CT gebaseerde evaluatie van karakteristieken van tibiaplateaufracturen varieerde tussen “matig” en “voldoende tot goed”. Diagnostische accuraatheid was beter voor specifieke karakteristieken die frequenter voorkomen (i.e., laterale en posteromediale component) en varieerde tussen 70% en 89%. Het toevoegen van 3DCT reconstructies aan de beoordeling leidde niet tot verbetering van inter-beoordelaarsbetrouwbaarheid of diagnostische accuraatheid.

Beoordelaarsbetrouwbaarheid voor de Schatzker en Luo classificatie

In hoofdstuk 9 was het doel de inter-beoordelaarsbetrouwbaarheid van de Schatzker[3] en Luo classificatie[4] voor 2D- en 3DCT evaluatie te onderzoeken. In totaal werden 81 beoordelaars, orthopedische (trauma)chirurgen en arts-assistenten, gerandomiseerd voor beoordeling van 2DCT of 2D- en 3DCT scans van patiënten met complexe tibiaplateaufracturen.

De beoordelaarsbetrouwbaarheid was “matig” voor beide fractuurclassificatiesystemen. Echter, de overeenkomst tussen beoordelaars was significant hoger voor de Schatzker classificatie vergeleken met de Luo classificatie. De toevoeging van 3DCT reconstructies aan de evaluatie resulteerde niet in verbetering van de beoordelaarsbetrouwbaarheid voor CT gebaseerde evaluatie van bovenstaande classificatiesystemen.

Beoordelaarsbetrouwbaarheid voor proximale humerusfracturen

Het doel van hoofdstuk 10 was het effect te onderzoeken van het trainen van beoordelaars in een simpele classificatie van proximale humerusfracturen op inter-beoordelaarsbetrouwbaarheid. Honderdvijfentachtig beoordelaars (i.e., orthopedisch chirurgen) werden gerandomiseerd voor het ontvangen van training of geen training alvorens het beoordelen van 30 preoperatieve röntgenfoto’s van patiënten die operatief zijn behandeld.

De beoordelaarsbetrouwbaarheid was “gering” voor beide groepen en er was geen significant verschil tussen chirurgen in de training en geen training groep. Echter, subgroep analyse liet zien dat training de overeenkomst verbeterde tussen algemene orthopedisch chirurgen, orthopedisch chirurgen werkzaam in de Verenigde Staten en chirurgen met relatief weinig ervaring (≤5 jaar).

DEEL IV: ANALYSE VAN DE INVLOED VAN FRACTUURKARAKTERISTIEKEN OP BESLUITVORMING: EVALUATIE VAN VARIATIE IN BEHANDELING

Variatie in behandeling van trochantere fracturen

In hoofdstuk 11 was het doel de variatie in behandeling van stabiele (AO/OTA 31-A1) en instabiele (AO/OTA 31-A2) trochantere fracturen te bestuderen en tevens de invloed van patiënt-, chirurg- en fractuurkarakteristieken op de besluitvorming te onderzoeken. In totaal namen 128 orthopedisch chirurgen deel aan deze studie waarbij hen werd gevraagd 30 röntgenfoto's van patiënten met een A1 of A2 trochantere fractuur te beoordelen en daarna de behandeling van eerste keuze te bepalen: intramedullaire nagel (IMN) of extramedullaire glijdende heupschroef (GHS).

De overeenkomst tussen orthopedisch chirurgen voor de behandeling van A1 en A2 trochantere fracturen was "matig". Factoren geassocieerd met voorkeur voor IMN waren chirurgen werkzaam in de Verenigde Staten vergeleken met Europa of het Verenigd Koninkrijk; gebruik van alleen IMN gedurende de opleiding vergeleken met chirurgen die zijn opgeleid met beide implantaten (i.e., IMN en GHS); en A2 vergeleken met A1 trochantere fracturen.

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2. Doornberg, J.N. and D. Ring, Coronoid fracture patterns. J Hand Surg Am, 2006. 31(1): p. 45-52.
3. Schatzker, J., R. McBroom, and D. Bruce, The tibial plateau fracture. The Toronto experience 1968-1975. Clin Orthop Relat Res, 1979(138): p. 94-104.
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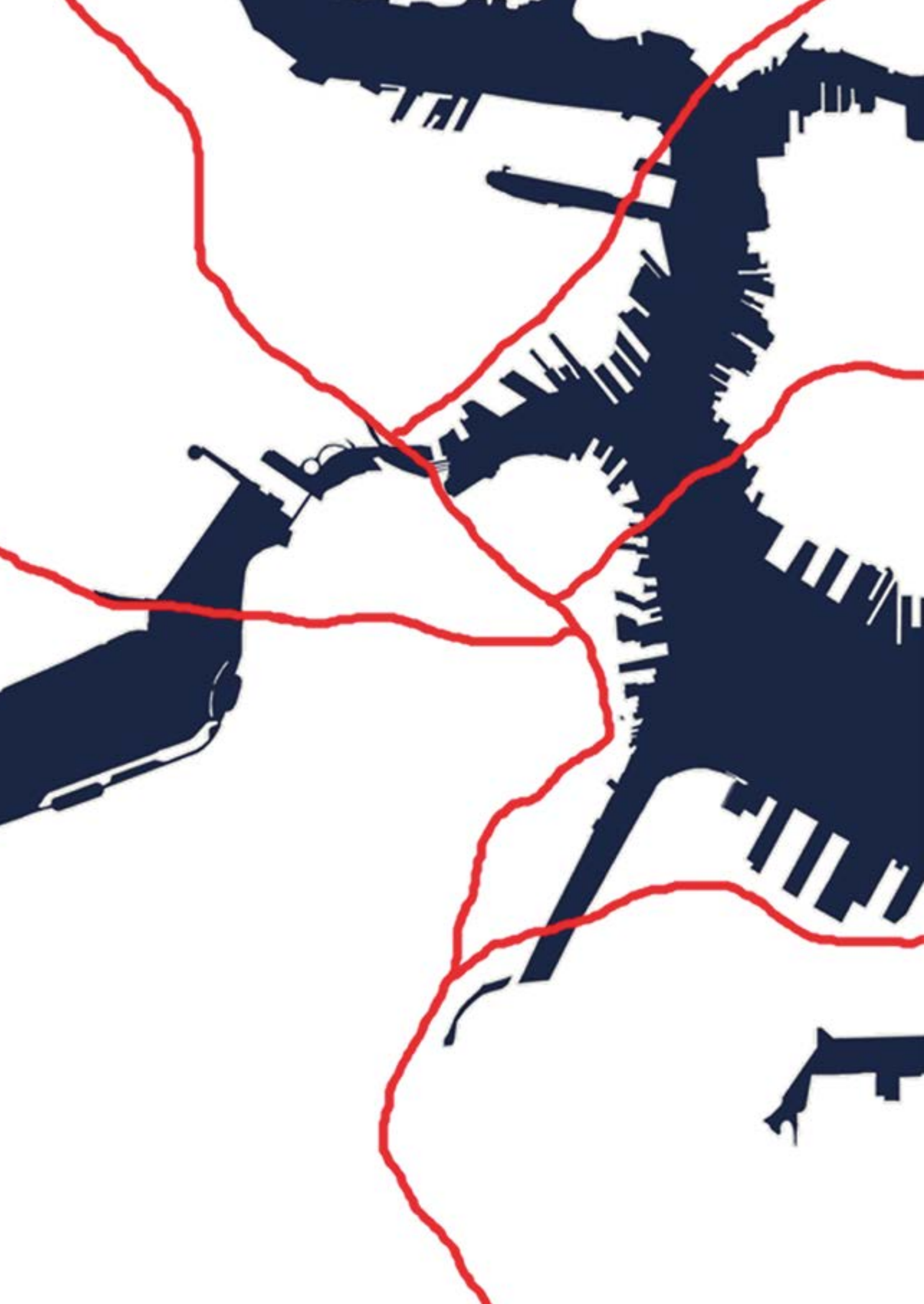

ADDENDUM

DANKWOORD (ACKNOWLEDGEMENT)

De afgelopen jaren heb ik met veel plezier onderzoek mogen doen. Voor de totstandkoming van dit proefschrift ben ik veel mensen dankbaar die mij geïnspireerd, ondersteund en geholpen hebben.

Om te beginnen wil ik Job Doornberg, mijn copromotor, bedanken. Mijn avontuur is bij jou begonnen in de Blaffende Vis. Een fantastisch moment om op klaarlichte dag in een kroeg midden in de Jordaan een onderzoek te starten. Een mooi voorbeeld hoe jij werk (i.e., onderzoek) met plezier en andersom kan combineren. Je hebt mij gelanceerd naar Boston, ondersteund bij beursaanvragen en geholpen met het vormgeven van dit proefschrift. Dank voor jouw tijd, energie, inspiratie en natuurlijk het (werk)plezier!

Dan mijn promotoren,

Dear David, I want to thank you for the great “Boston experience”. It felt like a privilege to work with you and others at MGH. I have great memories of biking across the Longfellow Bridge in the early morning, working in your office together with Mariano, and lunch outside the Yawkey Center. Being a “long-termer” as part of the Research Factory has been an unforgettable experience. I’m very grateful for the opportunities. Thanks again for your time, day and night, energy, patience, and guidance.

Beste professor Van Dijk, van begin af aan heeft u mijn ambitie om te promoveren ondersteund. Ik kijk met veel plezier terug naar onze ontmoetingen in binnen- en buitenland. In Amsterdam op de vertrouwde 4^{e} verdieping, of Boston tijdens een van uw flitsbezoeken, en zelfs Las Vegas tijdens de Annual Meeting van AAOS. Een mooie reflectie van uw internationale netwerk en loopbaan. Dank voor uw betrokkenheid en mede mogelijk maken van dit proefschrift.

Opponenten en leden van de leescommissie: dr. L.M.G. Geeraedts, prof. dr. M. Maas, prof. dr. M.P.J. van den Bekerom, prof. dr. A.H. Zwinderman, prof. dr. D. Eygendaal en dr. F.F.A. IJpma. Dank voor het beoordelen van mij proefschrift en de bereidheid om zitting te nemen in de promotiecommissie.

Ook wil ik mijn co-auteurs bedanken, onder andere George Dyer, Rik Molenaars, Peter Kloen, Amir Reza Kachooei, Matthew Tarabochia, Neal Chen, Stein Janssen, Thierry Guitton, Marilyn Heng, Lucian Solomon, Michael Kuntz, Tundi Schouten en Daniël Haverkamp. Mooi teamwork en trans-Atlantische samenwerking hebben de studies tot stand gebracht.

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Gino, dank voor jouw support. Van het terras in Boston tot de OK in het AMC en daarbuiten. Cheers!

Collega's en stafleden van de afdeling chirurgie in het Rode Kruisziekenhuis (vooropleiding), en orthopedie in het Slotervaatziekenhuis, AMC en Amphia, dank voor de teamspirit, samenwerking en het werkplezier.

Onderzoekers in Boston, longtermers en shorttermers, dank voor de mooie tijd.

Het secretariaat kan ik natuurlijk niet vergeten. Tineke, Ellen, en ook Rosalie, veel dank. Zonder jullie hulp was er niks van de grond gekomen.

Broers en zussen, Mark, Wouter, Maartje, Sjaak en Charlotte, ik ben super trots dat mijn naam in dit rijtje thuishoort. Aan talent in de familie geen gebrek, alleen is "nummer 3" misschien net even iets knapper dan de rest. Zonder gekheid, dank voor jullie aanmoedigingen gedurende mijn (lange) PhD traject.

Inne, Pauline, Thom, Annelot, René, dank voor het uithouden met de Mellema's.

Van der Sande's, ook jullie hebben mijn promotieplannen van A tot Z meegemaakt. En vertrouwen gehad in een goede afloop van mijn tijd in Boston; eerst zonder en daarna samen met Anita. Dank voor het geven van vertrouwen, steun, en liefde.

Geneeskundevriendjes, Ben, Tom, Luc, Thom, vriendjes van vroeger, Berend en AF, en Rienk, dank voor alle zin en onzin die geholpen hebben bij het afronden van dit proefschrift of juist niet. In ieder geval veel gelachen om de gezonde scepsis rondom de langverwachte afronding van mijn boekje. Hier is ie dan!

Ouders, pa en ma, zonder jullie had ik niet gestaan waar ik nu sta en was ik niet de persoon geworden die ik nu ben. Jullie zijn betrokken in elk aspect van mijn leven. Dank daarvoor. Dank voor de stabiele basis, de thuishaven, betrokkenheid, liefde, vertrouwen, steun en niet onbelangrijk ook het papa-en-mama-fonds.

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En natuurlijk, niet in de laatste plaats, ben ik God dankbaar. U zij de glorie!

PORTFOLIO

Name PhD student: Jos J. Mellema
PhD period: 2013-2021
Name PhD supervisor: C. Niek van Dijk and David C. Ring

PhD training

Research Courses	Year
Course Biomedical Research Investigators and Personnel – MGH, Boston, MA, USA	2013
Biostatistics Course – MGH, Boston, MA, USA	2014
Problem-Based Biostatistics for the Clinical Investigator – MGH, Boston, MA, USA	2015
Certificate in Applied Biostatistics – HMS, Boston, MA, USA	2015

Seminars, workshops and master classes	Year
Journal Club Orthopedic Hand Service – MGH, Boston, MA, USA	2014
Grand Rounds Department of Orthopedic surgery – MGH, Boston, MA, USA	2014
The NAF connection – Fulbright, New York, NY, USA	2014
Enrichment Seminar – Fulbright, Portland, OR, USA	2014
Journal Club Orthopedic Hand Service – MGH, Boston, MA, USA	2015
Orthopedic surgery: pearls and pitfalls – MGH, Boston, MA, USA	2015
Basiscursus Heelkunde Specialismen – CCN, Utrecht, Nederland	2016
Advanced Trauma Life Support – ACS, Philadelphia, PA, USA	2016
Chirurgische Anatomie – VUmc, Amsterdam, Nederland	2016
Basic Principles of Fracture Management – AO Nederland, Oisterwijk, Nederland	2017

Presentations

Podium Presentation	Year
Mellema JJ, Doornberg JN, Guitton TG, Ring D. Biomechanical Studies in Orthopaedic Surgery: Science (f)or Common Sense? - 41st New England Hand Society Meeting, 6 december, 2013, Sturbridge, MA, USA.	2013
Mellema JJ, Doornberg JN, Guitton TG, Ring D. Biomechanical Studies in Orthopaedic Surgery: Science (f)or Common Sense? - Combined Meeting of Orthopaedic Research Societies, 14 oktober, 2013, Venetië, Italië. - EFORT Congress, 4 juni, 2014, London, United Kingdom.	2013/2014
Mellema JJ, Janssen SJ, Guitton TG, Ring D. Quantitative Three-Dimensional Computed Tomography Measurements of Coronoid Fractures. - 42nd New England Hand Society Meeting, 4 december, 2014, Sturbridge, MA, USA.	2014
Molenaars RJ, **Mellema JJ**, Doornberg JN, Kloen P. Tibial Plateau Fracture Characteristics: Computed Tomography Mapping of Lateral, Medial, and Bicondylar Fractures - Traumadagen 2014, Amsterdam, the Netherlands	2014
Mellema JJ, Doornberg JN, Dyer GS, Ring D. Mapping of Coronoid Fractures: Patterns and Distribution of Fracture Lines of Specific Injury Patterns of the Coronoid. - 25th Annual Richard J. Smith Day, 30 mei, 2014, Cambridge, MA, USA. - AAOS Annual Meeting, 24 maart, 2015, Las Vegas, Nevada, USA.	2014/2015

	Year
Mallee WH, Mellema JJ, Guitton TG, Goslings JC, Ring D, Doornberg JN. Accuracy and Reliability of 6-Week Radiographs for Scaphoid Fractures: Online Radiographs in JPEG versus DICOM format.	2015
- 26th Annual Richard J. Smith Day, 29 mei, 2015, Cambridge, MA, USA.	
Mellema JJ, Kuntz MT, Guitton TG, Ring D (presented by Hartveldt S). Simplifying classifications and training observers do not improve interobserver reliability for proximal humeral fractures.	2015
- 26th Annual Richard J. Smith Day, 29 mei, 2015, Cambridge, MA, USA.	
Burton KR, **Mellema JJ**, Menendez ME, Ring D, Chen NC. The Yield of Subsequent Radiographs During Nonoperative Treatment of Radial Head and Neck Fractures.	2015
- 43rd New England Hand Society Meeting, 4 december, 2015, Sturbridge, MA, USA.	
Kachoei AR, **Mellema JJ**, Tarabochia MA, Chen N, Van Dijk CN, Ring D. Involvement of the Lesser Sigmoid Notch in Elbow Fracture Dislocations.	2016
- IFSSH 50th anniversary, 28 October 2016, Buenos-Aires, Argentina	
Oflazoglu K, **Mellema JJ**, Menendez ME, Mudgal CS, Ring D, Chen NC. Prevalence and Factor with Major Depression in Hand Surgery Patients	2016
- 44th New England Hand Society Meeting, 2 december, 2016, Sturbridge, MA, USA.	
Ozkan S, **Mellema JJ**, Nazzal A, Lee SP, Ring D. Online Health Information Seeking in Hand and Upper Extremity Surgery.	2016
- 44th New England Hand Society Meeting, 2 december, 2016, Sturbridge, MA, USA.	
Mellema JJ, Heng M, Van Dijk CN, Ring D, Doornberg JN. Quantitative 3D CT Analysis of the Posteromedial Fragment in Complex Tibial Plateau.	2017
- Wetenschapsdag Heelkunde VUmc, 31 mei, 2017, Amsterdam, Nederland	

Poster Presentation	Year
Molenaars R, **Mellema JJ**, Doornberg JN, Kloen P. Tibia Plateau Fracture Characteristics	2014
- EFORT Congress, 4-6 juni, 2014, London, United Kingdom.	
Mellema JJ, Doornberg JN, Dyer GS, Ring D. Mapping of Coronoid Fractures: Patterns and Distribution of Fracture Lines of Specific Injury Patterns of the Coronoid.	2014
- 69th Annual Meeting of the ASSH, 18-20 september, 2014, Boston, MA, USA.	
Mellema JJ, Janssen SJ, Guitton TG, Ring D. Quantitative Three-Dimensional Computed Tomography Measurements of Coronoid Fractures.	2014
- MGH Clinical Research Day, 9 oktober, 2014, Boston, MA, USA.	
Burton KR, **Mellema JJ**, Menendez ME, Ring D, Chen NC. The Yield of Subsequent Radiographs During Nonoperative Treatment of Radial Head and Neck Fractures	2015/2016
- MGH Clinical Research Day, 8 oktober, , Boston, MA, USA.	2015
- 76th Annual Soma Weiss Medical and Dental Student Research Day, Harvard Medical School, 12 januari 2016, Boston, MA, USA	
Mellema JJ, Eygendaal D, Van Dijk CN, Ring D, Doornberg JN. Fracture Mapping of Displaced Partial Articular Fractures of the Radial Head.	2016
- 71th Annual Meeting of the ASSH, 29 september- 1 oktober, 2016, Austin, TX, USA.	
Oflazoglu K, **Mellema JJ**, Menendez ME, Mudgal CS, Ring D, Chen NC. Prevalence and Factor with Major Depression in Hand Surgery Patients	2016
- MGH Clinical Research Day, 6 oktober, 2016, Boston, MA, USA.	

Portfolio (continued)

(Inter)national conferences	Year
41st New England Hand Society Meeting, Sturbridge, MA, USA	2013
69th Annual Meeting of the ASSH, Boston, MA, USA	2014
25th Annual Richard J. Smith Day, Cambridge, MA, USA	2014
Inaugural Jesse B. Jupiter International Hand Forum, Cambridge, MA, USA	2014
42nd New England Hand Society Meeting, Sturbridge, MA, USA	2014
Harvard Orthopedic Trauma Research Day, Boston, MA, USA	2014
AAOS Annual Meeting, Las Vegas, Nevada, USA	2015
26th Annual Richard J. Smith Day, Cambridge, MA, USA	2015
Second Annual Jesse B. Jupiter International Hand Forum, Cambridge, MA, USA	2015
Harvard Orthopedic Trauma Research Day, Boston, MA, USA	2015

Teaching

Supervising, tutoring, and mentoring	Year
Casey M. O'Connor – MGH, Boston, MA, USA	2013
Frans J. Mulder – MGH, Boston, MA, USA	2014
Femke M. Claessen – MGH, Boston, MA, USA	2014
Aditya Gill – MGH, Boston, MA, USA	2014
Rik Molenaars – AMC, Amsterdam, Netherlands	2014
Kyle R. Burton – MGH, Boston, MA, USA	2014
Ankit Sood – MGH, Boston, MA, USA	2014
Michael T. Kuntz – MGH, Boston, MA, USA	2014
Rinne M. Peters – MGH, Boston, MA, USA	2015
Nicky Stoop – MGH, Boston, MA, USA	2015
Kamil Oflazoglu – MGH, Boston, MA, USA	2015
Zichao Xue, MGH – Boston, MA, USA	2015
Reinier B. Beks – MGH, Boston, MA, USA	2015
Sezai Ozkan, MGH – Boston, MA, USA	2015
Suzanne C. Wilkens – MGH, Boston, MA, USA	2015
Tom J. Crijns – AMC, Amsterdam, Netherlands	2018

Parameters of Esteem

Grants	Year
Fulbright Scholarship	2013
VSBfonds beurs	2013
Fellowship Netherland-America Foundation	2013
Vreedefonds	2014
Scholten-Cordes Fonds	2014
Stichting Prof. Michaël-van Vloten Fonds	2014
Haak Bastiaanse-Kuneman Stichting	2014
MGH Orthopaedic Research Grant	2015

Portfolio (continued)

Awards and Prizes	Year
Traumaplatform Award – First Podium Presentation	2015
Paper of the Month – Graduate Student Division, Center for Faculty Development, Massachusetts General Hospital. "Prevalence and Factor with Major Depression in Hand Surgery Patients."	2015

Publications

Peer reviewed	Year
Tosti R, Ilyas AM, **Mellema JJ**, Guitton TG, Ring D. Interobserver Variability in the Treatment of Little Finger Metacarpal Neck Fractures. J Hand Surg Am. 2014 Jul 14.	2014
Mellema JJ, Doornberg JN, Dyer GS, Ring D. Distribution of Coronoid Fracture Lines by Specific Patterns of Traumatic Elbow Instability. J Hand Surg Am. 2014 Jul 25.	2014
Mellema JJ, Doornberg JN, Guitton TG, Ring D. Biomechanical Studies: Science (f)or Common Sense? Injury. 2014 Sep 28.	2014
Mellema JJ, Janssen SJ, Guitton TG, Ring D. Quantitative Three-Dimensional Computed Tomography Measurements of Coronoid Fractures. J Hand Surg Am. 2014 Dec 13.	2014
Mellema JJ, O'Connor CM, Overbeek C, Hageman MG, Ring D. The effect of feedback regarding coping strategies and illness behavior on hand surgery patient satisfaction and communication: a randomized controlled trial. HAND. 2015 Feb 18.	2015
Heus C, **Mellema JJ**, Giannakopoulos GF, Zuidema WP. Outcome of penetrating chest injuries in an urban level I trauma center in the Netherlands. Eur J Trauma Emerg Surg. 2015 Apr 25.	2015
Molenaars R, **Mellema JJ**, Doornberg JN, Kloen P. Tibial Plateau Fracture Characteristics: Computed Tomography Mapping of Lateral, Medial, and Bicondylar Fractures. JBJS Am. 2015 Sep 16.	2015
Moradi A, **Mellema JJ**, Oflazoglu K, Isakov A, Ring D, Vranceanu, AM. The Relationship between Catastrophic Thinking and Hand Diagram Areas. J Hand Surg Am. 2015 Sep 22.	2015
Mangnus L, Meijer D, Stufkens SA, **Mellema JJ**, Steller EPh, Kerkhoffs GMMJ, Doornberg JN. Posterior Malleolar Fracture Patterns. J Orthop Trauma. 2015 Sep 29.	2015
Lubberts B, Janssen SJ, **Mellema JJ**, Ring D. Quantitative 3-Dimensional Computed Tomography Analysis of Olecranon Fractures. J Shoulder Elbow Surg. 2015 Dec 17.	2015
Menendez ME, Mellema JJ, Ring, D. Attitudes and Self-Reported Practice of Hand Surgeons Regarding Prescription Opioid Use. HAND. 2015 Dec.	2015

	Year
Claessen FM, **Mellema JJ**, Stoop N, Lubberts B, Ring D, Poolman RW. The Influence of Priming on Patient Reported Ouctome Measures (PROMs). Psychosomatics. 2016 Jan-Feb.	2016
Peters R, Menendez ME, **Mellema JJ**, Ring D. Sleep Disturbance and Disability in Upper Extremity Illness. Arch Bone Jt Surg. 2016 Jan.	2016
Gill A, **Mellema JJ**, Menendez ME, Ring D. Articular Osteotomy of the Distal Humerus and Excision of Extensive Heterotopic Ossification. Injury. 2016 Jan 11.	2016
Mellema JJ, Doornberg JN, Molenaars R, Ring D, Kloen P. Interobserver Reliability of The Schatzker and Luo Classification Systems for Tibial Plateau Fractures. Injury. 2016 Jan 2.	2016
Oflazoglu K, **Mellema JJ**, Menendez ME, Mudgal CS, Ring D, Chen NC. Prevalence and Factor with Major Depression in Hand Surgery Patients. J Hand Surg Am. 2016 Feb.	2016
Mellema JJ, Lindenhovius AL, Jupiter JB. The Posttraumatic Stiff Elbow: An Update. Curr Rev Musculoskelet Med. 2016 Mar 17.	2016
Mallee WH, **Mellema JJ**, Guitton T, Goslings JC, Ring, Doornberg JN. 6-week radiographs unsuitable for diagnosis of suspected scaphoid fractures. Arch Orthop Trauma Surg. 2016 Mar 30. * shared first authorship	2016
Mellema JJ, Eygendaal D, Van Dijk CN, Ring D, Doornberg JN. Fracture Mapping of Displaced Partial Articular Fractures of the Radial Head. J Shoulder Elbow Surg. 2016 Apr 1.	2016
Kachoei AR, **Mellema JJ**, Tarabochia MA, Chen N, Van Dijk CN, Ring D. Involvement of the Lesser Sigmoid Notch in Elbow Fracture Dislocations. J Shoulder Elbow Surg. 2016 May 24. * shared first authorship	2016
Mellema JJ, Doornberg JN, Molenaars R, Ring D, Kloen P. Diagnosis of Tibial Plateau Fracture Characteristics: Reliability and Diagnostic Accuracy. J Orthop Trauma. 2016 May	2016
Burton KR, **Mellema JJ**, Menendez ME, Ring D, Chen NC. The Yield of Subsequent Radiographs During Nonoperative Treatment of Radial Head and Neck Fractures. J Shoulder Elbow Surg. 2016 Aug.	2016
Mulder FJ, **Mellema JJ**, Ring D. Proximity of Vital Structures to the Clavicle: Comparison of Fractured and Non-Fractured Side. Arch Bone Jt Surg. 2016 Oct.	2016
Talaei-Khoei M, Mohamadi A, **Mellema JJ**, Tourjee SM, Ring D, Vranceanu AM. The direct and indirect effects of the negative affectivity trait on self reported physical function among patients with upper extremity conditions. Psychiatry Res. 2016 Oct.	2016
Ozkan S, **Mellema JJ**, Nazzal A, Lee SP, Ring D. Online Health Information Seeking in Hand and Upper Extremity Surgery. J Hand Surg Am. 2016 Oct 14.	2016

Portfolio (continued)

	Year
Lubberts B, **Mellema JJ**, Janssen SJ, Ring D. Fracture Line Distribution of Olecranon Fractures. Arch Orthop Trauma Surg. 2016 Nov 10.	2016
Bernstein DN, Sood A, **Mellema JJ**, Li Y, Ring D. Lifetime Prevalence of and Factors Associated with Non-Traumatic Musculoskeletal Pains amongst Surgeons and Patients. Int Orthop. 2016 Nov 18.	2016
Braun Y, **Mellema JJ**, Peters RM, Curley S, Burchill D, Ring D. The Relationship between Therapist-Rated Function and Patient-Reported Outcome Measures. J Hand Ther. 2016 Nov 29.	2016
Mellema JJ, Kuntz MT, Guitton TG, Ring D. The Effect of Two Factors on Interobserver Reliability for Proximal Humeral Fractures. J Am Acad Orthop Surg. 2016 Nov 30.	2016
Wilkens SC, Xue Z, **Mellema JJ**, Ring D, Chen N. Unplanned Reoperation after Trapeziometacarpal Arthroplasty. HAND. 2016 Nov 15.	2016
Ozkan S, **Mellema JJ**, Ring D, Chen NC. Interobserver Variability of Radiographic Assessment Using a Mobile Messaging Application as a Teleconsultation Tool. Arch Bone Jt Surg. 2017 Sep 5.	2017
Beks RB, **Mellema JJ**, Menendez ME, Chen N, Ring D, Vranceanu AM. Does Mindfulness Correlate With Physical Function and Pain Intensity in Patients With Upper Extremity Ilness? HAND. 2017 Mar 1.	2017
Stoop N, Menendez ME, **Mellema JJ**, Ring D. The PROMIS Global Health Questionnaire Correlates With the QuickDASH in Patients with Upper Extremity Illness. HAND. 2017 Feb 1.	2017
Peters R, Menendez ME, **Mellema JJ**, Ring D, Smith RM. Axillary Artery Injury Associated with Proximal Humerus Fracture: a Report of 6 Cases. Arch Bone Jt Surg. 2017 Jan.	2017
Mellema JJ, Mallee WH, Guitton TG, Van Dijk CN, Ring D, Doornberg JN. Online Studies on Variation in Orthopedic Surgery: Observer Participation and Satisfaction. J Digit Imaging. 2017 Jan 24.	2017
Crijns TJ, **Mellema JJ**, Ozkan S, Ring D, Chen N. Classification of Tibial Plateau Fractures Using 3DCT with and without Subtraction of Unfractured Bones. Injury. 2020 Jul 21.	2020
Mellema JJ, Janssen S, Schouten T, Haverkamp D, Van den Bekerom MPJ, Ring D, Doornberg JN. Orthopaedic Surgeons' Variation in Choice of Sliding Hip Screw versus Intramedullary Nailing for A1 and A2 Trochanteric Hip Fractures: What Factors Influence Decision-Making? Bone Joint J. (Manuscript Accepted)	2021

MGH = Massachusetts General Hospital
HMS = Harvard Medical School
CCN = Collegium Chirurgicum Neerlandicum
ACS = American College of Surgeons
AMC = Academisch Medisch Centrum

ABOUT THE AUTHOR

Jos Jasper Mellema was born on July 7, 1987, in Nieuwegein, the Netherlands. After graduating high school (VWO, Guido de Brès, Amersfoort) he started medical school at the VU University, Amsterdam, in 2006.

After receiving his medical degree in 2013, Jos started working as a Research Fellow under the guidance of Professor David Ring and Job Doornberg at the Hand and Upper Extremity Service, Department of Orthopedic Surgery, Massachusetts General Hospital, carrying a NAF-Fulbright Scholarship. In collaboration with prof. dr. C. Niek van Dijk, Department of Orthopedic Surgery, Academic Medical Center, Amsterdam, he outlined his PhD plan and was part of the Boston-Amsterdam research collaboration between 2013-2015.

In 2016 he started the orthopedic surgery residency program (Academic Medical Center, Amsterdam; under supervision of prof. dr. Gino M.M.J. Kerkhoffs) at the Department of General Surgery, Rode Kruis Ziekenhuis, Beverwijk. He started working as an orthopedic surgery resident at MC Slotervaart, Amsterdam, in 2018. Subsequently, he worked for 2 years at the Department of Orthopedic Surgery, Academic Medical Center, Amsterdam, and in 2021 he continued his residency at the Department of Orthopedic Surgery, Amphia Hospital, Breda.

He is married to Anita (2019), father of Tammo (2020) and living in Amsterdam.