Advancements in classification, treatment and outcome of radial head fractures
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CHAPTER 4

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

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David Zurakowski, PhD
Chaitanya Mudgal, MD
David Ring, MD PhD

Submitted
Abstract

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

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

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

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

Level of Evidence: Diagnostic, Level I

Introduction

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

Three-dimensional models that are constructed based on CT images and can be held in the hand and, may facilitate fracture characterization and surgical planning. Computer-generated bone models have been used in the planning of osteotomy of multidirectional distal radius malunions.

This investigation tests the hypothesis that 3D-CT images identify and predict fracture characteristics more accurately than 2D-CT images and radiographs, using a prospective study design with intraoperative inspection as the reference standard. A secondary hypothesis was that 3D physical models predict fracture characteristics more accurately than 2D and 3D-CT images and radiographs.

Material and Methods

Inclusion and Exclusion Criteria

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

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

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

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

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

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

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

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

Table I. Interobserver Agreement for Classification and Treatment of Radial Head and Neck Fractures for Each CT Method and Direct Operative View

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>2D CT</th>
<th>2D/3D CT</th>
<th>2D/3D CT With Model</th>
<th>Operative View (Gold Standard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broberg-Morrey</td>
<td>0.23*</td>
<td>0.26*</td>
<td>0.37*</td>
<td>0.38*</td>
</tr>
<tr>
<td>Fracture line</td>
<td>0.69†</td>
<td>0.54†</td>
<td>0.51†</td>
<td>0.54†</td>
</tr>
<tr>
<td>Comminution</td>
<td>0.31†</td>
<td>0.48†</td>
<td>0.53†</td>
<td>0.40†</td>
</tr>
<tr>
<td>Articular surface</td>
<td>0.12</td>
<td>0.28</td>
<td>0.22</td>
<td>0.28</td>
</tr>
<tr>
<td>Gap &gt;2 mm</td>
<td>0.37†</td>
<td>0.59†</td>
<td>0.57†</td>
<td>0.37†</td>
</tr>
<tr>
<td>Impaction</td>
<td>0.17</td>
<td>0.24</td>
<td>0.12</td>
<td>0.23</td>
</tr>
<tr>
<td>&gt;3 fragments</td>
<td>0.29</td>
<td>0.50†</td>
<td>0.64†</td>
<td>0.57†</td>
</tr>
<tr>
<td>Small Fragments</td>
<td>0.26</td>
<td>0.34*</td>
<td>0.33†</td>
<td>0.47†</td>
</tr>
<tr>
<td>Proposed Treatment</td>
<td>0.42†</td>
<td>0.53†</td>
<td>0.69†</td>
<td>0.85†</td>
</tr>
</tbody>
</table>

Data are kappa (κ) values based on 39 cases evaluated by two independent surgeons. Guidelines for strength of observer agreement: k = 0.00-0.20 (slight); k = 0.21-0.40 (fair); k = 0.41-0.60 (moderate); k = 0.61-0.80 (substantial); k = 0.81-1.00 almost perfect. Significant interobserver agreement beyond chance level (k < 0.05; p < 0.05).
The addition of 3D-CT and the 3D models to 2D-CT and radiographs led to significant improvements in sensitivity for diagnosis of fracture line separation of the entire articular surface from the radial neck, comminution of the radial neck, involvement of the articular surface, articular gap or step of 2 millimeters or greater, central impaction of the articular surface, presence of more than 3 articular fragments and to the presence of articular fragments too small to repair (all p < 0.01, Table II). There were no significant changes in specificity between the three methods.

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>2D CT Alone</th>
<th>2D/3D CT</th>
<th>2D/3D CT with Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Specificity</td>
<td>Sensitivity</td>
</tr>
<tr>
<td>Fracture Line</td>
<td>85</td>
<td>100</td>
<td>95*</td>
</tr>
<tr>
<td></td>
<td>(91-99)</td>
<td>(90-100)</td>
<td>(78-100)</td>
</tr>
<tr>
<td>Comminution</td>
<td>98</td>
<td>93</td>
<td>81*</td>
</tr>
<tr>
<td></td>
<td>(89-99)</td>
<td>(80-100)</td>
<td>(67-100)</td>
</tr>
<tr>
<td>Articular Surface</td>
<td>94</td>
<td>67</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>(84-99)</td>
<td>(56-98)</td>
<td>(88-100)</td>
</tr>
<tr>
<td>Gap &gt; 2 mm</td>
<td>93</td>
<td>78</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>(81-99)</td>
<td>(66-96)</td>
<td>(86-100)</td>
</tr>
<tr>
<td>Impaction</td>
<td>57</td>
<td>88</td>
<td>86*</td>
</tr>
<tr>
<td></td>
<td>(42-80)</td>
<td>(65-97)</td>
<td>(74-97)</td>
</tr>
<tr>
<td>&gt;3 Fractured Fragments</td>
<td>55</td>
<td>82</td>
<td>100*</td>
</tr>
<tr>
<td></td>
<td>(44-74)</td>
<td>(66-95)</td>
<td>(80-100)</td>
</tr>
<tr>
<td>Small Fragments</td>
<td>74</td>
<td>83</td>
<td>100*</td>
</tr>
<tr>
<td></td>
<td>(56-88)</td>
<td>(57-97)</td>
<td>(53-100)</td>
</tr>
<tr>
<td>Proposed Treatment</td>
<td>74</td>
<td>83</td>
<td>89*</td>
</tr>
<tr>
<td></td>
<td>(56-88)</td>
<td>(57-97)</td>
<td>(54-97)</td>
</tr>
</tbody>
</table>

Values are percentages with results are based on attending surgeon for each method compared to intraoperative direct view gold standard (N = 39 paired cases). * Statistically significant compared to sensitivity for 2D CT alone (all p < 0.01). There were no significant differences detected in specificity between the three methods.
Discusison
The strengths of this investigation include the prospective design, the relatively large number of patients, and an intra-operative reference standard. The limitations of this investigation include the fact that images were usually rated after surgery (in part due to the inherent delay in receiving the physical 3D model), so that ratings of the radiological images were—in essence—retrospective; the injuries were relatively complex resulting in a spectrum bias in terms of all fractures of the radial head, although our work is representative of the types of fractures that would be studied with CT and operated on; two patients (one with addition of a capitellum/trochlea fracture and one anterior-transolecranon fracture dislocation) had non-displaced fractures of the radial neck, which are relatively unusual—both fractures were seen only on operative exposure; and multiple physicians were involved in the ratings at two sites, which makes the results more generalizable, but less consistent. These data should also be interpreted in light of the fact that the first assistant was usually a resident or fellow, so that the observer variability may largely reflect differences in training and experience.

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

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

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

Figure 3: Sensitivity and specificity according to Broberg and Morrey modification of the Mason classification stratified by 2D-CT, 2D/3D-CT and 2D/3D-CT with model.
References