Advancements in classification, treatment and outcome of radial head fractures
Guitton, T.G.

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Part II: Classification

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

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

Abstract

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

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

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

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

Level of evidence: Level IV, Diagnostic Study

Introduction

The morphology of the healthy radial head has been investigated with calliper ruler, osteometric board, coordinator measuring machine (CMM), X-ray, CT scan, Magnetic Resonance Imaging (MRI) and Computer-Aided Design (CAD) software in the past 1, 2, 4-8, 10-15, 17, 19, 20, 22, 23. Prior studies found differences between genders 6, 15, 22 and no side-to-side differences 20. Some studies have small numbers of subjects 1, 5, 10, 14, 15, 19, 20, 23, some used non-digital measurement tools 15, 19, 23, or old skeletons 2 and others use non-standard software with low quality CT scans 20. Three-dimensional CT models provide more detailed information 18. We developed a quantitative 3-dimensional computed tomography (Q3D-CT) modeling technique that can measure size, shape and proximal articular surface area.

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

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

Materials and Methods

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

Modelling Technique

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

**Evaluation**

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

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

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

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

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

Table I. Overall Results and Comparisons Between Men and Women

<table>
<thead>
<tr>
<th></th>
<th>All Patients</th>
<th>Men</th>
<th>Women</th>
<th>Men and Women Compared</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N = 50)</td>
<td>(N = 19)</td>
<td>(N = 31)</td>
<td></td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>P-Value</td>
<td></td>
</tr>
<tr>
<td>Age, (y)</td>
<td>53.22</td>
<td>46.22</td>
<td>58.21</td>
<td>0.06</td>
</tr>
<tr>
<td>Height, (m)</td>
<td>1.68 ± 0.13</td>
<td>1.74 ± 0.07</td>
<td>1.64 ± 0.14</td>
<td>&lt; 0.05*</td>
</tr>
<tr>
<td>Weight, (kg)</td>
<td>73.16 ± 2.0</td>
<td>78 ± 2.0</td>
<td>70 ± 2.0</td>
<td>&lt; 0.05*</td>
</tr>
<tr>
<td>Radial Head diameter, (mm)</td>
<td>22 ± 2.2</td>
<td>23 ± 2.0</td>
<td>20 ± 1.0</td>
<td>&lt; 0.01*</td>
</tr>
<tr>
<td>Radial Neck diameter, (mm)</td>
<td>15 ± 1.6</td>
<td>16 ± 2.0</td>
<td>14 ± 1.0</td>
<td>&lt; 0.01*</td>
</tr>
<tr>
<td>Radial Head Volume, (mm³)</td>
<td>3327 ± 901</td>
<td>4301 ± 585</td>
<td>2730 ± 386</td>
<td>&lt; 0.01*</td>
</tr>
<tr>
<td>Radial Head Surface, (mm²)</td>
<td>365 ± 83</td>
<td>441 ± 319</td>
<td>319 ± 44</td>
<td>&lt; 0.01*</td>
</tr>
</tbody>
</table>

* = Significant difference

Radial head volume (Tables II, III)
There were significant correlations between total radial head volume and height (r = 0.44; p<0.001), weight (r = 0.29; p<0.05), radial head diameter (r = 0.83; p<0.001), radial neck diameter (r = 0.74; p<0.001), coronoid diameter (r = 0.78; p<0.001), and gender (p<0.001). The strongest multivariable model (F = 118.3; p<0.001) consisted of the variables radial head diameter, coronoid diameter, and gender, and accounted for 88.5% of the variation in radial head volumes. The strongest model without the variable radial head diameter consisted of the variables radial neck diameter, coronoid diameter, and gender, and accounted for 86.2% of the variation in radial head volumes (F = 95.4; p<0.001).
Radial head articular surface

There was significant correlation between total radial head surface and height ($r = 0.40; p<0.001$), weight ($r = 0.37; p<0.001$), radial head diameter ($r = 0.82; p<0.001$), radial neck diameter ($r = 0.68; p<0.001$), coronoid diameter ($r = 0.71; p<0.001$), and gender ($p<0.001$). The strongest multivariable model ($F = 44.9; p<0.001$) consisted of the variables radial head diameter, coronoid diameter, and gender, and accounted for 74.5% of the variation in radial head articular surfaces. The strongest model without the variable radial head diameter consisted of the variables radial neck diameter, coronoid diameter, and gender, and accounted for 66.0% of the variation in radial head articular surfaces ($F = 29.8; p<0.001$).

Modeling/predictions

The following fitted equation resulted for radial head volume:

$$\text{Radial Head Volume} = -1926.64 + 146.50 \times \text{Radial Head Ø} + 70.72 \times \text{Coronoid Ø} + 769.78 \times \text{Gender}$$

The following fitted equation resulted for radial head surface:

$$\text{Radial Head Surface} = -212.15 + 19.81 \times \text{Radial Head Ø} + 5.43 \times \text{Coronoid Ø} + 32.85 \times \text{Gender}$$

The predictive linear model estimated the radial head volumes between 507 mm$^3$ more and 575 mm$^3$ less than the actual volumes based on 95% CI, and the average relative difference was 0.53%. The predictive linear model estimated the radial head surface area between 75 mm$^2$ more and 81 mm$^2$ less than the actual volumes based on 95% CI, and the average relative percent difference was 0.51%.

We tested the basic mathematical formula assuming the radial head is round. If we compare $R^2$ (the variability explained) we found 0.75 for our empiric formula and 0.66 for the $\pi r^2$ formula.

The 5 consecutively built models had a mean radial head volume of 3179 mm$^3$.
mm³ (SD = 16.4 mm³, 95% CI = 3159 - 3199 mm³) and a CV of 0.5%. The mean radial head articular surface was 592 mm² (SD = 0.8 mm², 95% CI = 591 - 593 mm²) and a CV of 0.14%. The radial head and radial neck diameter measurements variation was zero because all 5 readings were identical and thus, based on the sample data, the repeatability was 100% (Table IV).

Table IV. Measurements of Repeatability

<table>
<thead>
<tr>
<th>Model</th>
<th>Volume</th>
<th>Articular Surface</th>
<th>Radial Head Diameter</th>
<th>Radial Neck Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3161.42</td>
<td>592.04</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>2</td>
<td>3199.95</td>
<td>591.27</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>3</td>
<td>3168.77</td>
<td>591.74</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>4</td>
<td>3172.43</td>
<td>593.36</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>5</td>
<td>3192.29</td>
<td>592.50</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>Mean</td>
<td>3178.97</td>
<td>592.18</td>
<td>25.58</td>
<td>22.41</td>
</tr>
<tr>
<td>SD</td>
<td>16.37</td>
<td>0.80</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>95% CI</td>
<td>3159 - 3199</td>
<td>591 - 593</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CV</td>
<td>0.50%</td>
<td>0.14%</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

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

Discussion

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

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

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

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

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

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