Validation of quantitative surface area and volume measurement and analysis of glenoid fractures using three-dimensional computed tomography models.

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Abstract:

Purpose:
To assess the accuracy of quantitative three-dimensional computed tomography surface area and volume measurement. To apply quantitative three-dimensional computed tomography measurements to a series of glenoid fractures to describe the average articular surface area and volume of glenoid fracture fragments.

Materials and Methods:
Ten geometric objects were manually measured and subsequently surface area and volume were calculated. Computed tomography images of the objects were acquired in 3 different slice-thicknesses to create three-dimensional models with 3D Slicer. The difference between the manual measurements and the quantitative three-dimensional computed tomography measurements was tested for statistical significance. The precision of measurements was presented as the average absolute relative error. The influence of slice thickness on surface area and volume measurements was statistically tested.

Three-dimensional computed tomography models of a series of 53 patients with glenoid fractures were created. Fracture fragments were digitally reduced and surface area and volume of the fragments was quantitatively measured and presented in relation to the total glenoid.

Results:
There was no significant difference between the manual measurements and the quantitative three-dimensional computed tomography measurements of the geometric objects for all 3 slice-thicknesses for both surface area and volume. Quantitative three-dimensional computed tomography measurement was applied to a series of fractured glenoids. The mean percentage of fractured articular surface area compared to the total articular surface was 17% for the 28 anterior fractures; 15% for the 3 posterior fractures; 63% for the 14 transverse or oblique fractures; and 57% for the 8 multi fragmentary fractures. The mean percentage of fracture volume compared to the total volume was 19% for the 28 anterior fractures; 25% for the 3 posterior fractures; 60% for the 14 transverse or oblique fractures; and 58% for the 8 multi fragmentary fractures.

Conclusion:
Based upon the results of this study both surface area and volume can be measured accurately using quantitative three-dimensional computed tomography models. This method was applied to a series of glenoid fractures. We conclude quantitative three-dimensional computed tomography analysis is a feasible method to describe fracture morphology. The results of this study might aid in a better understanding of glenoid fractures.
**Samenvatting:**

*Doel:*
De precisie bepalen van quantitatieve drie-dimensionale computed tomography oppervlakte en volume metingen. Quantitatieve drie-dimensionale computed tomography metingen toepassen op een serie glenoid fracturen om het gemiddelde oppervlakte en volume van glenoid fractuur fragmenten te beschrijven.

*Materiaal en Methode:*
Tien geometrische objecten werden handmatig gemeten en vervolgens werd het oppervlakte en het volume berekend. Er werden CT-scans gemaakt van de geometrische objecten met 3 verschillende slice diktes. Met de computed tomography scans werden vervolgens modellen gemaakt met 3D Slicer. Het verschil tussen de handmatige metingen en de drie-dimensionale computed tomography metingen werd getest op statistische significantie. De precisie van de metingen werd gepresenteerd als de average absolute relative error. De invloed van de computed tomography slice dikte werd statistisch getoetst.

Er werden drie-dimensionale computed tomography modellen van 53 patienten met een glenoid fractuur gemaakt. De fractuur fragmenten werden digitaal gereduceerd en oppervlakte en volume van de fragmenten werd quantitatief gemeten en gepresenteerd in verhouding tot het totale glenoid.

*Resultaten:*
Er werd geen significant verschil gevonden tussen de handmatige metingen en de quantitatieve drie-dimensionale computed tomography metingen voor alle verschillende slice diktes voor zowel oppervlakte als volume. Een serie glenoid fracturen werd quantitatief gemeten met deze methode. Het gemiddelde gefractureerde gewrichtoppervlakte in verhouding tot het totale gewrichtoppervlakte was 17% voor de 28 anterior fracturen; 15% voor de 3 posterior fracturen; 63% voor de 14 transversale of oblique fracturen; and 57% voor de 8 multi-fragmentaire fracturen. Het gemiddelde percentage gefractureerd volume in vergelijking met het totale volume was 19% voor de 28 anterieure fracturen; 25% voor de 3 posterieure fracturen; 60% voor de 14 transversale of oblique fracturen en 58% voor de 8 multi-fragmentaire fracturen.

*Conclusie:*
Gebaseerd op de resultaten van deze studie zijn zowel oppervlakte als volume betrouwbaar te meten met behulp van quantitatieve drie-dimensionale computed tomography modellen. Deze methode werd toegepast op een serie glenoid fracturen. We concluderen dat quantitatieve drie-dimensionale computed tomography een goede methode is om fractuur pathologie te beschrijven. De resultaten van deze studie kunnen een bijdrage leveren aan de kennis over glenoid fracturen.
Validation of quantitative surface area and volume measurement and analysis of glenoid fractures using three-dimensional computed tomography models.

Introduction:
Quantitative three-dimensional (3D) computed tomography (CT) modeling techniques are used to measure volume and surface area of anatomical structures(1-4). It is increasingly utilized in clinical and research settings and can aid in the understanding and description of normal or abnormal anatomical structures (5). It is widely applicable, varying from articular surface area measurement to monitoring the progress of hepatic metastasis and brain tumors(1, 6, 7).

Quantitative 3D CT measurement works as follows. First a CT-scan of a structure of interest has to be acquired. Subsequently this structure has to be identified on each separate CT-slice. There are several methods to identify a structure, it can be done manually by encircling the structure of interest, or automated. The automated method commonly uses Hounsfield units (HU) to identify a structure. The Hounsfield Units scale is used to define the radiodensity of a substance on a CT-scan. After the structure of interest is identified in all CT-slices this selection has to be merged to create a 3D model(8). For this process it is important to note that there are intervals between the images of a CT-scan. This is known as the CT-slice thickness and it commonly ranges from 0.6mm to 3.0mm. To maintain proportions of the original object, the CT-slice thickness is the distance that has to be maintained when stacking up the images in the rendering process. Finally the selected areas are merged and a 3D model is created from the stacked up images(9).

The accuracy of quantitative 3D CT measurements has been studied for linear and volumetric measurements in 3D models and has been found accurate(6, 9-11). Surface area measurements however have been found to overestimate the surface area of 3D models when compared with manual measurements(5). It is assumed that the inflation of the surface area measurements is caused by a stairstep effect, which is caused by the stacking up of CT images in the rendering process of 3D models. Smaller CT slices will result in smaller stairsteps and smoother 3D models(5, 12).

In a prior study by Whyms et al. a 60% inflation of surface area was found with the use of quantitative 3D CT measurement. This outcome would indicate that measurement on 3D models is not suitable for estimation of surface area. Whyms et al. assessed the accuracy of both volume and surface area measurement on 3 mandibles. The reference volume of the mandibles was measured by submerging the mandibles in water and subsequently measuring water displacement. The reference surface area of the mandibles was measured by applying clear graph paper along the curvature of the specimens. They describe that CT-scan slice thickness has the most profound effect on the accuracy of 3D CT measurement. To our knowledge this is the only study that describes the accuracy of quantitative 3D CT surface area measurement.

To assess the accuracy of quantitative 3D CT surface area and volume analysis we measured 10 geometric objects with a method similar to the one used by Whyms et al. As a reference standard we used surface area and volume that was calculated from manual linear measurements. We specifically studied the influence of CT-scan slice thickness on quantitative 3D CT measurements. To test the feasibility of quantitative 3D CT surface area and volume measurement we applied this method to a series of 53 fractured glenoids.

The indication for surgery in the treatment of glenoid fractures is often debated and surgical treatment is based on the size of a glenoid articular surface area defect(13, 14). Articular incongruity of the glenoid fossa is often well tolerated and recommendations for surgery usually emphasize the potential for subluxation or dislocation of the shoulder(15). An important diagnostic criterion for glenohumeral joint instability is glenoid articular surface area loss. It has been found in up to 85-90% of patients with recurrent dislocations(16-18). There is no agreement however on the exact amount of bone loss for a lesion to be significant but most experts suggest between 20-30%(19). Therefore the amount of bone loss plays a crucial role in surgical decision making and the prognosis of shoulder instability(14).
Several prior studies have presented methods to measure articular surface area defects of the glenoid. In 2000 Burkhart et al. used arthroscopy to look at loss of the characteristic pear shaped contour of the glenoid. The formation of an inverted-pear shape was an indication for a clinically relevant loss of articular surface area. In a later study in 2002 Burkhart et al. used a marked probe to arthroscopically measure the distance from the posterior, the anterior and the inferior glenoid rim to the bare spot of the glenoid articular surface. They concluded the bare spot was virtually equidistant to the posterior, anterior and inferior glenoid rim and can be used as a reference point to quantify the percentage of bone loss. This can be done by measuring the diameter of the glenoid anteroposteriorly and comparing this with the distance from the unfractured rim to the bare spot. The distance from the unfractured rim to the bare spot multiplied by 2 will represent the original diameter.

In 2003 Griffith et al. measured loss of articular surface area in 2D multiplanar reconstructions (MPR) of CT scans. An MPR slice can be generated in any position and orientation through the 3D volume with the use of the original CT-scan orientations. With the use of this technique a CT slice was positioned ‘en face’ to the glenoid rim. In this 2D plane the surface area was be quantitatively measured by encircling the outer contours of the glenoid rim.

With the use of volume rendered 3D CT models Sugaya et al. used two-dimensionally measured surface area loss. This was done by digitally extracting the humeral head from the 3D model to visualize the glenoid. Subsequently they measured the articular surface area of the glenoid by drawing a circle on the infero part of the glenoid pear contour. The inferior part of the glenoid can be approximated to a true circle. Subsequently they measured the surface area of the fragment and compared this to the surface area of the circle to calculate the loss of articular surface area.

Gerber and Nyffeler used volume rendered 3D CT models to quantitatively measure glenoid bone defects by comparing the length of the defect with the anteroposterior length of the widest part of the glenoid articular surface. This method was adopted by several later studies who related these measurements to clinical outcome.

Chuang et al. and Griffith et al. also used volume rendered 3D CT models to perform 2D measurements. Chuang et al. compared measurements on 3D models with their findings during arthroscopy. The arthroscopical measurements were done using a marked probe to measure the distance to the bare spot as described by Burkhart et al. They concluded measurements on 3D CT models are reliable and can be used for preoperative planning. Griffith et al. compared their measurements on 2D multiplanar CT reconstructions with arthroscopic measurements as described by Burkhart et al. They found a good agreement between both methods regarding the detecting of bone loss. Finally Magarelli et al. compared 2D measurement on 3D CT models with 2D measurement on multiplanar reconstructions. They found a high agreement and they conclude that the different methods can be considered interchangeable.

Diederichs et al. quantified the loss of articular surface area and volume of glenoid rim defects with the use of a second CT-scan of the healthy contralateral glenoid. They created a 3D reconstruction of the glenoid rim defect by comparing 3D models of the injured and the healthy glenoid. This 3D reconstruction was made for preoperative planning of surgical bone augmentation. With the use of the reconstruction they were also able to measure surface area and volume loss.

Recently published studies describe the use of magnetic resonance imaging (MRI) to quantify fracture surface loss of the glenoid. Both Lee et al. and Tian et al. demonstrated an excellent correlation between CT imaging and MRI imaging using a measurement method similar to the one used earlier by Griffith et al. MRI proves to be almost as accurate as CT and a promising substitute in the assessment of glenoid bone loss.
The primary aim of this study was to assess the accuracy of both quantitative 3D CT surface area and volume measurements. The influence of CT-scan slice thickness on surface area and volume measurements of 3D CT models was evaluated for slice thicknesses ranging from 0.6 mm to 2.0 mm.

The secondary study aim was to quantitatively analyze 3D CT glenoid fracture morphology. Three-dimensional quantitative analysis of computed tomography scans provides information about the size, shape, location, and fragmentation of fractures and may provide a more detailed understanding of fracture morphology. This might aid in the understanding of injury patterns and for planning operative exposure and fixation of the glenoid.

Materials and Methods

Materials

Ten geometric objects (Learning Resources, Inc., Vernon Hills, IL, US) were scanned in this study. A 1) cube, 2) square pyramid, 3) cylinder, 4) triangular pyramid, 5) hemisphere, 6) triangular prism, 7) sphere, 8) rectangular prism, 9) hexagonal prism, and 10) cone were used. All objects were hollow and made of plastic (Figure 1). This set of objects was chosen because they have geometric shapes, which allows mathematical calculation of volume and surface.

![Figure 1: 1) cube, 2) square pyramid, 3) cylinder, 4) triangular pyramid, 5) hemisphere, 6) triangular prism, 7) sphere, 8) rectangular prism, 9) hexagonal prism, and 10) cone](image)

Patient selection

After approval from our institutional review board, 319 patients with a glenoid fracture were identified using billing and diagnostic codes between 2003 and 2013 in Massachusetts General Hospital and Brigham and Women’s Hospital. Of these patients 133 had a computed tomography scan (CT-scan) of their injured shoulder.

Inclusion criteria were: (1) intra-articular glenoid fracture, and (2) patient age 18 years or greater. Exclusion criteria were: (1) post-operative CT-scan, (2) CT-scan with intra-articular contrast injection, and (3) CT-scan slice thickness above 1.5mm (CT-scan slice thickness below 1.5mm is required for adequate 3-dimensional modeling).
This resulted in 53 patients with adequate CT-scans for 3-dimensional modeling. Forty (75%) patients were men and 13 (25%) women with a mean age of 46 (standard deviation 18; range 18-88) (Table 1).

<table>
<thead>
<tr>
<th>Table 1 Patient Demographics</th>
<th>n=53</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr (mean, ±SD, range)</td>
<td>46, 18, 18-88</td>
</tr>
<tr>
<td>Men</td>
<td>40 (75%)</td>
</tr>
<tr>
<td>Left sided fractures</td>
<td>31 (58%)</td>
</tr>
</tbody>
</table>

\( yr = \text{year}, \ SD = \text{standard deviation} \)

**Measurements of geometric objects**

Linear measurements of the geometric objects were done independently by 2 raters with a 150mm digital caliper. Subsequently, each rater calculated the surface area and volume. For volume cubic millimeters were used, for surface square millimeters. The 2 raters independently calculated the volume and surface area of the models.

**Computed Tomographic (CT) acquisition**

CT datasets of the geometric objects were acquired at Brigham and Womens hospital (Boston, Massachusetts) with the Siemens Biograph40 mCT (Siemens, Erlangen, Germany) software version Syngo MI.PET/CT 2011A. Images were acquired with a preset shoulder protocol with a tube voltage of 120 kV, a spiral pitch factor of 0.8, a single collimation width of 0.6, a 512 X 512-mm field of view and an x-ray tube current 19.0 mA. Three CT-scans were made with slice thicknesses of 0.600mm, 1.00mm and 2.00mm. The geometric objects were positioned on the CT-table in a random configuration and were not moved in between CT-scans.

Due to the retrospective acquisition of computed tomography scans of the fractured glenoid, several different CT-scanners were used with a tube voltage up to 140kV, 500-700 mAs, and slices from 8 to 64/Dual source.
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3D model rendering

CT scans were saved as DICOM (Digital Imaging and Communications in Medicine) images and were then loaded into 3D Slicer (version 4.2.0 Boston, Massachusetts, United States). A threshold of -300 Hounsfield Units (HU) was used to identify the plastic outline of the objects. Because the objects were hollow they had to be filled in 3D Slicer to create solid models (Figure 2).

Figure 2: A) CT-slice with topview of the objects which are identified by numbers. B) The dense plastic walls have been identified using a threshold for Hounsfield units. C) The models have been filled to create mesh models of solely the outer surface.

This process was repeated for all 3 CT-scans with different slice thicknesses. In 3D Slicer 3D polygon mesh models (Figure 3) of solely the outer surface were created. The default model maker parameters in 3D Slicer were used(Smooth iterations: 10.0, Decimation resolution: 0.25)

Figure 3: 3D polygon mesh models in Rhino 3D of the 2.00 mm slice thickness CT-scan. A) Rectangular pyramid B) sphere.
A threshold of 250 Hounsfield Units was used to identify bony structures of the glenoid and neck of the scapula (figure 1A&1B). Trabecular bone had to be identified manually within the borders of the cortical bone because it was not dense enough for automatic threshold identification. In 3D Slicer mesh models of the outer surface of each fracture fragment were created. (Figure 1C&1D).

Subsequently all 3D mesh models were exported from 3D Slicer as .stl files (StereoLithography) to be analyzed in Rhinoceros (Rhinoceros 5.0, McNeel, Seattle, Washington, United States). In Rhinoceros the 3D models of the geometric objects were separately analyzed for surface area and volume.

Measurement of the glenoid was done as follows: first all fragments were digitally reduced to their original location (Figure 5A). Next, the glenoid was oriented so that the superior rim (12 o’clock position) and the 5 and 7 o’clock positions were in a horizontal plane. A planar surface was drawn just under the surface of the deepest point of the central articular surface of the glenoid fossa. This surface intersected with the glenoid fragments and split them. The volume of the fragments above this surface was measured using the standard feature for volumetric measurement in Rhinoceros (Figure 5B. Next, a line was drawn on the watershed (most prominent) part of the glenoid rim. This line was used as the limit of the articular surface area for each fracture fragment (Figure 5C). The surface area that was attached to the processus coracoideus and the acromion was defined as the unfractured part of the glenoid.

![Figure 4: A&B) Transversal view in 3D Slicer, identifying bone using hounsfield units threshold. C) Lateral view on 3D model of left glenoid in 3D Slicer. D) 3D Polygon mesh model for analysis in Rhino 3D.](image)

![Figure 5: A) Lateral view of the glenoid mesh model. Fragments have been reduced. B) anteroinferior view of the glenoid mesh model. A plane is drawn under the deepest point of the glenoid fossa to measure volume of the glenoid. C) A line is drawn on the watershed part of the glenoid rim to measure surface area.](image)
Both surface area and volume measurement are standard features in Rhinoceros. The volume of the 3D models was calculated in cubic millimeters up to 2 decimals. The surface area was measured in square millimeters up to 2 decimals. This process was repeated for the 3 different slice thickness CT-scans.

Fractures classification
The glenoid fractures were classified according to the 4 major categories as described by the AO/OTA scapula fracture classification system that focuses on fractures of the glenoid fossa(13).

Statistical analysis
Variables were presented with frequencies and percentages for categorical variables and as mean with standard deviation or median with interquartile range for respectively normal or non-normal distributed continuous variables. Normality of continuous distributed variables was tested using the Shapiro-Wilk test.

The inter-observer agreement of the manual object measurements among the 2 raters was evaluated with an intraclass correlation coefficient through a two-way mixed effects model with absolute agreement. Absolute agreement in an intraclass correlation assesses how much each measurement performed per rater differs from the other raters.

The volume and surface area of geometric objects manually measured by the 2 observers was averaged. The averaged manual measurements were used as the reference standard for comparison with the 3D model measurements.

The volume and surface area of each 3D model calculated in Rhinoceros was compared per slice thickness to the manual measurements and was presented with percentages in graphs. The Mann-Whitney test was used to test the difference between the manual measurements for geometric objects with the 3D model measurements for the 3 slice-thicknesses for both surface area and volume measurements. The accuracy of 3D model measurements was assessed by comparing the average of all models with the average manual measurements for each separate slice thickness. This was done by calculating the average absolute relative error (ARE) as defined in the following formula.

\[
ARE = \frac{1}{n} \sum_{i=0}^{n} \frac{|3D\ model\ measurement - manual\ measurement|}{manual\ measurement}
\]

The influence of slice thickness on the 3D model volume and surface area measurements was assessed with the Kruskal-Wallis test.

The difference between percentage of articular surface and volume between fracture classification groups was tested using the one-way ANOVA with Bonferroni correction for multiple testing.
Results

There was no significant difference between the average of manual measurements and the quantitative 3D CT measurements for all 3 different slice thicknesses for both volume and surface area (Table 2).

<table>
<thead>
<tr>
<th></th>
<th>Area</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean (in mm2)</td>
<td>mean (in mm3)</td>
</tr>
<tr>
<td>Average manual</td>
<td>20635</td>
<td>215617</td>
</tr>
<tr>
<td>measurements</td>
<td>20130</td>
<td>211015</td>
</tr>
<tr>
<td>0.6mm slice thickness</td>
<td>0.76</td>
<td>0.94</td>
</tr>
<tr>
<td>1.0mm slice thickness</td>
<td>20635</td>
<td>215617</td>
</tr>
<tr>
<td></td>
<td>20063</td>
<td>210872</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td>0.94</td>
</tr>
<tr>
<td>2.0mm slice thickness</td>
<td>20635</td>
<td>215617</td>
</tr>
<tr>
<td></td>
<td>19953</td>
<td>208475</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td>0.88</td>
</tr>
</tbody>
</table>

*mann-witney U test for nonparametric continuous variables*
The average absolute relative error was <0.05 for both volume and surface area measurements for all 3 different slice thicknesses which reflects an average difference of less than 5% between manual and quantitative 3D CT measurements (Table 3).

| Table 3 ARE and SD per slice thickness for area and volume |
|-----------------------------------------------|---------|-------|
| Slice thickness | ARE     | SD    |
| Area            |         |       |
| 0.6 mm          | 0.019   | 0.027 |
| 1.0 mm          | 0.022   | 0.026 |
| 2.0 mm          | 0.028   | 0.026 |
| Volume          |         |       |
| 0.6 mm          | 0.006   | 0.060 |
| 1.0 mm          | 0.007   | 0.063 |
| 2.0 mm          | 0.019   | 0.061 |

ARE: absolute average relative error. SD: standard deviation

The surface area of the 3D models compared to the manual measurements for the 0.6 mm slice thickness varied from 95% to 104% for the individual geometric objects (Graph 1).

Graph 1: The 3D model area measurements compared with the manual measurements for slice thicknesses 0.6 mm, 1.0mm and 2.0 mm.
The volume measurements of the 3D models, with a 0.6 mm slice thickness, compared to the manual measurements, varied from 88% to 111% for the individual geometric objects (Graph 2).

Graph 2: The 3D model volume measurements compared with the manual measurements for slice thicknesses 0.6 mm, 1.0mm and 2.0 mm.

The intraclass correlation coefficient for the manual measurements of the objects showed an intraclass correlation coefficient of 1 (95% confidence interval 1.00-1.00) between the two observers for both volume and surface. The comparison of the accuracy of volume and area measurements of the geometric models measured with 0.6 mm, 1.0 mm and 2.0 mm CT-slice thickness showed no significant difference in volume or surface area measurement (Table 4).

<table>
<thead>
<tr>
<th>Table 3 Influence of slice thickness on area and volume measurements</th>
<th>N = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area</strong></td>
<td></td>
</tr>
<tr>
<td>Slice thickness</td>
<td>N</td>
</tr>
<tr>
<td>0.6mm</td>
<td>10</td>
</tr>
<tr>
<td>1.0mm</td>
<td>10</td>
</tr>
<tr>
<td>2.0mm</td>
<td>10</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td></td>
</tr>
<tr>
<td>Slice thickness</td>
<td>N</td>
</tr>
<tr>
<td>0.6mm</td>
<td>10</td>
</tr>
<tr>
<td>1.0mm</td>
<td>10</td>
</tr>
<tr>
<td>2.0mm</td>
<td>10</td>
</tr>
</tbody>
</table>

* Kruskall-Wallis for nonparametric continuous variables
The mean articular surface area of the glenoids was 796 (range, 457-1211). The median number of fragments per glenoid was 1 (range 1-5). (Table 5)

<table>
<thead>
<tr>
<th>Table 2 Glenoid characteristics</th>
<th>n=53</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of fragments</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Median (IQR)</strong></td>
<td><strong>Range</strong></td>
</tr>
<tr>
<td>Men</td>
<td>1 (1 - 2)</td>
</tr>
<tr>
<td>Women</td>
<td>1 (1 - 2)</td>
</tr>
<tr>
<td><strong>Surface area</strong></td>
<td><strong>Range</strong></td>
</tr>
<tr>
<td>Surface area*</td>
<td>796 (±166)</td>
</tr>
<tr>
<td>Surface area women</td>
<td>602 (±101)</td>
</tr>
<tr>
<td>Surface area man</td>
<td>860 (±130)</td>
</tr>
</tbody>
</table>

*IQR = interquartile range, SD = standard deviation, *surface in mm2*

The fractured part of the articular surface of the glenoid was 274 mm2 representing 35% of the total articular surface (range, 46-782 mm2; range, 6-91%).

The mean percentage of fractured articular surface area compared to the total articular surface was 17% for the 28 anterior fractures; 15% for the 3 posterior fractures; 63% for the 14 transverse or oblique fractures; and 57% for the 8 multi fragmentary fractures. The mean percentage of bone loss volume compared to the total volume was 19% for the 28 anterior fractures; 25% for the 3 posterior fractures; 60% for the 14 transverse or oblique fractures; and 58% for the 8 multi fragmentary fractures (Table 6).

<table>
<thead>
<tr>
<th>Table 6 Size of fragments in reference to the total size of the glenoid</th>
<th>n=53</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AO/OTA glenoid classification</strong></td>
<td><strong>Nr of fragments</strong></td>
</tr>
<tr>
<td></td>
<td><strong>N (%)</strong></td>
</tr>
<tr>
<td>Anterior</td>
<td>28 (53%)</td>
</tr>
<tr>
<td>Posterior</td>
<td>3 (6%)</td>
</tr>
<tr>
<td>Transverse</td>
<td>14 (26%)</td>
</tr>
<tr>
<td>Multi-fragmentary</td>
<td>8 (15%)</td>
</tr>
</tbody>
</table>

*IQR = interquartile range, SD = standard deviation*
There is a significant difference in the percentage of both fractured volume (P-value < 0.001) and surface area (P-value < 0.001) among the classification groups (Table 7)

Table 7: The difference between classification group for surface area and volume n=53

<table>
<thead>
<tr>
<th>Area</th>
<th>Anterior</th>
<th>Posterior</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior</td>
<td>2% (1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>46% (&lt;0.001)</td>
<td>-48% (&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Multi-fragmentary</td>
<td>-40% (&lt;0.001)</td>
<td>-42% (0.001)</td>
<td>6% (1.0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume</th>
<th>Anterior</th>
<th>Posterior</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior</td>
<td>-8% (1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>-4% (&lt;0.001)</td>
<td>-29% (&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Multi-fragmentary</td>
<td>-41% (&lt;0.001)</td>
<td>-33% (0.001)</td>
<td>-4% (1.0)</td>
</tr>
</tbody>
</table>

*Bonferroni, absolute difference in percentage and (P-value), significant values are bold*

Discussion

The primary aim of this study was to assess the accuracy of quantitative 3D CT volume and surface area measurements. The null hypothesis that there is a significant difference between our reference standard measurements and the quantitative 3D CT measurements was rejected. Therefore it can be concluded that both quantitative 3D CT volume and surface area measurement is accurate.

The influence of CT-slice thickness on quantitative 3D CT surface area and volume measurements of the geometric objects was evaluated for 3 different CT-slice thicknesses. The null hypothesis that a larger slice thickness will result in a significant change in measurement outcome was rejected.

In previous studies quantitative 3D CT measurement has already been proven accurate for volume and linear measurements(6, 9-11). One of the main concerns in the measurement of surface area was inflation because of stairstep artifacts resulting from stacked up CT-slices as noted in earlier studies(5, 12) and as can be seen on the sphere in figure 3B made with the 2.00mm slice thickness. Although we also note the stairstep artifacts, they turn out not to result in significant inflation of the surface area. However, there is a slight but not significant increase in deviation from the manually measured reference standard with the use of a larger slice thickness.
The secondary study aim was to use quantitative 3D CT analysis to describe glenoid fracture morphology. A series of 53 glenoid fractures was quantitatively measured for surface area and volume. The fracture classification groups show significant differences in both volume and surface area. We conclude quantitative 3D CT analysis is a feasible method to describe fracture morphology.

When interpreting the results of this study certain limitations have to be taken into account. 1) The geometric objects that were examined in this study were not anatomical structures. The measurements on the fractured glenoids were validated with plastic phantoms. A cadaver study or comparison with an arthroscopic measuring method would probably be a more accurate method of validation. Additional research could be necessary to validate this method for specific anatomical structures. 2) Only the influence of slice thickness on the measurement of 3D models was examined. The images were acquired with a single CT-scanner and the influence of pitch, scanner current, and beam collimation was not investigated. Therefore the findings of this study might not be directly applicable to other CT scanners or volume rendering software. 3) Two models were slightly fused with the CT-table on which they stood because of similarity in density. They had to be manually separated to allow correct rendering of 3D mesh models. 4) Although only the highest quality CT-scans of fractured glenoid were selected, they were collected retrospectively, and there was variety in the CT-scan parameters. 5) Possibly only patients with relatively severe injuries undergo a CT-scan. Therefore the cases in this study might not be representative for the average patient with a glenoid fracture. 3) Drawing a line on the watershed of the glenoid rim to select articular surface area was done manually. This leaves room for interobserver variability.

The strengths of this study include: 1) The use of geometric models which allows mathematical calculation of surface area and volume. 2) The objects were not moved in between CT-scans but as you can see on Figure 3B the CT slices cut through the objects in an angle that is depending on their position on the CT-scanner table. As a result a cube that is positioned and scanned diagonally will have more stairsteps in its surface and could therefore have a different surface area or volume. A diversity of models was used to take into account these different angles of CT-slices and the variety of curvature. 3) The study has an accurate and reproducible methodology. The Dicom files of the geometric objects can be downloaded from [www.slicer.org](http://www.slicer.org). 4) The relatively large number of glenoid fracture cases, which allows a wide variety of patterns to be studied even though anterior fractures predominate. 2) The method of 3D model rendering left little room for inter observer variability due to the use of an automated threshold for bone density. 5) With quantitative 3D CT analysis articular surface area can be measured in 3 dimensions. Other methods do not take into account the bowl shape of the glenoid and in theory would underestimate the surface area of the glenoid.

The quantification of glenoid articular surface area loss is useful because it predicts the recurrence rate of dislocation and it can be used to determine the need for surgery(18, 20, 26). As described in the introduction of this study, several methods have been developed to measure the loss of articular surface area using CT based techniques or arthroscopy(2, 18, 20, 21, 23, 26, 27, 29, 30). The technique used in this study has advantages over other techniques. It requires a CT scan of only the affected shoulder because the injured glenoid is reconstructed by digital reduction of fracture fragments. Therefore there is no need to perform a CT of the contralateral shoulder. This is an advantage because radiation exposure is a relevant problem and as can be seen in the demographics of this study most patients are relatively young. Also in cases with bilateral injury the method described in this study can still be used.

As noted in prior research(2, 27) scanning of only the injured shoulder also has disadvantages. In cases where there is an impaction fracture there will possibly be no fragments to reconstruct the glenoid. In these cases a CT-scan of the healthy side is needed to accurately measure the loss of articular surface area.
Even though this study shows volume and surface area can be accurately measured with the use of CT scans with slice thicknesses of up to 2.0 mm there are more requirements to a CT-scan to allow clinical use of quantitative 3D CT measurement. To be able to separately analyze smaller structures or individual fracture fragments they have to be identifiable. In the glenoid fracture 3D modeling process it became clear that adequate identification of fracture fragments, requires CT-scans with a slice thickness of 1.5 mm or smaller. CT-scans also require a field of view (FOV) that focuses on the shoulder in order to ensure adequate image resolution for the identification of fracture fragments.

The method described in this study is labor intensive. Quantitative 3D analysis of a fractured glenoid takes about 45 minutes to 1 hour. The identification and reduction of fracture fragments are processes that should be further automated because currently this method is too time consuming to be used for routine clinical purposes.

The pattern of changing glenoid shape that is commonly seen in glenohumeral joint instability tends to be more a compression injury rather than an avulsion fracture(22). This has been studied earlier by two-dimensionally measuring the degree of flattening of the glenoid fossa in a transversal plane(22). In our study we described glenoid fractures in general rather than focussing on glenohumeral joint instability. Instead of measuring articular surface area loss, in future studies quantitative 3D CT volume measurement could be able to further describe a change of glenoid fossa shape. The relation between the shape of the glenoid fossa and the humeral head can also be evaluated with motion analysis on 3D CT models(31, 32). With the use information from cadaveric studies, kinematic models can be created from patient CT-scans to evaluate contact and resistance between articular surfaces.

Labral lesions and soft tissue injuries around the glenoid are best visualized with MRI and therefore MRI is often used in the evaluation of glenohumeral joint instability. Theoretically quantitative 3D measurements can also be performed on MRI scans. The use of MRI scans however is more labor intensive because MRI images do not allow the use of Hounsfield Units for automated detection of osseous structures. On the other hand, MRI enables the visualization of cartilage and other soft tissue. Changes in these structures have proven to be a predictor of glenohumeral joint instability(33, 34). In future studies these changes could be further quantified with the use of quantitative 3D measurements.

**Conclusion:**

Based upon the results of this study both surface area and volume can be measured accurately using 3-dimensional computed tomography models.

This quantitative 3-dimensional analysis was applied to glenoid fractures to describe fracture morphology.

As can be concluded from this study quantitative 3-dimensional computed tomography measurement is both an accurate and feasible method to measure anatomical structures.

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