ORIGINAL ARTICLE

Three-dimensional measurement method of arthritic glenoid cavity morphology: Feasibility and reproducibility

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Accepted: 22 June 2012

KEYWORDS
Osteoarthritic glenoid cavity;
3D reconstruction;
Reproducibility;
CT scan

Summary
Introduction: Glenoid component loosening is the main complication of total shoulder arthroplasty. Better knowledge of the arthritic glenoid cavity anatomy can help in developing new implants and techniques. The goal of this study was to describe and validate the reproducibility of a CT scan-based, 3D measurement method used to describe various parameters characterizing arthritic glenoid cavity morphology.

Materials and methods: Twelve CT scans and 29 CT arthrogram were evaluated. These scans were taken from 41 patients with glenohumeral osteoarthritis who received an anatomical shoulder prosthesis. A 3D reconstruction of the scapula was performed based on the DICOM files. Following the 3D volume acquisition, points on the glenoid articular surface were manually extracted by three observers, each one three times, allowing one week between readings, to determine the inter- and intra-observer reproducibility. The intraclass correlation coefficient (ICC) was calculated on five 3D parameters that were automatically calculated: glenoid height, glenoid width, height at maximum width glenoid version and radius of the articular surface best-fit sphere.

Results: The intra-observer and inter-observer ICC were 0.91 to 0.99, and 0.95 to 0.99, respectively.

Discussion: This study is the first to report on a reproducible 3D measurement method, based on CT scans, for the arthritic glenoid cavity, which derives the joint radius of curvature among other morphology parameters. These 3D measurements are advantageous because they are free of problems related to patient positioning in the CT scanner and to the choice of slices,
Introduction

Because of the significant loosening rate, survival of the glenoid implant component over time is the main challenge with anatomical total shoulder arthroplasty (TSA) [1]. Many factors affect glenoid loosening such as implant position (version and inclination), cementing technique, type of implant and more recently, the amount of reaming [1]. In 1972, Neer used a single glenoid component size, which was completely made of polyethylene, during the first TSA cases [2]. Currently, most of the implants have three to five sizes that gradually increase in height (superior-inferior) and width (anterior-posterior) but have a single radius of curvature at the bone/interface implant. The choice of size and radius of curvature for these implants is based on the results of anatomical studies performed on healthy (non-arthritic) glenoid articular surfaces [3,4].

Information about various 3D parameters of arthritic glenoid anatomy, especially the radius of curvature of the articular surface, would seem to be important information to improve the design of the glenoid implant component. To our knowledge, this parameter has never been evaluated in 3D on arthritic glenoids, in contrast to version [5–7] and the bone architecture of the glenoid vault [8,9].

The goal of this study was to describe and validate the reproducibility of a CT scan-based, 3D measurement method used to describe various parameters of arthritic glenoid morphology, including size, version and radius of curvature.

Material and methods

Starting with a database of 145 CT scans or CT arthrography scans digitized onto CD that belonged to patients receiving anatomical TSA for primary glenohumeral osteoarthritis, 12 CT scans and 29 CT arthrography scans were analysed for this study. These 41 files were chosen from the database by drawing lots. In 26 cases, the arthritic glenoid had a Type A wear pattern, and in 15 cases, it had a Type B pattern [10].

3D reconstruction of the scapula

Two different protocols were used with the CT scan and CT arthrography scan digitized DICOM data to perform a 3D reconstruction of the scapula. For all the CT scans, 3D reconstruction of the scapula was performed using an automated segmentation process in the Glenosys 1.0 software (Imascap; Brest; France). The morphological structure of the proximal humerus, scapula and glenoid is analysed and automatically recognized by the software. For all the CT arthrography scans, a three-step, semi-automated segmentation process was used: automatic thresholding based on pixel intensity; manual extraction of intra-articular contrast product (same density as the bone cortex) and automated 3D reconstruction with image smoothing.

With these 3D reconstructed scapulas, three experienced orthopaedic surgeons used the Glenosys software to manually extract the contour of the glenoid articular surface (Fig. 1). Based on these extracted points, the glenoid articular surface was defined for each scapula. Then the superior point (SUP = highest point on the glenoid articular surface) and the inferior point (INF = lowest point on the glenoid articular surface) were chosen manually with the same software (Fig. 1).

Measurement of various parameters to describe arthritic glenoid morphology

After the glenoid articular surface and superior and inferior points on the 3D scapula were acquired, the Glenosys software calculated the following five morphology parameters: height (H) and width (L) of the glenoid articular surface; height at the maximum width (Hw); glenoid version (V) and glenoid articular surface best-fit sphere.

Height, width and height at max width were calculated in the glenoid coordinate system and the best-fit sphere was calculated in the scapula coordinate system. Each
3D measurement of arthritic glenoid morphology

Figure 2  The centre of the two coordinate systems corresponds to the centre of gravity of the glenoid surface (G). The glenoid coordinate system is defined by three vectors (SUPglen, ANTglen and LATglen). The scapula coordinate system is defined by three vectors (SUPscap, ANTsccap and LATscap).

coordinate system was defined by a centre and three orthogonal vectors (Fig. 2). The centre (centre of gravity of the glenoid articulate surface) was automatically calculated and was the same for both coordinate systems (G). The three vectors of the scapula coordinate system were the SUP Scap (vertical axis formed by the intersection of the scapula plane and the glenoid plane, oriented from lower to upper), ANT Scap (sagittal axis oriented back to front and perpendicular to the scapula plane) and LAT Scap (frontal axis oriental medial to lateral and perpendicular to the other two vectors). The three vectors of the glenoid coordinate system were the SUP Glen (vertical axis formed by the intersection of the scapula plane and the glenoid plane, oriented from lower to upper), LAT Glen (frontal axis oriental medial to lateral and perpendicular to the glenoid plane) and ANT Glen (sagittal axis oriented back to front and perpendicular to the other two vectors):

- the height of the glenoid articulate surface was calculated as the 3D Euclidean distance between the superior and inferior point of the articulate surface (Fig. 3);
- the width of the glenoid articulate surface was calculated as the 3D Euclidean distance between the anterior (ANTi) and posterior (POSTi) points on the articulate surface. These two points (anterior and posterior) were automatically calculated and defined as belonging to the contour of the glenoid articulate surface and to the plane (L-plane) perpendicular to the SUP/INF axis where the 3D Euclidean distance (d(ANT–POST)) is the greatest (Fig. 3);
- the height at maximum width was calculated as the 3D Euclidean distance along the INF/SUP axis, between the inferior point and the intersection of the two lines (ANTi–POSTi) and (SUP–INF) (Fig. 3).

Figure 3  Measurements made on the glenoid articulate surface: height (H); width (L); height at Max Width (H3); anterior (ANTL) and posterior (POSTL) points; superior (SUP) and inferior (INF) points.

- version was calculated between the scapula and glenoid planes, and also corresponds to the angle between the anterior vector in the scapula coordinate system (ANT Scap) and the anterior vector in the glenoid coordinate system (ANT Glen). The scapula plane was defined as the average plane calculated from the least-square method applied to all the scapula points, by weighing them differently. This plane was automatically calculated by the Glenosys software. The glenoid plane was calculated with the least squares method applied to all the points on the manually extracted glenoid articulate surface (Fig. 4);

Figure 4  Glenoid and scapula planes on a 3D reconstructed scapula.

Reproducibility study

The reproducibility of measuring the five previously described parameters [11,12] was evaluated here.

Intra-observer reproducibility: the same observer manually extracted the glenoid articular surface and the superior and inferior points on the 41 reconstructed scapulas three times with one week between each trial. The intraclass correlation coefficient (ICC) was determined for the five calculated parameters (H, L, HL, v, radius of best-fit sphere) along with 95% confidence intervals.

Inter-observer reproducibility: three observers manually extracted the glenoid articular surface and the superior and inferior points on the 41 reconstructed scapulas twice, with one week between each trial. Two intraclass correlation coefficients were determined for the five calculated parameters (H, L, HL, v, radius of best-fit sphere) along with 95% confidence intervals. One ICC was determined for the first series of measurements for each observer and a second ICC was determined for the second series of measurements.

Results

The measurement results from all three observers are summarized in Table 1.

For the intra-observer reproducibility, the correlation coefficient ranged from 0.91 to 0.99 for the five measurements (Table 2). For the interobserver reproducibility, the correlation coefficient ranged from 0.95 to 0.99 (Table 3).

Discussion

Because CT scans are better than conventional X-rays [13], glenoid anatomy [10,14] and version [15] are typically evaluated on 2D slices from the raw CT scan images during preoperative planning for total shoulder arthroplasty. More recently, 3D measurements from CT scan reconstructions were developed to evaluate glenoid version [5–9,16–21]. Most of these studies were performed on healthy glenoids, cadaver specimens or patients with a proximal humerus fracture [15–21], then adapted to pathological glenoids [5–9].

Our results confirm the hypothesis that our 3D measurement method of arthritic glenoid morphology based on CT scan 3D reconstructions is feasible and has very good intra- and inter-observer reproducibility (correlation coefficient always greater than 0.91).

The reproducibility of CT scan 2D measurements for glenoid version had previously been demonstrated [9,15,16], with measurement variability around 1.5° and correlation coefficients between 0.95 and 0.98 [9,16,21]. However, according to Friedman et al. [15], the errors associated with this type of measurement are mainly due to patient positioning during acquisition of the CT scan images [6,22,23]. Bokor et al. [22] showed that a 15° variation in scapula orientation relative to the reference position during image acquisition leads to errors of more than 10° in version measurement. Hoenecke et al. [6] compared the measurement of glenoid version on raw CT scan images to the version measured on slices from 3D reconstruction. In 20% of cases, the error was more than 10°; an average of 7° variation in the version measurement occurs if the selected slice is just below the end of the coracoid process. This variability can be attributed to the glenoid having a different version, depending on the height of the chosen slice [19]. Hoenecke et al. reported that the version measurement error was 1° or less in 91% of cases with their method. They concluded that use of 3D reconstruction was preferable when choosing which 2D slice to use to reliably measure the glenoid version [6]. Budge

Table 1  Results for the five measured parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (± SD)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (mm)</td>
<td>41.33 (± 5.5)</td>
<td>31.5</td>
<td>55.1</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>29.35 (± 5.2)</td>
<td>19.6</td>
<td>44.8</td>
</tr>
<tr>
<td>Height at Max Width (mm)</td>
<td>19.95 (± 3.1)</td>
<td>15.1</td>
<td>28.4</td>
</tr>
<tr>
<td>Version (°)</td>
<td>−12.1° (± 10.8)</td>
<td>23.1</td>
<td>−28.7</td>
</tr>
<tr>
<td>Radius of best-fit sphere (mm)</td>
<td>34.9 (± 9.2)</td>
<td>21.7</td>
<td>65.5</td>
</tr>
</tbody>
</table>

SD: standard deviation.
et al. validated a measurement method that was similar to the one used by Hoenecke [21]. These methods [6,21] correspond to a first attempt to calculate a fully 3D glenoid version, based on CT scan reconstruction [5,8,9,16,17]. The accuracy of using CT scan 3D reconstruction by segmenting raw CT scan images relative to taking real measurements on cadaver scapula specimens was demonstrated by both Kwon [16] and Bryce [23].

Three-dimensional measurement methods for glenoid version consist of calculating the angle between the scapula plane and the glenoid plane. These methods require manual acquisition of at least three points on the scapula to define the scapula plane and at least three point on the glenoid articular surface to define the average glenoid plane [17]. At least three points are needed to define a plane. The glenoid plane can be defined in the most reproducible manner with three points: anterior, posterior and inferior [24]. But this method does not take the entire superior part of the glenoid into account. We chose to use to use all the glenoid-defining points to obtain the best reproducibility when calculating the average glenoid plane, which makes it independent of manually acquiring only three points. This also applies to the scapula plane, which is defined by three points in the published literature [16,17,19,24]. The reproducibility of these 3D measurements, validated on non-arthritic glenoids, is good (correlation coefficient between 0.90 and 0.99) [9,17,19].

The measurement of radius of curvature of the glenoid articular surface has been described little in the published literature [19,20,25,26]. The radius of curvature has only been evaluated in non-arthritic glenoids based on X-ray [25,26], 2D CT scan [25], 3D CT scan reconstructions [19,20] and even MRI [27] studies. Lewis et al. [19] use a similar approach to ours to calculate the best-fit sphere for the manually extracted glenoid articular surface, using CT scan 3D reconstructions. They also described an original method to calculate 3D version and inclination from the best-fit sphere with good intra- and intra-observer reproducibility (correlation coefficient greater than 0.90). As with the glenoid version measurement, it is preferable to evaluate the glenoid radius of curvature by evaluating the average curvature of the entire glenoid surface with a best-fit sphere instead of calculating the curvature of the glenoid surface with only one slice. Similarly to version, the radius of curvature of the glenoid cavity varies as a function of glenoid height [23].

But our radius of curvature results are difficult to compare with other studies because, many authors validated their methods on healthy patients, cadaver specimens or non-arthritic glenoids [19,20]; the measurement method was different (X-ray and CT scan) [25,26]. The average glenoid version measured with 3D methods was between –8.6° and –19° [6,7,9]. Our average version was in this range. These differences can be explained by patient selection based on glenoid wear according to the Walch classification on one hand, and by the different measurement methods used, on the other hand.

Our method to measure arthritic glenoid morphology parameters (version, radius of curvature, height and width) from CT scan 3D reconstructions has many advantages:

- all the measurements are calculated in 3D coordinate systems and from 3D planes instead of 2D calculations from 3D reconstructions;
- our method is highly automated relative to other 3D methods, which reduces subjectivity and observer variability. This most likely explains the very good correlation coefficients for our method;
- our method takes into account the entire glenoid surface and entire scapula to calculate the respective planes, unlike typical methods that use only three points to define a plane;
- as far as we know, this is the first study of 3D radius of curvature on pathological, arthritic glenoids.

However our method has some weak points:

- it was not validated against a gold standard. In vivo measurements cannot be performed on our cohort of patients with shoulder arthritis;
- our method is feasible but much less automated when CT arthrography is used because the intra-articular contrast product and the cortical bone have similar

### Table 2  Intra-observer reproducibility.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ICC</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>0.94</td>
<td>0.89 to 0.96</td>
</tr>
<tr>
<td>Width</td>
<td>0.99</td>
<td>0.98 to 0.99</td>
</tr>
<tr>
<td>Height at Max Width</td>
<td>0.91</td>
<td>0.86 to 0.95</td>
</tr>
<tr>
<td>Version</td>
<td>0.997</td>
<td>0.96 to 0.998</td>
</tr>
<tr>
<td>Radius of best-fit sphere</td>
<td>0.96</td>
<td>0.94 to 0.98</td>
</tr>
</tbody>
</table>

### Table 3  Interobserver reproducibility.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1st acquisition</th>
<th>2nd acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>95% CI</td>
</tr>
<tr>
<td>Height</td>
<td>0.97</td>
<td>0.95 to 0.98</td>
</tr>
<tr>
<td>Width</td>
<td>0.98</td>
<td>0.96 to 0.99</td>
</tr>
<tr>
<td>Height at Max Width</td>
<td>0.95</td>
<td>0.90 to 0.97</td>
</tr>
<tr>
<td>Version</td>
<td>0.998</td>
<td>0.997 to 0.999</td>
</tr>
<tr>
<td>Radius of best-fit sphere</td>
<td>0.98</td>
<td>0.96 to 0.99</td>
</tr>
</tbody>
</table>

density. Our method could not be used with MRI images;

- our calculations do not take cartilage thickness into
  account, as cartilage is not visible on CT scans. The
  impact of this error is small, since the thickness of the
  remaining cartilage is much less in cases of glenohumeral
  osteoarthritis than with healthy glenoids.

Now that the validity of our method has been established,
we can extend these glenoid morphology measurements
to a larger cohort of patients with primary glenohumeral
osteoarthritis. The goal is to adapt the design of current
glenoid implant components, as needed, based on morpho-
logical data on a larger scale. This is especially worthwhile
for the radius of curvature of the bone/implant interface.
It should be as close as possible to the radius of
curvature of the native pathological glenoid to preserve
an optimal amount of subchondral bone during reami-
ng. Our image processing methodology also allows us to
continue developing tools to help with 3D preoperative
planning, as some have already advocated [6,7], and tools
for intraoperative navigation during total shoulder arthro-
plasty.

Disclosure of interest

Dr. Moineau has been asked by Tornier to speak at confer-
ences.

Dr. Young has no conflict of interest.

Dr. Walch, Levigne and Boileau receive royalties from
Tornier relative to prosthesis patents.

Dr. Levigne was employed as a consultant by Tornier to
perform various measurements during this study.

Financial support: Tornier (USA) provided financial sup-
port for this study through Imascap (Brest, France), which
developed the Glenosys software and performed the various
measurements.

Acknowledgements

The authors are grateful to Pierrick Deransart, Lucille Ferrand
and Jean Chaouli for their technical help.

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