Radiographic assessment of prosthetic humeral head size after anatomic shoulder arthroplasty

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Background: Restoring the premorbid proximal humeral anatomy during shoulder arthroplasty is critical yet can be difficult because of the deformity of the arthritic head. The purpose of this study was to measure the variation between surgeons and between types of prosthetics in reproducing the anatomic center of rotation (COR) of the humeral head after anatomic shoulder arthroplasty.

Methods: The anteroposterior radiographs of 125 stemmed and 43 resurfacing shoulder arthroplasties, performed by 5 experienced surgeons, were analyzed. All patients had primary replacement for treatment of end-stage glenohumeral arthritis. A best-fit circle to preserved nonarticular humeral landmarks was used to define the difference between the anatomic COR and the prosthetic COR. A difference in COR of >3.0 mm was considered clinically significant and analyzed for the cause of this deviation.

Results: The average deviation of the postoperative COR from the anatomic COR was 2.5 ± 1.6 mm for stemmed cases and 3.8 ± 2.1 mm for resurfacings. Thirty-nine stemmed cases (31.2%) and 28 resurfacings (65.1%) were beyond 3.0 mm of deviation and regarded as outliers. The majority of the stemmed outliers and all resurfacing outliers were overstuffed. An improper humeral head size selection and inadequate reaming were the main reasons for the deviation in stemmed and resurfacing outliers, respectively.

Conclusion: A large percentage of shoulder replacements demonstrated significant deviations from an anatomic reconstruction. Resurfacing arthroplasty exhibited significantly greater deviations compared with stemmed arthroplasty (P < .001), indicating that surgeons have more difficulty in restoring the anatomy with resurfacings. Further studies are needed to assess the clinical impact of these deviations.

Level of evidence: Basic Science, Anatomy, Imaging.

Keywords: Anatomic shoulder arthroplasty; humeral head arthroplasty; resurfacing; humeral head size; glenohumeral arthritis; shoulder replacement
especially the humeral head, is critical, as component malpositioning can result in pain, clinical symptoms, worse outcomes, and increased complication and failure rates.\textsuperscript{3,5,7,9,16}

Sizing of the humeral head during shoulder arthroplasty is often performed at the time of surgery with a combination of dimensions of the prepared bone surface, the resected head, the size of the glenoid component (when present), and soft tissue balancing. This is usually accomplished with the use of trial implants and sizing templates provided by commercial implant vendors. These methods focus only on the articular surface and do not use the anatomic concept of the sphericity of the proximal humerus. However, because the articular surface is generally deformed from the arthritic process, it is often difficult to accurately assess the correct size of the premorbid humeral head.

We have previously demonstrated that premorbid humeral head size and COR in the arthritic shoulder can be accurately predicted from preserved nonarticular bone landmarks by a best-fit sphere or circle fitted to the proximal humerus. Sphere placement requires use of 3-dimensional computed tomography; circle placement can be performed in the mid–coronal plane of the proximal humerus, obtained from either a 2-dimensional computed tomography scan or a true anteroposterior (AP) radiograph of the shoulder.\textsuperscript{17} The goal of the current radiographic study, therefore, was to apply this method to assess the ability to accurately restore humeral head anatomy in shoulder arthroplasty. We used the best-fit circle technique to measure the deviation of the COR of the prosthetic humeral head from native anatomy after both stemmed and resurfacing humeral head arthroplasty. We hypothesized that there would be variation between surgeons in the restoration of the anatomic COR after shoulder arthroplasty and that the magnitude of the deviation would be greater after resurfacing arthroplasty compared with stemmed arthroplasty.

Materials and methods

Patient selection

The AP radiographs of 275 consecutive stemmed anatomic humeral head arthroplasties performed for end-stage glenohumeral arthritis between April 2008 and July 2012 by 1 of 5 academic fellowship-trained shoulder surgeons were identified. The radiographs of 125 arthroplasties (117 patients) met the study inclusion criteria; the rest were excluded because of inadequate radiographs. Cases were evenly distributed among the 5 surgeons, totaling 25 cases per surgeon. AP radiographs of 53 consecutive humeral head resurfacings performed for end-stage glenohumeral arthritis or avascular necrosis between June 2007 and July 2008 by 4 of the 5 shoulder surgeons performing the stemmed arthroplasties were also identified. The radiographs of 43 resurfacings (40 patients) met the study inclusion criteria; the rest were excluded because of inadequate radiographs. Inclusion criteria for both groups included primary cases performed for either hemiarthroplasty or total shoulder arthroplasty with a postoperative AP radiograph.

Figure 1  A postoperative AP radiograph of a patient demonstrating the anatomic circle with its COR (yellow circle) and the postoperative implant circle and its COR (blue circle). The three preserved bone landmarks (black x) used to generate the anatomic circle are also depicted.

having a near-perfect profile of the implant and the proximal humerus (Fig. 1), as described later. Exclusion criteria included revision cases, patients with evidence of a previous proximal humerus fracture or proximal humeral deformity, and cases in which the surgeon stated in the operative note that the sizing of the humeral head was adjusted from the expected anatomic size to account for other intraoperative concerns (e.g., soft tissue balancing, medialization of glenoid, bone loss).

The average age of patients with a stemmed humeral head arthroplasty was 64.8 \pm 11.5 years (range, 30-88 years), and 58 patients (46\%) were men. Ninety-one percent of the cases (114 cases) were total shoulder arthroplasties, and 9\% of cases (11 cases) were hemiarthroplasties. The average age of patients with a resurfacing humeral head arthroplasty was 46.7 \pm 10.1 years (range, 26-69 years), and 33 patients (76.7\%) were men. Only one case had a glenoid component inserted at the same time of the resurfacing.

Surgical technique

All cases were performed by a standard deltopectoral approach. The subscapularis was managed with a lesser tuberosity osteotomy or a tenotomy. For all cases, the humeral head size was chosen at the discretion of the treating surgeon, with the goal of restoring the anatomic relationships of the proximal humerus and soft tissue balancing. For stemmed humeral head arthroplasty, the Global AP (DePuy Johnson & Johnson, Warsaw, IN, USA) implant was used in 74 cases, the Aequalis (Tornier, Bloomington, MN, USA) in 25 cases, the Affinity (Tornier) in 25 cases, and the Equinoxe (Exactech, Gainesville, FL, USA) in 1 case. Among all implants, a fixed-angle prosthesis was used in 118 cases, whereas a variable-neck prosthesis was used in 7 cases. Use of a fixed-angle or variable-neck prosthesis was at the discretion of the treating surgeon, again with the goal of restoring the anatomic relationships of the proximal humerus and soft tissue balancing. For resurfacings, the Global CAP (DePuy Johnson & Johnson) implant was used in 39 cases, the Aequalis Resurfacing (Tornier) in 2 cases, the Copeland resurfacing (Biomet, Warsaw, IN, USA) in 1 case, and the HemiCAP (Arthrosurface, Franklin, MA, USA) full resurfacing in 1 case.
Radiographic criteria

A postoperative true AP radiograph (Grashey view) with the entire humeral prosthesis in near-perfect profile, defined by limited (<2 mm) overlap of the metallic humeral head at the level of the osteotomy surface, was selected for analysis. The greater tuberosity and medial calcar also needed to be in profile with minimal overlap of the prosthesis and lateral or medial bone (Fig. 1).

The magnification coefficient from radiographs was calculated by use of a magnification marker with a 12.5-mm radius inserted beside the shoulder when the radiograph was taken (6 cases). When this was not present (162 cases), the magnification coefficient was calculated by dividing the radius of curvature (ROC) of the implanted humeral head (identified as the size noted in the operative log) by the ROC of the radiographically measured humeral head.

Center of rotation measurements

Measurements were performed by AutoCAD (Autodesk Inc, San Francisco, CA, USA). A best-fit circle was placed on the AP image with three preserved bone landmarks: the lateral cortex of the greater tuberosity, the medial calcar at the inflection point where calcar meets the articular surface, and the greater tuberosity at the medial supraspinatus insertion (Fig. 1). A second circle, the implant-matched circle, was placed to fit the curvature of the prosthetic humeral head (Fig. 1). The COR was then identified from each circle, and the distance, in millimeters, between the CORs of the anatomic and implant circles was calculated. All measurements were normalized for magnification on the basis of the magnification coefficient. A coordinate system was then generated from the anatomic COR, with the y-axis aligned parallel to the intramedullary axis and the x-axis defined as perpendicular to this line. This created four regions in which the location of the deviation of COR could be defined: superior medial, inferior medial, superior lateral, and inferior lateral (Fig. 2). Medial and superior deviations were deemed positive. Cases with a deviation of >3.0 mm were considered clinically significant outliers and defined to be caused by improper humeral head selection (height or ROC) or improper humeral neck cut (or head reaming). Outlier cases were considered to be a result of improper humeral head selection if the radius of the implant-matched circle was at least 2 mm different from the radius of the anatomic circle because, in most commercial companies, a 2-mm-radius difference would indicate that a different humeral head size was more suitable to be selected. Outlier cases were considered to be a result of improper humeral neck cut or head reaming if there was remaining humeral head bone present medial to the anatomic neck of the proximal humerus, either along the greater tuberosity or at the inflection point along the medial calcar region of the humeral head. Outlier cases were considered to be a result of a combination of both improper humeral head selection and improper humeral neck cut or head reaming when both of these factors were present. Medial deviation of the COR was defined as overstuffing.

Statistical analysis

A 3-way analysis of variance with a Bonferroni correction was used to compare the average deviation of the 5 surgeons for stemmed implants and the 4 surgeons for resurfacings. A 3-way analysis of variance with a Bonferroni correction was also used to compare the average deviation of the different implant brands. The deviation in COR and surgeon were set as variables. Because an analysis of our data showed no strong deviations from normality, a Student t test was used to compare deviations between stemmed arthroplasty cases and those with resurfacing arthroplasty. Significance was set at a P value of ≤ .05.

Results

Stemmed humeral head replacement

The average deviation (± standard deviation) of the postoperative implant COR from the anatomic COR for all 125 cases was 2.5 ± 1.5 mm (range, 0.0-8.1 mm). The average deviation for each of the 5 surgeons is demonstrated in Table I. There was no statistically significant difference in the average deviation between the 5 surgeons (P = .36).

Of the 125 cases, the number of cases with a deviation of ≤2.0 mm, 2.1 to 3.0 mm, 3.1 to 4.0 mm, and >4.0 mm is shown in Table II. Thirty-nine cases (31.2%) exhibited a deviation of >3 mm and were considered outliers. The majority of the outliers were overstuffed, with 53.8% demonstrating a postoperative COR that was medial to the anatomic COR compared with 46.2% that were lateral to the anatomic COR (Fig. 3).

When outliers were analyzed for the main cause of the deviation, an improper humeral head size selection was the main reason for the deviation in 56.4% of cases, an
improper humeral neck cut in 20.5% of cases, and a combination of both factors in 23.1% of cases (Table III).

There was no statistically significant difference in the average deviation between the 3 main implants used for stemmed humeral head arthroplasty, with an average deviation of 2.5 ± 1.6 mm, 2.3 ± 1.2 mm, and 2.5 ± 1.5 mm for the DePuy Global AP, Tornier Affiniti, and Tornier Aequalis, respectively (P = .84).

**Resurfacing humeral head replacement**

The average deviation of the postoperative resurfacing head COR from the anatomic COR for all 43 cases was 3.8 ± 2.1 mm (range, 0.1-8.3 mm), and this was statistically larger than that for stemmed cases (P < .01). The average deviation for each of the 4 surgeons is shown in Table I. There was no statistically significant difference in the average deviation between the 4 surgeons (P = .44).

Of the 43 cases, the number of cases with a deviation of ≤2.0 mm, 2.1 to 3.0 mm, 3.1 to 4.0 mm, and >4.0 mm is shown in Table II. Twenty-eight cases (65.1%) exhibited a deviation >3 mm and were considered outliers. All the outliers (100%) were overstuffed with a postoperative COR that was medial and superior to the anatomic COR (Fig. 4).

When outliers were analyzed for the main cause of the deviation, inadequate humeral head reaming (i.e., not reaming lateral enough) was found in all outlier cases. An inappropriate implant size selection (thickness or ROC) was an additional contributing factor in 10.7% of cases (Table III).

**Discussion**

The purpose of this study was to apply a best-fit circle technique on plain radiographs to assess the ability to accurately restore humeral head anatomy in shoulder arthroplasty. We have previously validated this model for determining premorbid humeral head size and COR in the arthritic shoulder on the basis of sphere or circle placement relative to preserved nonarticulate bone landmarks.17 In the current study, we hypothesized that there would be variation between surgeons in the restoration of the anatomic COR after shoulder arthroplasty and that the magnitude of the deviation would be greater after resurfacing arthroplasty compared with stemmed arthroplasty. We found that significant deviation in the postoperative COR relative to the anatomic COR can occur even in the hands of experienced shoulder surgeons. Resurfacing humeral head arthroplasty resulted in twice as many deviations >3 mm relative to stemmed arthroplasty (P < .01), suggesting that it was more difficult to restore the premorbid anatomy after resurfacing compared with stemmed humeral head arthroplasty. Variation between surgeons was not statistically significant.

Our choice of 3 mm as a threshold for defining outliers is based on previous biomechanical studies examining the effects of humeral head position in shoulder arthroplasty. Multiple studies have demonstrated that 5 mm of malposition of the humeral head can result in impingement, increased subluxation risk, restricted range of motion and joint laxity, decreased abduction moment arms of the supraspinatus and infraspinatus, and increased stresses on the glenoid component.5,9,14 These studies, however, did not analyze values less than 5 mm. The study by Williams et al16 revealed that a 4-mm or less malposition in the offset of the humeral head resulted in decreased range of motion or impingement. Moreover, Favre et al5 showed that a 2.5-mm translation of the humeral head superiorly resulted in significant effects on the glenohumeral angle of elevation at inferior impingement. The use of 3 mm as a cutoff in the current study represents a number that lies between the values of these prior reports and a deviation we believe may be clinically relevant, with potential long-term clinical consequences. Nevertheless, we have also reported the number of cases with deviations ≤2.0 mm, 2.1 to 3.0 mm, 3.1 to 4.0 mm, and >4.1 mm for completeness (Table I).

Inaccurate sizing or positioning of a prosthetic humeral head can lead to overstuffing the joint and result in poor outcomes, including shoulder stiffness, rotator cuff tearing, poor subscapularis tendon healing, and increased glenoid component wear and loosening.2,5,9,14-16 However, the causes of humeral head malpositioning may differ for stemmed and resurfacing implants on the basis of the results of this study. Of the stemmed outliers, 80.0%, or 25.0% of all stemmed cases, displayed an improper prosthetic humeral head selection. In contrast, all of resurfacing outliers, or 65.1% of all resurfacing cases, demonstrated an inadequate reaming of the humeral head. These findings suggest that the humeral head can be more accurately cut along the anatomic neck during placement of a stemmed

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**Table I** The average deviation (± standard deviation) of the postoperative COR from the anatomic COR of stemmed shoulder arthroplasties compared with resurfacing shoulder arthroplasties for each surgeon and the average deviation for all cases

<table>
<thead>
<tr>
<th>Surgeon</th>
<th>Stemmed arthroplasty</th>
<th>Resurfacing arthroplasty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgeon 1</td>
<td>2.6 ± 1.1</td>
<td>3.7 ± 2.1</td>
</tr>
<tr>
<td>Surgeon 2</td>
<td>2.3 ± 1.2</td>
<td>3.4 ± 1.8</td>
</tr>
<tr>
<td>Surgeon 3</td>
<td>2.1 ± 1.4</td>
<td>3.3 ± 1.8</td>
</tr>
<tr>
<td>Surgeon 4</td>
<td>2.9 ± 2.2</td>
<td>4.7 ± 2.6</td>
</tr>
<tr>
<td>Surgeon 5</td>
<td>2.5 ± 1.5</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>2.5 ± 1.5</strong></td>
<td><strong>3.8 ± 2.1</strong>*</td>
</tr>
</tbody>
</table>

All measurements are in millimeters.

*Indicates significance; the average deviation of the resurfacing arthroplasties was statistically larger than that for stemmed arthroplasties.
prosthesis than can be reamed to this level during preparation for placement of a resurfacing implant. However, complete removal of the humeral head may make selection of the correct implant size more challenging than when only the articular surface is reamed away. Use of the described radiographic circle method preoperatively can potentially assist surgeons to avoid both types of errors by providing an approximation of the humeral head ROC and height that should be chosen and the anatomic neck cut that should be made. Intraoperative use of a best-fit circular instrument localized to the lateral nonarticular humeral landmarks may further assist surgeons in choosing the correct humeral head size (Fig. 5). Finally, intraoperative fluoroscopy may provide an additional check to confirm appropriate humeral head size and position. Ultimately, such preoperative and intraoperative techniques can be used to achieve the goals of optimal soft tissue balancing and stability.

Our results regarding resurfacing humeral head arthroplasty contrast with those of other published studies. Mansat et al. showed that resurfacing humeral head arthroplasty “reproduces the normal anatomy including humeral offset and compensates glenohumeral wear,”
although there was a tendency to position the resurfacing in varus. Thomas et al\textsuperscript{15} demonstrated that resurfacing shoulder arthroplasty restored humeral offset but reduced the humeral head radius by 3.5%. However, both of these studies compared postoperative radiographs after resurfacing arthroplasty with pathologic, arthritic preoperative radiographs for measurements of restoration of anatomy. Although both studies used a validated technique for measurement of COR as described by Rozing and Obermann,\textsuperscript{13} this method is based on average ratios taken from 23 cadaveric shoulders and is not specific to each patient’s anatomy. Moreover, because some of these measurements are based on nonpreserved landmarks of the preoperative pathologic humeral head, they can be inaccurate. Finally, a study by Hammond et al\textsuperscript{4} analyzed resurfaced and stemmed humeral head arthroplasty biomechanically and found that resurfacing arthroplasty better reproduced normal anatomy relative to stemmed arthroplasty. However, this was a cadaveric study using nonarthritic joints.

The primary limitation of the current study is the lack of clinical correlation to the reported radiographic findings. The use of 3 mm of deviation of the COR as a threshold for defining outliers was chosen arbitrarily as a number in the middle of values of prior reports, as discussed before. The clinical significance of this 3-mm deviation in COR is not currently known, and long-term clinical follow-up is needed to determine the consequences of this and other deviations. The majority of the current cases were performed within the last 2 years, and sufficient clinical follow-up data do not yet exist. In addition, we do not know if 3 mm of deviation will result in any clinical symptoms or long-term consequences, and clinical correlation is needed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{A graph demonstrating the deviation of the resurfacing arthroplasty outliers in the x- and y- axes for each of the surgeons. Both axes are in millimeters. The x-axis represents medial-lateral, with positive indicating medial. The y-axis represents superior-inferior, with positive indicating superior. The (0, 0) point indicates the center of the anatomic COR.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Intraoperative picture demonstrating a best-fit circle with the preserved humeral landmarks after the humeral head arthroplasty.}
\end{figure}
Furthermore, not all arthroplasty cases were included in this study; only cases with radiographs meeting our inclusion criteria were included.

**Conclusion**

This study has demonstrated that a large number of shoulder arthroplasty cases had more than 3 mm of deviation in the postoperative COR relative to the anatomic COR of the humeral head. This deviation most commonly resulted in overstuffing the reconstructed joint. Surgeons performed better at anatomically reproducing the premorbid humeral head anatomy with stemmed shoulder arthroplasty compared with resurfacing arthroplasty. The radiographic best-fit circle technique can be used to evaluate postoperative reconstruction. Further studies are needed to assess the clinical impact of these deviations.

**Disclaimer**

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**References**