Determining the ideal osteotomy for stemless total shoulder replacement – a cadaveric study.

Short title: Ideal Osteotomy Stemless Total Shoulder Replacement

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Abstract

Hypothesis: To determine the angle of osteotomy that produces a circular humeral cut surface.

Methods: 49 cadaveric shoulders, from 25 cadavers, underwent sequential humeral head osteotomy from 180 degrees (vertical, in line with the humeral diaphyseal shaft) in 10-degree increments, until the rotator cuff insertion was encountered. At each stage the antero-posterior and the supero-inferior distances were recorded. The data was analyzed for normality and then assessed to determine the optimum cut angle.

Results: The AP/SI ratio is an indication of roundness. Plotting values of 1-AP/SI (i.e. error) versus cut angle allows us to plot the likelihood of producing a circular cut surface using a third order curve which created the best fit to the data set ($R^2 = 0.99$). The results from this study suggest that the optimum osteotomy angle that produces a circular cut surface is 23 degrees from the vertical. The cohort data illustrates that at this angle the average roundness error is 1% with a 95% confidence limit of less than 1%. There is no significant difference ($p>0.05$) between genders.

Conclusion: The humeral head shape changes from an oval to circular, and then to an oval cut surface as the osteotomy angle increases from the vertical towards the horizontal. The range of angles within which the cut surface is circular, within 10% error, is 18-27 degrees from the vertical, which is much less than the traditional osteotomy angle of 45 degrees.

Keywords: Humeral replacement, stemless replacement, humeral osteotomy

Level of evidence: Anatomy Study; Cadaver Dissection
Accurate restoration of the center of rotation is a necessary requirement to restore rotator cuff tension and produce satisfactory function following total shoulder replacement. Precise humeral head alignment in the coronal, sagittal and transverse planes is desirable in order to achieve this. Stemmed humeral implants can limit the ability to restore the patient’s center of rotation due to the anatomical variation in the offset and longitudinal alignment between individuals. Humeral replacements, through numerous generations, have evolved to tackle these issues. First generation implants, reported in 1955 by Neer, consisted of monobloc designs with fixed anteroposterior and mediolateral offset. Second generation devices allowed limited modularity with the option of different sized heads for differing stem sizes. In order to better restore the original center of rotation, third generation implants increased implant variability in different planes. These designs allowed the modification of offset, version and humeral head inclination.

Stemless implants, the fourth generation of shoulder replacements, were first introduced in 2004. Bone anchorage was entirely in metaphyseal bone thus avoiding diaphyseal broaching. This allowed restoration of the anatomical center of rotation without reference to the humeral axis. Their use is predicted to outnumber stemmed implants by 2025. Stemless humeral implants are sized, based upon their humeral head diameter. As the replacement humeral head diameter increases, so the implant thickness increases with some companies offering different thicknesses of humeral head size for the same humeral head diameter.

Although replacement humeral heads are circular, published data has demonstrated that the native humeral head is non-spherical, and therefore, an osteotomy of the humeral head will not necessarily produce a circular base for accurate attachment of a circular implant.
Given that the implant is selected based on the circular diameter of the osteotomy, the procedure becomes prone to error if that osteotomy surface is oval rather than circular. Selecting an implant based on the minor diameter risks under-sizing, instability and poor cuff function. Selection based on the major diameter will result in implant overhang. This may potentially impinge on the rotator cuff, adversely affecting function and may lead to possible cuff failure.

Aims
This study aims to determine the ideal angle of humeral head osteotomy which produces a circular osteotomy surface allowing appropriate implant selection to replace the humeral head without compromise to adjacent soft tissues due to implant overhang.

Method
All investigations were carried out at the Keele University Medical School Anatomy Department. Permissions for the cadaveric study were obtained from Keele University in accordance with local regulations.

Cadaveric shoulders at our anatomy department were examined for inclusion in the study. Those with osteophytes preventing identification of the articular edge, post-fracture deformity or flattening of the humeral head that would prevent sequential osteotomy were excluded from the study. 50 shoulders from 25 cadavers were identified for investigation (13 Females and 12 Males). The average age of the subjects was 83 years (Female 84 years; Male 83 years) with an age range of 60-95 years. One shoulder (left, Male) had a large Hill-Sachs lesion, which would significantly affect the AP measurement, and was excluded. The
study contained a total of 49 shoulders (25 Right and 24 Left). Each humerus was explanted, and the maximum anteroposterior (AP) and supero-inferior (SI) diameters of the humeral head recorded. A 2.0mm guidewire was inserted, running from the subscapularis insertion anteriorly to the infraspinatus insertion posteriorly at the level of the equator of the humeral head, to define the version of the humeral head articular surface. The inferior margin of the articular surface was confirmed at the point the concave humeral neck transitioned to the convex humeral head. A 5-axis adjustable jig was designed and manufactured from 6061 aluminum (Figure 1.). This allowed accurate positioning of the device so that the osteotomy was correctly positioned in alignment with the humeral articular surface and the humeral shaft axis. The humeral diameter was measured at 2 points along the shaft of the humerus, in the plane of the articular surface, and a line drawn along the humeral length. This formed the axis along which the humeral jig was aligned using two fixation points. It was adjusted to match the anatomical version and offset of the cadaveric proximal humerus. Using the jig, the humeral head was sectioned using a hand saw, from 180 degrees (vertical, in line with the humeral diaphyseal shaft) in 10-degree increments until the rotator cuff insertion was encountered. Each angle was confirmed with a goniometer. For each incremental osteotomy, the AP and SI distances were recorded in addition to the distance from the superior margin of the osteotomy to the insertion of the rotator cuff. We called this the ‘cut to cuff’ distance (Figure 2.)

The osteotomies and measurements were carried out following validation of technique and the intra-observer error has been assessed, and the average variation between measurements was 2.08% with a 95% confidence interval of +/-0.1%.

Statistics:
All results were analyzed using Minitab 19 and Excel. Data was assessed for normality using a Shapiro-Wilk analysis and were found to be normal (p>0.05). Values for AP, SI, and AP/SI were assessed for variance between gender using a t-test (significance p<0.05). Averages and standard deviations were determined and confidence limits determined.

**Results**

Within the group there were 49 shoulders from 25 subjects. The average values for males, females and as a whole are given in Table I.

As the data for AP/SI ratio is not significantly different between males and females (p>0.05) the further analysis may be conducted on the cohort as a whole.

**Method for finding optimum angle.**

The AP/SI ratio is an indication of roundness. Plotting values of 1-AP/SI (i.e. error) versus cut angle results in Figure 3. A third order curve created the best fit to the data set (R² =0.99). This curve exhibits a minimum AP/SI roundness error at its minima. To be within the bounds of 95% round the AP/SI error should be <0.05 (5%). The graph suggests that to obtain a roundness error of <3% the osteotomy angle should be between 19 and 27 degrees, the optimum being at 23 degrees.

**Method for analyzing results at 23 degrees.**

The AP/SI ratios determined for 20 degrees and 30 degrees were linearly interpolated to estimate AP/SI ratios for all 49 samples at an osteotomy angle of 23 degrees. The results of this analysis is presented in Table II.
The results from this study suggest the optimum osteotomy angle (Fig 1) is 23 degrees. An analysis of the difference between genders (Table II) illustrates that there is no significant difference (p>0.05). The cohort data (Table II) illustrates that at this angle the average AP/SI ratio is within 1% of unity (i.e. circular) with a 95% confidence limit of less than 1%.

**Method for Determining “Cut to Cuff”**

The cut to cuff distance was investigated for each patient at a cut angle of 23 degrees. The average cut to cuff distance was 18.3 mm with a standard deviation of 4.5 mm, the maximum was 27.1 mm and the minimum 9.7 mm. This data suggests that a single value of cut to cuff that is valid for all different head sizes is not valuable. A method of predicting an optimum cut to cuff using an equation based on anatomical features, a nomogram or machine learning is being undertaken.

**Discussion**

The restoration of humeral head anatomy in anatomic shoulder arthroplasty, recreating the center of rotation, to allow optimal cuff function is a requirement for good postoperative function. The stepwise development of humeral arthroplasty since the first modern report of shoulder replacement by Neer has culminated in the current 4th generation of stemless implants allowing surgeons to position the humeral head independent of the humeral shaft alignment. This provides a greater opportunity to recreate the original center of rotation. The humeral cut surface however, will determine the size of the circular replacement that is implanted. The traditional shape of the cut surface at 135 degrees is oval from our study and others, and the considered approach is to use the ‘best fit’ method when choosing a replacement head, which if too large will overlap onto the anterior and posterior edges and potentially compromise the cuff integrity by impinging upon the
subscapularis anteriorly and the infraspinatus posteriorly. This could also over tension the 
rotator cuff causing pain and reduced function⁵. If one uses the minor diameter, the head will 
be undersized and risks point loading the articular surface of the glenoid or glenoid 
replacement. Under-sizing will also potentially risk under-tensioning and de-functioning the 
rotator cuff due to laxity and potential instability due to cuff dysfunction²⁴. Using the minor 
diameter as a size reference will also result in a lowering and lateralizing of the center of 
rotation, the effect of which when the cuff contracts, will be an elevation of the humeral head. 
Elevation of the humeral head can cause impingement²¹ and may compromise cuff integrity. 
By creating an osteotomy with a circular base, the implant can be more appropriately sized 
without implant overhang or under sizing. This will allow appropriate humeral head 
replacement to be performed without potential compromise of adjacent cuff or point loading 
of the glenoid or glenoid component. Humeral head height will influence the relationship 
also, contributing to cuff tension, but has not been investigated in this study.

Stemless shoulder arthroplasty usage has increased significantly over the past 10 years and is 
continuing to increase²⁵, with benefits noted for both biomechanical²² and clinical reasons⁹. It 
has been noted from finite element analysis²² that the biomechanical environment of the 
proximal humerus, in stemless implants, more closely recreates the proximal humeral stresses 
than do stemmed implants and implants with shortened stems. This allows bone biology that 
is closer to normal, to exist in this area especially when compared to stemmed prostheses⁵ or 
resurfacing arthroplasty, where stress shielding can occur at the edge of the implant and 
around the stem¹. A finite element analysis study looking at the effects of different stemless 
designs²³ demonstrated that central peg-design implants produced the least simulated bone 
resorbing potential in cortical and trabecular bone. From the surgical perspective, use of a 
stemless humeral replacement has been reported to produce less intra-operative blood loss
than a stemmed prosthesis\textsuperscript{4} and the lack of a prosthesis within the humeral shaft will likely reduce the revision morbidity\textsuperscript{9}.

Early and mid-term results for stemless designs have shown favorable results\textsuperscript{2,3,9,11,27} with good functional ranges and outcome scores, but there is limited evidence in the literature regarding long term results at this time\textsuperscript{18}. Published indications for revision of stemless prostheses include cuff failure\textsuperscript{9,27}, biceps stump impingement\textsuperscript{9} and glenoid loosening\textsuperscript{27} with revisions for cuff failure being carried out to reverse prostheses. In a direct comparison between a stemmed and a stemless prosthesis, Uschok et al\textsuperscript{27} noted good functional results of the stemless design which were comparable to the conventional stemmed designs at a minimum 5 year follow-up, but to date no comparative study has shown better results of a stemless design over a stemmed prosthetic design, with results generally being quoted as similar\textsuperscript{4,27}. A systematic review\textsuperscript{11} in 2016 looking at 11 studies and including 929 cases, concluded that mid-term results were promising but longer-term results were needed. At time of writing, the longest outcome results are for a single surgeon series with a mean follow-up of over 10 years (range 105 – 157 months) published by Magosch et al\textsuperscript{18}. The Kaplan-Meier analysis revealed a 10-year survivorship of 96.5\% for the stemless humeral component, but there was a published revision rate of 9.3\% to a reverse geometry prosthesis\textsuperscript{18}.

The lateral offset measurement is often seen as a proxy assessment for the glenohumeral relationship. Restoring lateral offset allows deltoid and supraspinatus moment arms to be restored\textsuperscript{17} but increasing lateral offset in total shoulder arthroplasty has been shown to have a negative effect on shoulder range of motion and subacromial impingement\textsuperscript{29} although one author has noted that the negative effect of the increased lateral offset noted at 3 months postoperatively, settled by the 1-year postoperation stage\textsuperscript{16}. Altering the osteotomy angle for
shoulder arthroplasty to a more vertically orientated position may increase the lateral offset
unless the reduced head height, that is excised, is accommodated for.

Humeral head morphology at an osteotomy angle of 135 degrees, reveals a long supero-
inferior axis and a shorter antero-posterior axis, which shows variation within the
population\textsuperscript{13} but as the head size increases this tends to increase proportionately, without
significant gender differences\textsuperscript{13}. This is consistent with the review of the results from our
cadaveric population confirming that there is significant consistency of the angles at which
the cut surface changes from an oval cut surface to a circular cut surface and then to an oval
cut surface again. The non-spherical features align with various authors who have previously
noted the oval shape of the humeral head\textsuperscript{12,28}. Degenerative humeral head changes have been
noted to fall into 2 main categories according to Habermeyer et al\textsuperscript{10}. In type 1 the superior
head is not involved in the degenerative process. In type 2 they noted that superior cartilage
erosion is seen in the superior quadrants in only 25% but this did not appear to involve the
articular surface immediately adjacent to the rotator cuff. Our results show that the angles
about which the circularity, within a 10% error margin, exists is from 18 degrees to 27
degrees. The angle about which the cut surface is consistently circular is 23 degrees, across
all head sizes with an $R^2$ value of 0.99. Intra-operatively, identification of the inferior
osteotomy line is relatively straightforward, it being the point where the shape of the humeral
neck changes from concave to convex. In the presence of an inferior osteophyte this point can
be carefully identified after removal of the osteophyte. Accurate measurement of the
osteotomy angle however, with the standard equipment available in theatre is challenging, as
the true longitudinal axis of the humerus is difficult to define intra-operatively through the
limited exposure of the humeral head.
This study identifies a range of cut angles that produce a circular cut surface during humeral head osteotomy. This will allow more accurate placement of a circular humeral head replacement on to the cut surface without potential cuff impingement. Further investigation, however, is needed on the potential variability of the height of the cut segment. Too shallow a replacement risks instability and too thick a replacement risks overstuffing the joint. If this can be determined it may better guide the accurate placement of the humeral head in the future using a more vertically-orientated humeral head osteotomy technique.

Although knowledge exists regarding humeral and glenoid contact in native shoulders, the exact amount of surface of the replacement humeral head that articulates with the glenoid following replacement shoulder arthroplasty is unclear but the factors influencing this are many and likely to include cuff dysfunction, humeral head osteophytes and capsular restriction. The optimum surface of humeral head that is needed to be replaced in order to restore the shoulder range of motion, therefore, is also not accurately known. If this were known we may better understand the head parameters that need reconstructing during humeral head arthroplasty. Furthermore, a more vertical placement of the humeral head replacement would alter the force characteristics acting on the humeral stem. The new cut angle is unlikely to unduly change the forces that act on the implant surface as the basic geometry should be consistent. However, the change in cut angle may influence the forces acting on the implant fixation in the humerus, and as a result could alter implant osseointegration. At present the potential effects are not fully understood and require further investigation to ascertain whether the clinical benefits of a more circular osteotomy surface outweigh additional risks associated with a change of cut angle. Simulations are being undertaken to understand the change in system mechanics to enable this risk assessment to be made.
At operation, a more useful measurement, rather than a cut angle that is difficult to define intra-operatively would be one that is easily made using only the surgical field accessed at the time of osteotomy. For this we used the ‘cut to cuff’ distance, that is, the distance from the osteotomy line to the edge of the rotator cuff in the plane of the humeral articular surface (Figure 2). The average cut to cuff distance at a cut angle of 23 degrees was 18.3 mm with a 95% CI = 1.37 mm. Unfortunately, the spread of data is wide which may make one single distance unviable as a clinical measurement. Methods to accurately determine the cut to cuff measurement for each patient intraoperatively using easily identifiable operative landmarks are currently being investigated to improve surgical technique.

There are limitations with our study in that we only performed cadaveric dissection on 49 shoulders but the R² value of 0.99 shows excellent correlation between measurements and we believe that they are transferrable to a general population, although we appreciate that despite the R² value, this may be due to a sampling error. The study has not investigated the head height of the osteotomized humeral head pieces and therefore no information is available regarding the size of the head fragments for each osteotomy angle. As the fragments were small in each case, the portion of the head that was removed as part of the cutting technique would have been too much proportionately to allow meaningful measurement and we feel that not having information regarding the removed head fragment height is a deficiency of this study. Furthermore, the results we present suggest that the outcomes are not patient specific. However, more data is required to confirm this conclusion.

Conclusion
As the osteotomy angle increases from the vertical towards the horizontal, the humeral head shape changes from an oval to circular and then to an oval cut surface. The range of angles within which the cut surface is circular, within 10% error, is 18-27 degrees from the vertical, which is much less than the traditional osteotomy angle of 45 degrees.

References


**Table Legends**

Table I – AP, SI and AP/SI ratio for males, females and whole cohort. Values are average values, and standard deviation and 95% confidence limits, are in parentheses.

Table II – Average AP/SI ratio for males, females, and the cohort as a whole, at an osteotomy angle of 23 degrees.

Figure 1. – 5-axis adjustable osteotomy jig

Figure 2. – Diagram describing anatomical landmarks and methodology for using cut to cuff distance for humeral head osteotomy.

Figure 3. - Roundness error versus osteotomy angle. The roundness error increases with cut angles either side of 23 degrees such that the traditional cut angle of 45 degrees produces an error larger than 9%. In comparison the roundness error is the smallest around angles of 23 degrees. The information currently lacking is the height of the humeral head that this corresponds to. If there is a wide variation in head height then this measure may not be useful. If, as is more likely, the height difference is minimal, then having a wide choice of osteotomy angle will accommodate for surgical variation at operation.
Table I.

<table>
<thead>
<tr>
<th></th>
<th>Male (N=13)</th>
<th>Female (N=12)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>47.8 (3.72,1.52)</td>
<td>40.9 (3.07,1.15)</td>
<td>&lt;0.05</td>
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<tr>
<td>SI</td>
<td>51.4 (2.51,1.03)</td>
<td>44.7 (3.17,1.19)</td>
<td>&lt;0.05</td>
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<tr>
<td>AP/SI</td>
<td>1.08 (0.072,0.03)</td>
<td>1.1 (0.064,0.024)</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Whole cohort

AP, SI and AP/SI ratio for males, females and whole cohort. Values are average values, and standard deviation and 95% confidence limits, are in parentheses.
Table II – Average AP/Sl ratio for males, females, and the cohort as a whole, at an osteotomy angle of 23 degrees. Values are average values, and standard deviation and 95% confidence limits, are in parentheses.
**Cut angle**

**Point of inflexion**
(change of shape from convex to concave)

**Visible boundary of the cuff**

**Cut to cuff distance**
Figure 3.

Optimum = 23 degrees

$R^2 = 0.99739$

Roundness Error (Percent)

Osteotomy Angle (degrees)

$\text{Run and Neck Errors (Percent)}$

$\text{Osteotomy Angle (degrees)}$

$\text{R^2} = 0.99739$

$0.00 \ldots 5.00 \ldots 10.00 \ldots 15.00 \ldots 20.00 \ldots 25.00 \ldots 30.00 \ldots 35.00 \ldots 40.00 \ldots 45.00$

$0.00 \ldots 1.00 \ldots 2.00 \ldots 3.00 \ldots 4.00 \ldots 5.00 \ldots 6.00 \ldots 7.00 \ldots 8.00 \ldots 9.00$

$\text{Roundness Error (Percent)}$

$\text{Osteotomy Angle (degrees)}$