Comparison of reconstructive procedures for glenoid bone loss associated with recurrent anterior shoulder instability

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\textbf{Hypothesis:} A tibial plafond allograft, iliac crest allograft, and coracoid autograft in a congruent arc Latarjet reconstruction better restore radius of curvature, depth, and surface area for glenoid bone loss in recurrent instability compared with the coracoid autograft in a standard Latarjet reconstruction for anteroinferior glenoid bone loss of the shoulder.

\textbf{Methods:} Three-dimensional shoulder models were generated from bilateral computed tomography scans in 15 patients, who were a mean (standard deviation [SD]) age of 23 (7.7) years, with recurrent anterior shoulder instability and known glenoid bone loss. The surface areas of the glenoid in the involved and contralateral normal shoulder were measured. Virtual surgery was then performed using standard and congruent arc Latarjet reconstruction, tibial plafond, and iliac crest allografts. Grafts were optimally positioned to restore articular congruity and defect fill. Radius of curvature and restoration of glenoid depth were compared with the contralateral glenoid.

\textbf{Results:} Glenoid surface area (11.04% [6.95% SD]) and depth (0.75 [0.57 SD] vs 1.44 [0.65 SD] mm) were significantly reduced ($P < .012$) in the injured glenoid. The mean (SD) coronal plane radius of curvature of the congruent arc Latarjet reconstruction (60.3 [39.0 SD] mm) more closely matched the radius of curvature of the injured glenoid (67.5 [33.2 SD] mm) compared with the other grafts. Restored glenoid depth was greater in the tibial plafond (1.8 [1.1 SD] mm) and iliac crest (2.0 [0.6 SD] mm) allografts compared with other grafts ($P < .002$).

\textbf{Conclusion:} Congruent arc Latarjet reconstruction more closely restores native glenoid coronal radius of curvature, whereas tibial plafond and iliac crest allografts more adequately restore depth compared with standard Latarjet reconstruction.

\textbf{Level of evidence:} Basic Science, Computer Modeling Study.

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\textbf{Keywords:} Bone loss; glenoid; instability; shoulder; Latarjet; allograft

The protocol of this study was approved by the University of Michigan Institutional Review Board (Study eResearch ID HUM00051862).

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Unaddressed significant glenoid bone loss is a known risk factor for recurrence and failure after arthroscopic stabilization surgery of the shoulder. Several autologous and allograft options for glenoid reconstruction have been described as having favorable clinical outcomes in small case series and technical notes. Coracoid-based autograft options include the standard and congruent arc (CA) Latarjet-Patte procedures, whereas allograft options to restore glenoid bone stock include tibial plafond, iliac crest, and glenoid. Although coracoid-based autograft constructs, such as the Latarjet procedure, have shown excellent long-term restoration of shoulder stability and clinical outcomes, questions remain regarding the development of postdislocation arthropathy.

The use of an iliac crest allograft or a CA-type Latarjet has been shown to optimally restore glenohumeral contact pressures in a cadaveric model of glenoid bone loss, which theoretically, could be important in the development of arthropathy.

No studies to date, however, have compared all of these graft options with respect to their ability to restore glenoid articular surface congruity, surface area, and radius of curvature. Differences in these parameters may have important implications for glenohumeral kinematics, contact mechanics, and the risk for secondary arthrosis after reconstructive procedures for glenoid bone loss secondary to recurrent anterior instability. Our hypothesis was that tibial plafond allograft, iliac crest allograft, and CA Latarjet reconstruction with coracoid autograft would better restore radius of curvature, surface area, and depth for glenoid bone loss in recurrent shoulder instability compared with the standard Latarjet reconstruction with coracoid autograft.

Materials and methods

Three-dimensional (3D) models of the shoulder were generated from bilateral computed tomography (CT) scans in 15 patients (2 females and 13 males, 6 left and 9 right), who were a mean (standard deviation [SD]) age of 23 (7.7) years, with recurrent anterior shoulder instability, known glenoid bone loss, and an uninjured contralateral shoulder using the Mimics 13.0 computer software program (Materialise, Ann Arbor, MI, USA). This software program uses DICOM (Digital Imaging and Communications in Medicine) data to create a 3D model of the proximal humerus and scapula and has been used in other projects examining anatomic relationships of osseous structures. Once created, the model can be rotated and viewed from all angles and can be manipulated and sectioned along cut lines, allowing “virtual surgery” to be performed.

Models and measurements

The surface areas of the injured and contralateral intact glenoid were measured in their entirety with the surface area function in Mimics software, which was then used to precisely calculate the area of bone loss for the injured glenoid. The radius of curvature (ROC) was measured along the defect (Fig. 1) using the Mimics 3-point best-fit arc method and was labeled as ROC coronal. We defined a positive coronal ROC as a radius that matched the intact concave glenoid, whereas a negative ROC had the opposite convex curvature. A 3D model for the contralateral, intact shoulder was generated as a control. This intact model was then mirrored to allow for an overlay of the intact glenoid to be superimposed upon the injured glenoid. Point and global registration methods were used to match the contours of the glenoids as closely as possible.

Virtual surgery was then performed to address the bone loss using standard and CA Latarjet reconstruction according to the techniques of Walch and deBeer and Roberts tibial plafond according to the technique of Provencher et al, and iliac crest according to the technique of Warner et al. Grafts were optimally positioned to restore articular congruity and defect fill while ensuring that no part of the glenoid adjacent graft was proud in relation to the intact glenoid surface, thereby creating an “idealized” surgical model to maximize the potential result with regards to restoration of native anatomy.

For the Latarjet-Patte reconstructions, the coracoid was sectioned at the elbow just distal to the insertion of the coracoclavicular ligaments and moved into position in the standard (inferior border in contact with glenoid) or CA (medial border in contact with glenoid) method. Slight overlapping of the coracoid and the glenoid was allowed to simulate the use of a saw or burr to optimally smooth the contacting surfaces during surgery. Areas of the articular surface of the coracoid grafts were calculated for each position using the surface area function. The coronal ROC was calculated for each graft position (Fig. 2, A and B).

For each of the allograft techniques, 20 CT scans of intact pelvic and tibial plafonds were used from a database of high-resolution studies obtained for an evaluation unrelated to the study. CT scans were acquired using a 64-channel high-resolution CT scanner and bone acquisition and standard reformatting algorithms; slice thickness was 0.625 mm.

Pelvis CT scans were reviewed from 20 individuals (mean age, 28.9 [6.9 SD] years) undergoing our typical femoroacetabular impingement imaging protocol, which allowed us to compile 20 CT scans of normal iliac crests. Ankle CT scans obtained for foot trauma not involving the tibial plafond were reviewed from 20 individuals.
(mean age, 27.7 [5.8 SD] years), which allowed us to compile a database of 20 normal plafonds. The lateral portion of the plafond was used as described by Provencher et al,13 as was the inner table of the iliac crest as described by Warner et al,18 with the first vertical cut located 2 cm posterior to the anterior-superior iliac spine.

Because these were allografts, size could be greatly influenced by the amount resected; for this reason, we fashioned 1-cm-wide allografts (2 cm in length for iliac crest). Once all allografts were created, we measured the coronal ROC for each graft and generated descriptive data, including mean and median dimensions for all 20 grafts. A representative graft for each type was selected by picking the graft representing the median coronal ROC for each group. This median ROC graft was felt to be representative of what a surgeon might receive from an allograft supplier. This representative graft was used for all individuals in the study. As with the Latarjet-Patte reconstruction, each graft was carefully positioned to provide optimal fill and congruity to the defect, with no portion of the graft sitting proud relative to the glenoid surface (Fig. 2, C and D). Surface areas for each allograft were measured.

A vertical axis was drawn from the supraglenoid tubercle on the intact glenoid. A second orthogonal axis was defined at the widest anterior-posterior dimension of the intact glenoid. This was chosen as our sectioning line, which would allow us to examine depth and axial ROC of the glenoid and grafts. Once all of the graft types were placed appropriately, both glenoids were sectioned using the “simulation” and “cut orthogonal” commands in Mimics. We then analyzed the distal fragments to allow for measurement of depth and axial ROC. We calculated the axial ROC for the glenoid bone loss fragment by measuring the ROC for the portion of mirrored intact glenoid, which was evident after it was superimposed on the injured glenoid (Fig. 3). We defined a positive axial ROC as a radius that matched the intact glenoid, whereas a negative ROC had the opposite curvature. We then compared the intact ROC with the axial ROC for each of the sectioned grafts (Fig. 4, A-D).

Glenoid depth at the section line was calculated by drawing a line from each side of the glenoid, or from the intact glenoid edge to the edge restored by the graft, and then measuring from this line to the deepest portion of the glenoid. This was performed by using a Boolean subtraction of a superimposed cylinder in the Mimics simulation menu. The depth of each injured glenoid/graft construct was compared with the depth of the contralateral mirrored intact glenoid.
To further evaluate the ability of the 2 allografts to best match individualized glenoid defects, we attempted to match the coronal ROC from each of the injured glenoids with a “best fit” allograft from each of the 2 databases.

**Statistical analysis**

A one-way analysis of variance was used to assess for a main effect for the following variables: total surface area of the glenoid/graft construct (including intact glenoid, injured glenoid, and injured glenoid with each different graft in place), ROC coronal, ROC axial, and glenoid depth. If a main effect was detected, specific contrasts were evaluated between each graft and the injured glenoid by independent group \( t \) tests using a Bonferroni correction, which is a mathematical adjustment made to the defined significant \( P \) value given multiple comparisons. Statistical analyses were performed using SPSS 20 software (IBM, Armonk, NY, USA), and statistical significance was set at \( P \) value of .05.

**Results**

All results are presented as mean (SD) values. For the subject group, mean coracoid length was 45.0 (3.8) mm and mean coracoid base width was 27.9 (2.5) mm. Mean loss of surface area for the injured glenoid was 11.0% (range, 4.6%-32.0%; \( P = .014 \)). As reported in Table I, all graft options completely restored the deficient surface area (\( P < .001 \)).

The coronal ROC of the injured portion of glenoid was 67.5 mm, which was statistically different from all of the grafts except the CA Latarjet (\( P < .005 \)). When all graft conditions were compared, the standard Latarjet differed from all other graft choices due to its negative ROC, indicating a convex curvature relative to the concave glenoid surface (\( P < .001 \); Table II). The coronal ROC for the 20 tibial plafond allografts ranged from 38.7 to 56.8 mm (SD, 5.49 mm). Corresponding coronal ROC for the 20 iliac

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**Table I  Surface area of glenoid and graft constructs**

<table>
<thead>
<tr>
<th>Construct</th>
<th>Total surface area *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact glenoid</td>
<td>839.3 (111.5)</td>
</tr>
<tr>
<td>Injured glenoid</td>
<td>743.0 (88.2)</td>
</tr>
<tr>
<td>With standard Latarjet</td>
<td>993.9 (108.9)</td>
</tr>
<tr>
<td>With congruent arc Latarjet</td>
<td>1091.8 (120.0)</td>
</tr>
<tr>
<td>With tibia plafond</td>
<td>992.9 (88.2)</td>
</tr>
<tr>
<td>With iliac crest</td>
<td>932.8 (88.2)</td>
</tr>
</tbody>
</table>

* SD, standard deviation.

* All areas SD from injured glenoid (\( P < .001 \)).
Crest allografts ranged from 44.0 to 271.7 mm (SD, 67.6 mm). The axial ROC of the injured glenoid was 36.6 mm, which was statistically different from all of the graft choices except the iliac crest ($P < .001$). Of note, the statistical difference between the tibial plafond and the injured glenoid was likely due to the large but negative ROC of the tibial plafond, which, similar to the iliac crest, was essentially flat (Table III).

The depth of the injured glenoid compared with the intact glenoid was reduced by nearly 50% ($P = .005$). Tibia plafond and iliac crest both restored depth better than did the standard or CA Latarjet ($P < .002$; Table IV).

When attempting to match the coronal ROC of the injured glenoid with a “best fit” allograft from each database, we were able to match coronal ROC within 5% in 6 of 15 individuals (40%) using tibial plafond allografts and in 12 of 15 (80%) using iliac crest allografts.

### Discussion

The purpose of this study was to compare the ability of the tibial plafond allograft, iliac crest allograft, and standard and CA Latarjet (coracoid autograft) reconstructions to restore surface area, ROC, and depth of the glenoid after bone loss secondary to recurrent shoulder instability. In this group of recurrent shoulder instability patients with glenoid bone loss, all graft choices were able to restore intact glenoid surface area. This may partly reflect that the mean surface area lost was 11% (range, 4.6%-32.0%) compared with osteotomy-type defects created in the laboratory, which often range up to 50% of the glenoid area.

The coronal plane ROC of the CA Latarjet reconstruction (60.3 mm) more closely matched the coronal ROC of the injured glenoid (67.5 mm) compared with the standard Latarjet or allografts. The standard Latarjet reconstruction was the most incongruent, displaying a convex ROC (−119.9 mm) compared with the concave coronal ROC of the injured glenoid.

The axial plane ROC for the injured glenoid was 36.6 mm, which was statistically different from all of the grafts except for the iliac crest. The coracoid-based reconstructions as well as the tibial plafond all displayed negative or convex axial ROC compared with the concave axial ROC of the injured glenoid. Bone loss on the injured glenoid led to a depth reduction of nearly 50%, which was more completely restored by the tibial plafond and iliac crest allografts than by the coracoid autograft reconstructions.

### Table II: Coronal radius of curvature (ROC) for each condition, compared with the injured glenoid and compared with all graft selections

<table>
<thead>
<tr>
<th>Condition</th>
<th>Coronal ROC*</th>
<th>Statistically different from injured glenoid?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injured glenoid</td>
<td>67.5 (33.2)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Standard Latarjet</td>
<td>−119.9 (78.7)</td>
<td>Yes ($P &lt; .001$)</td>
</tr>
<tr>
<td>CA Latarjet</td>
<td>60.3 (39.0)</td>
<td>No ($P = .59$)</td>
</tr>
<tr>
<td>Tibia plafond</td>
<td>41.3 (0)</td>
<td>Yes ($P = .005$)</td>
</tr>
<tr>
<td>Iliac crest</td>
<td>99.2 (0)</td>
<td>Yes ($P &lt; .001$)</td>
</tr>
</tbody>
</table>

CA, congruent arc; SD, standard deviation.

* P values are shown for Bonferroni post hoc testing.

** Negative ROC value indicates convexity as opposed to native glenoid concavity.

### Table III: Axial radius of curvature (ROC) for each condition, compared with the injured glenoid and compared with all graft selections

<table>
<thead>
<tr>
<th>Condition</th>
<th>Axial ROC</th>
<th>Statistically different from injured glenoid?*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injured glenoid</td>
<td>36.6 (47.5)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Standard Latarjet</td>
<td>−12.3 (11.7)</td>
<td>Yes ($P &lt; .001$)</td>
</tr>
<tr>
<td>CA Latarjet</td>
<td>−27.8 (11.5)</td>
<td>Yes ($P &lt; .001$)</td>
</tr>
<tr>
<td>Tibia plafond</td>
<td>−162.5 (118.3)</td>
<td>Yes ($P &lt; .001$)</td>
</tr>
<tr>
<td>Iliac crest</td>
<td>106.6 (328.9)</td>
<td>No ($P = .42$)</td>
</tr>
</tbody>
</table>

CA, congruent arc; SD, standard deviation.

* P values are shown for Bonferroni post hoc testing.

** Negative ROC indicates convexity as opposed to native glenoid concavity.

### Table IV: Glenoid depth for each condition, percentage of intact glenoid depth, comparison with injured glenoid, and comparison with all graft selections

<table>
<thead>
<tr>
<th>Condition</th>
<th>Depth</th>
<th>Intact depth (%)</th>
<th>Statistically different from injured glenoid? *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact glenoid</td>
<td>1.4 (0.65)</td>
<td>100</td>
<td>Yes ($P = .005$)</td>
</tr>
<tr>
<td>Injured glenoid</td>
<td>0.8 (.6)</td>
<td>52</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Standard Latarjet</td>
<td>0.9 (.5)</td>
<td>65</td>
<td>No ($P = .03$)</td>
</tr>
<tr>
<td>CA Latarjet</td>
<td>1.3 (.9)</td>
<td>92</td>
<td>No ($P = .71$)</td>
</tr>
<tr>
<td>Tibia plafond</td>
<td>1.8 (1.1)</td>
<td>127</td>
<td>Yes ($P = .002$)</td>
</tr>
<tr>
<td>Iliac crest</td>
<td>2.0 (.6)</td>
<td>136</td>
<td>Yes ($P &lt; .001$)</td>
</tr>
</tbody>
</table>

CA, congruent arc; SD, standard deviation.

* P values shown for Bonferroni post hoc testing.
and ROC with Latarjet-Patte reconstructive procedures of the glenoid. One suggested technique is to rotate the coracoid 90° to place the inferior surface parallel to the joint surface in an attempt to more closely match the ROC of the native glenoid. Although others have examined the ability of the coracoid to restore the area of the glenoid and to match the glenoid ROC of glenoid in bony defects created by a simulated osteotomy in cadaveric models, no studies have assessed these parameters in vivo in patients with recurrent instability and secondary glenoid bone loss.

The current model allows for examination in this patient population using their own autogenous coracoid with an idealized, optimal surgical technique. Furthermore, the model allows for direct comparison of these Latarjet-Patte reconstructions with idealized iliac crest or tibial plafond allograft reconstructions for the same glenoid defects. In this capacity, we are able to provide the first direct comparison of graft options with regard to the time-zero restoration of native glenoid anatomy in patients with traumatic lesions, independent of variable surgical technique, defect size, and other patient demographics. In this group of recurrent shoulder instability patients with glenoid bone loss, all graft choices were able to restore intact glenoid surface area. This may partly reflect that the mean surface area lost was 11% (range, 4.6%-32.0%) compared with osteotomy-type defects created in the laboratory, which often range up to 50% of glenoid area.

The coronal ROC is a consideration in identifying the optimal glenoid graft for restoring bone stock. It is logical that a graft that more closely matches the ROC of the native glenoid may lead to reduced contact pressures, improved contact area, and perhaps mitigate the risk of postsurgical arthritis. Ghodadra et al demonstrated reduced contact pressures in certain shoulder positions when using an iliac crest allograft or CA Latarjet as opposed to the standard Latarjet in a cadaveric model. In our series, the coronal ROC of the injured glenoid was matched most closely by the CA Latarjet. In contrast, when the inferior border of the coracoid was placed adjacent to the injured glenoid (standard Latarjet), it was apparent that the coronal ROC was in the opposite, convex direction relative to the concave missing defect; thus, the negative ROC listed in Table II. This finding is in agreement with the results of Armitage et al, who reported the ROC for a coracoid placed in CA fashion closely matched an intact glenoid.

It was interesting to examine the amount of variability in the coronal ROC of the 2 allografts. The distal tibia allografts displayed a small SD of 5.5 mm, whereas the iliac crest specimens showed a much larger SD of 67.6 mm. The large range of curvatures in the iliac crest allografts allowed us to closely (within 5%) match the coronal ROC in a larger percentage of injured glenoids in our data set (80% vs 40% using distal tibia allografts). This may be an important point when planning a bone loss surgery, particularly if the bone loss is significant, which may lead to the need for longer graft options with larger (flatter) coronal ROC. If allograft suppliers were to provide ROC for available allograft options, it might allow for the selection of a graft that closely matches a given patient’s bony defect.

With much discussion regarding the ability of the different grafts to minimize contact pressures, the measurement of axial ROC and glenoid depth may be important to appropriate graft selection with reconstructive surgery for glenoid bone loss. None of our graft choices closely matched the injured glenoid anatomy. When the graft anatomy was examined, the iliac crest and the plafond grafts were essentially flat when sectioned in the axial plane. The measured ROC for the plafond had a slight convexity (axial ROC of −162.5 mm) compared with a slightly concave iliac crest (axial ROC of 106.6 mm). This convexity was likely a slight artifact of how the bone was cut or a slight error in the 3-point system of measuring the ROC, but essentially, both allograft options were very flat. These differences led to a statistically similar result for axial ROC when comparing the injured glenoid and iliac crest allograft, but there are likely no clinical differences between the large negative ROC for the plafond vs the large positive ROC for the iliac crest.

Our study has several limitations. We used CT scans that measure the subchondral bone. There may be subtle differences in the measures of the articular cartilage surfaces, although the subchondral bone is certainly representative of this contour and congruity. The mean loss of surface area for the injured glenoids was 11.0% (range, 4.6%-32.0%), and in this capacity, our study group represents a relatively heterogeneous population of mild to severe glenoid bone loss.

The surgical positioning of each graft was subjective, with each graft placed in a location to optimally recreate the anatomy of the lost glenoid bone. This was done by placing the grafts and viewing them from a 360° field of view. Although this is not possible in the operating room, we felt this provided an “ideal case” scenario to allow for graft comparisons that eliminated the confounding effect of variable surgical technique and experience.

Finally, this is a study of time-zero geometry only and does not provide any direct measures of contact pressures or glenohumeral stability. It also does not account for the possibility of graft resorption, which would alter the anatomic relationships. Although intuitively closer matches to ROC and depth would seem to be beneficial for the longevity of the reconstructed shoulder, it remains a focus for subsequent studies that build on this work and clinical studies that correlate these findings with objective patient outcomes. Future studies are also necessary to provide insights into the differences between these grafts with regards to ultimate incorporation and healing to the injured glenoid.

**Conclusions**

Although all graft choices were able to restore lost surface area, the tibial plafond and iliac crest allografts were better able to match axial ROC and restore lost...
depth, whereas the CA Latarjet reconstruction more closely restored the native glenoid coronal radius of curvature compared with the standard Latarjet reconstruction for anteroinferior glenoid bone loss. None of the grafts perfectly recapitulated native anatomy, which provides impetus to consider other options, including the possibility of size-matched, fresh glenoid osteoarticular allografts. The variable ability of these bone grafts to restore native glenoid anatomy may have important implications for glenohumeral kinematics, contact mechanics, and risk of secondary arthrosis after reconstructive procedures for recurrent anterior instability.

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References