Augmented glenoid component designs for type B2 erosions: a computational comparison by volume of bone removal and quality of remaining bone

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\textbf{Background:} The purpose of this computational modeling study was to compare the volume of glenoid bone removal required to implant 3 augmented component designs for management of B2 erosions. In addition, we assessed bone quality of the supporting bone directly beneath the implants by measuring bone density and porosity.

\textbf{Methods:} Three augmented component designs—full-wedge, posterior-wedge, and posterior-step—were studied by virtual implantation in a cohort of 16 patients with B2 glenoids. B2 retroversion was corrected to 0\degree\ and 10\degree. The outcome variables were the volume of glenoid bone removal required for implantation and the density and porosity of the bone immediately beneath the implant.

\textbf{Results:} Implant design had a significant effect on the volume of bone removal ($P < 0.001$). When correcting to 0\degree, the posterior-wedge implant removed less bone than the posterior-step ($P < 0.001$) and the full-wedge ($P = 0.004$). At 10\degree retroversion, the posterior-wedge removed less bone ($P = 0.029$) than the posterior-step but was no different than the full-wedge ($P = 0.143$). The residual glenoid bone density with the posterior-wedge was significantly greater than with the posterior-step ($P = 0.048$), with no other significant differences ($P > 0.05$). Residual glenoid bone porosity was not significantly different between implants ($P > 0.262$).

\textbf{Conclusions:} Augmented components can provide a bone-preserving option for B2 glenoid management. Substantial variations in the volume of bone removal and the quality of the remaining glenoid bone were found between 3 different designs of augmented implants. Simulations with the posterior-wedge implant resulted in substantially less glenoid bone removal, with the remaining supporting bone being of better quality.

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

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Excessive acquired glenoid retroversion, as seen in patients with posterior bone loss due to advanced osteoarthritis, is poorly understood and is challenging to manage with standard glenoid components. This erosive bone loss pattern has been classified as type B2 by Walch et al. Several treatment options exist for the management of type B2 erosions; however, none has demonstrated clinical superiority. The surgical options available to manage B2 glenoids include hemiarthroplasty, eccentric reaming and hemiarthroplasty, eccentric reaming and standard total shoulder arthroplasty, structural glenoid bone grafting, augmented glenoid components, and reverse total shoulder arthroplasty.

Presently, several implant manufacturers are releasing or have commercially released augmented glenoid components to account for the posterior bone loss. These implants are typically designed with a posteriorly oriented step or wedge, which assumes that the maximum glenoid erosion is oriented 90° to the implant’s superior-inferior axis. Although these implants are intended to conserve subarticular bone, it has been suggested that B2 bone loss is not oriented purely in the posterior direction. Recent literature has demonstrated that the average B2 glenoid has bone loss in the posterior-inferior quadrant directed toward the 8-o’clock position (right shoulder). This pattern of bone loss may not be completely accounted for by the axisymmetric posterior augments of the available implant designs. Consequently, this may result in increased bone removal in the posterosuperior quadrant or possibly malrotation of components to facilitate full backside seating. In addition, the distribution of subarticular bone density in B2 glenoids is characteristically different compared with symmetrically eroded glenoids. Bone density is greatest in the subarticular zone only and diminishes with greater depth. Augmented implant preparation techniques that involve removal of substantial amounts of the neoglennonoid bone may leave behind less dense bone with greater porosity to support the implant for its life span.

The purpose of this anatomic computational modeling study was to compare the volume of glenoid bone removal required to implant 3 different designs of posterior augmented components for the management of type B2 erosions. In addition, we wanted to compare the quality of the remaining glenoid bone directly below the various implants by assessing residual bone density and porosity as indicators of implant stability and fixation.

Methods

Augmented implant models

Three augmented glenoid component designs—posterior-step, full-wedge, and posterior-wedge—were created as computer models by computer-aided design (CAD) software (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA) (Fig. 1). These implant CAD models were created according to the precise dimensions and sizes of augmented implant designs. The posterior-step implant (Steptech; DePuy Synthes, Warsaw, IN, USA) consisted of 5 sizes based on the bearing diameter (40, 44, 48, 52, and 56 mm) and step height (3, 5, and 7 mm), resulting in 15 right and 15 left implant models. The full-wedge implants (Equinoxe; Exactech, Gainesville, FL, USA) were created in small, medium, large, and extralarge sizes with wedge angles of 8°, 12°, and 16°. These implants are anatomically shaped, with left and right models, resulting in a total of 24 implants. Finally, the posterior-wedge implant models (Posterior Augmented Glenoid; Tornier, Bloomington, MN, USA) consisted of small, medium, large, and extralarge sizes, with wedge angles of 15°, 25°, and 35°. These implants were also anatomic and were produced in left and right models for a total of 24 implants. Fixation features (i.e., pegs or keels) were not included in the CAD models to avoid confounding bias in bone removal due to fixation designs.

Glenoid models and virtual implantation

To test the augmented glenoid component designs in a clinically important manner, the implants were virtually implanted in a study cohort of 16 patients (age, 66 ± 11 years; range, 42-84 years; 8 men) who were classified as type B2 by a fellowship-trained shoulder surgeon (G.S.A.) using a clinically validated method. Preoperative computed tomography (CT) scans in digital imaging and communications in medicine (DICOM) format were acquired by multislice CT scanners with standard clinical settings (120-140 kVp, 512 × 512 resolution). A 3-dimensional (3D) virtual model of each patient’s scapula was created in medical imaging software (Mimics v. 17.0; Materialise NV, Leuven, Belgium) from the DICOM data with standard segmentation techniques. A minimum threshold of 200 Hounsfield units (HU) was used to preserve both cancellous and cortical bone in the model geometry.

Osseous landmarks were used to define the coronal scapular plane and the 0° version plane, as previously described. A plane was also created to define the 3D version of the neoglennonoid plane and the 0° version plane, as previously described. A plane was also created to define the 3D version of the neoglennonoid
plane, termed the neo-version plane, by a method similar to the intermediate plane,\textsuperscript{1} and the version plane.\textsuperscript{14,16} The neo-version plane was defined by 3 points; one point was placed on the inferior aspect of the ridge of bone separating the neoglenoid from the paleoglenoid, a second point was placed on the superior aspect of the ridge of bone separating the neoglenoid from the paleoglenoid, and a third point was placed on the most medial point of the posterior rim of the eroded glenoid (Fig. 2). The neo-version plane was used to position the implant in 2 versions (0° and 10°) and assisted with step height and wedge angle determination, per the individual implant designs (Table I).

Each patient’s 3D model and the accompanying planes were separately imported into 3-Matic (v. 9.0; Materialise) as stereolithography files for implant placement. Implant positioning was performed by a fellowship-trained shoulder surgeon (G.S.A.) as previously described by Sabesan et al.\textsuperscript{14,16} Each individual implant was aligned with the 0° version plane, and the implant size was selected to completely cover the glenoid surface without overhang. The implant could be manipulated to rotate (clockwise/counterclockwise and superoinferior) and to translate (anteroposterior and superoinferior) as long as there was no overhang. To obtain full backside seating of the implant, it was incrementally medialized to simulate an absolute minimal amount of paleoglenoid reaming. Then, the step/wedge was selected to adequately correct for posterior bone loss with the smallest augment while ensuring complete backside contact and 0° version.\textsuperscript{14,16} This process was repeated for each implant design in randomized order.

![Figure 2](image-url)

**Figure 2** A 3D scapular model of a patient with B2 erosion (A) representing the points (red dots) used to create the 3D version plane of the neoglenoid facet, termed the neo-version. Three points were used to define the neoglenoid version plane. One point was placed on the inferior aspect of the ridge of bone separating the neoglenoid from the paleoglenoid, a second point was placed on the superior aspect of the ridge of bone separating the neoglenoid from the paleoglenoid, and the third point was placed on the most medial point of the posterior rim of the eroded glenoid. A 3D scapula viewed from the inferior vantage point (B) depicts the neoglenoid version plane and the 0° version plane.

**Table I** Patient data with neo-version angle and the corresponding implant selection

<table>
<thead>
<tr>
<th>Patient</th>
<th>Gender</th>
<th>Neo-version angle (°)</th>
<th>0° Version</th>
<th>10° Retroversion</th>
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<td></td>
<td></td>
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<td>Posterior-wedge</td>
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<td>24</td>
<td>Large 8°</td>
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<td>Extralarge 16°</td>
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\(1220\) N.K. Knowles et al.
This process was also repeated for all implant designs with a clinical scenario of version restoration to 10° of retroversion. At this new version angle, the implant size and step/wedge height were reassessed and altered if required to ensure full backside contact and no implant overhang (Table I).

Volume of bone removal

Before implant insertion, the volume of each patient’s scapular model was recorded. After implant placement, the intersecting implant was removed from the scapula using a Boolean subtraction in Mimics (Fig. 3). This was completed separately for each of the 3 implant designs, for the 2 version angles (0° and 10°), and for each of the 16 patients, for a total of 96 testing conditions. The volume of the scapular model, after implant subtraction, was remeasured and then differentiated from the index volume. This resulted in the volume of bone removed, in cubic millimeters, to fully seat the backside morphology of each particular implant. To remove bias due to implant surface area and its effect on bone removal, each volume of bone removal was also normalized by the 2-dimensional area (i.e., footprint area) of the implant (Table II). This metric, in units of millimeters, represents the ratio of the removed bone volume to the implant’s footprint area, which is independent from size but dependent on the backside morphology (step or wedge) or any other distinguishing backside features.

Density and porosity of bone beneath the implant

To measure the density and porosity of bone immediately beneath the implant, a 2.5-mm-thick section of glenoid was studied. To obtain a 2.5-mm-thick volume of bone that matched each implant’s backside characteristics, each implant was further medialized 2.5 mm from its index position. This was performed for both the 0° version and 10° retroversion placements. Again using a Boolean subtraction, a 2.5-mm-deep volume of bone under the implant was created (Fig. 4). A mask of this model was then created in Mimics to register the geometry of the bone section to the original DICOM images. Using a minimum threshold of 200 HU to preserve both cancellous and cortical bone,2,10 bone density and porosity were measured as previously described by Knowles et al.10 The bone density was measured in Hounsfield units with the built-in Mimics measurement tools, and bone porosity was calculated as the ratio of void volume (cysts or low-density cancellous bone below the 200 HU threshold) to total volume. This measurement region represents the bone 0 to 2.5 mm below the implant, on which the implant rests.

Statistical analysis

The total volume and normalized volume of bone removed were compared by 2-way analysis of variance (ANOVA) and Tukey tests for pairwise comparisons for all patients and by gender and version angle (SigmaPlot v. 11.0; Systat Software Inc., Erkrath, Germany). Density and porosity were compared for all patients by 2-way ANOVA and Tukey tests for pairwise comparisons for all patients and 3-way ANOVA with Tukey tests for pairwise comparisons by gender.

Results

Volume of bone removal

The choice of implant design had a significant effect on the volume of glenoid bone removal ($P < .001$) (Fig. 5, A).
When using the augmented implants to correct retroversion to an ideal 0°/C14, the posterior-wedge implant removed a mean of 1347 mm³ less total bone than the posterior-step implant (P < .001) and a mean 1010 mm³ less than the full-wedge implant (P = .004). There was no significant difference between the total bone removal of the posterior-step and full-wedge implants (P = .509). When correcting version to 10° of retroversion, the posterior-wedge implant removed significantly less total bone (mean, 790 mm³; P = .029) than the posterior-step implant. However, there was no significant difference in total bone removed between the posterior-wedge and full-wedge implants (P = .509). When correcting version to 10° of retroversion, the posterior-wedge implant removed significantly less total bone (mean, 790 mm³; P = .029) than the posterior-step implant. However, there was no significant difference in total bone removed between the posterior-wedge and full-wedge implants (P = .509).

When the volume of bone removed was normalized to the implant’s footprint area, implant choice again had a significant effect (P < .001) (Fig. 5, B). There was a significant difference between the posterior-wedge and both the posterior-step (0° version, P < .001; 10° retroversion, P = .003) and full-wedge (0° version, P < .001; 10° retroversion, P = .037) but no difference between the posterior-step and full-wedge (P ≥ .335) at either version angle.

Male patients had significantly more bone removal than female patients at 0° version for the full-wedge (P = .019) but no significant difference for the posterior-step (P = .053) or posterior-wedge (P = .076) implants (Fig. 6). At 10° retroversion, male patients had significantly more bone removal than female patients for the full-wedge (P = .016) and the posterior-step (P = .018) but no significant difference for the posterior-wedge implant (P = .403). These significant differences were not observed.

Figure 4  Representative images of the underlying bone 0 to 2.5 mm below virtually implanted augmented glenoid implants. The bone density in Hounsfield units (HU) and porosity were calculated anterior (yellow) and posterior (orange) to the implant’s centerline (A). The underlying bone volumes studied for a posterior-wedge (B), full-wedge (C), and posterior-step (D) are depicted. The bone porosity is the ratio of void volume (cysts or low-density cancellous bone below the 200 HU threshold) to total volume.

Figure 5  Glenoid bone removed by the 3 augmented glenoid implants. (A) The total volume of glenoid bone removed at 0° version and 10° retroversion. (B) The bone removed normalized by the footprint area of the implant at 0° version and 10° retroversion. Significant difference is indicated by bars sharing a common letter/symbol.
Figure 6  Bone removed by 3 augmented glenoid implants in male (n = 8) and female (n = 8) patients. (A) Volume of bone removed at 0° version. (B) Volume of bone removed at 10° retroversion. (C) Bone removed normalized by the footprint area of the implant at 0° version. (D) Bone removed normalized by the footprint area of the implant at 10° retroversion. Significant difference is indicated by bars sharing a common letter/symbol.

Figure 7  Glenoid bone density and porosity 0 to 2.5 mm below the 3 augmented implant designs for all patients (N = 16). (A) Bone density in the anterior and posterior regions by implant when placed at 0° version. (B) Bone density by implant when placed at 10° retroversion. (C) Bone porosity by implant when placed at 0° version. (D) Bone porosity by implant when placed at 10° retroversion. Significant difference is indicated by columns sharing a common letter/symbol. The bone porosity is the ratio of void volume (cysts or low-density cancellous bone below the 200 HU threshold) to total volume.
when the bone removal was normalized by the implant’s footprint area \( (P \geq .084) \) (Fig. 6).

**Density and porosity**

Within the posterior half of the glenoid, the density of the remaining bone when using the posterior-wedge implant was significantly denser (mean 83 HU greater) than the posterior-step implant \( (P = .048) \) at 0° version. There were no other significant differences in bone density between the other implants within the anterior or posterior regions \( (P \geq .380) \) at this version angle. When comparing bone density in the anterior to the posterior regions of the glenoid by implant type, the full-wedge was a mean 196 HU more dense \( (P < .001) \), the posterior-wedge a mean 177 HU more dense \( (P < .001) \), and the posterior-step a mean 100 HU more dense \( (P = .005) \) in the posterior compared with the anterior region (Fig. 7). For the models corrected to 10° retroversion, there was also a significant difference in underlying bone density posterior and anterior \( (P < .001) \) but no significant differences between implants \( (P = .370) \).

When assessing porosity for the 0° version correction cohort, there was a significant difference in the underlying bone porosity comparing anterior to posterior regions \( (P < .001) \) but no significant differences between implants \( (P = .262) \) (Fig. 7, C). For the 10° retroversion cohort, there was also a significant difference in underlying bone porosity comparing anterior to posterior regions \( (P < .001) \) but also no differences between implants \( (P = .624) \).

For male and female patients at 0° version, there were significant differences in underlying bone density in the anterior and posterior regions when allowing the effects of all other factors \( (P \leq .001) \). There were no significant differences between implant types \( (P = .500) \). At 10° retroversion, there were also significant differences in underlying bone density in the anterior and posterior regions when allowing the effects of all other factors \( (P \leq .035) \). There were no significant differences between implant types \( (P = .366) \) or underlying bone porosity by implant type when allowing all other factors \( (0° \) version, \( P = .163; 10° \) retroversion, \( P = .573) \).

**Discussion**

The results of this study indicate that there are substantial differences in the amount of glenoid bone removal required to fully seat different designs of posterior augmented implants. Aside from bone removal, it is apparent that the density and porosity of the remaining supporting bone immediately beneath the implant substantially vary among implant designs. Recent literature has demonstrated that preservation of glenoid subarticular bone is important in resisting implant migration and loosening. When inserting an augmented implant, therefore, we can postulate that the same principles may be important and bone removal should be minimized to maximize implant support and to decrease the risk of implant subsidence or migration.

In this study, we chose to correct version to an ideal 0° and to 10° of retroversion to account for the variation of native retroversion that may exist within the population. It can be inferred that as the severity of posterior erosion increases, the size of the step/wedge must also increase to account for the missing bone. This was confirmed with our results, as generally greater degrees of pathologic neo-version required progressively larger posterior augments (Table 1). In addition, in assessing the 10° retroversion sample, we found that by lessening the degree of correction, we were able to downsize the posterior augment. We initially postulated that lessening the degree of correction and downsizing the step/wedge may result in less bone removal. Interestingly, our results did not support this, as we found no significant reduction in the bone removal when downsizing. However, when correcting to 10° retroversion, the bone density and porosity in the anterior and posterior halves of the glenoid were more uniform, which may provide some favorable biomechanical properties for initial implant stability.

When bone removal was normalized by the implant’s footprint area—a metric that more accurately represents the variation between implant shape and bone removal—the posterior-wedge implant removed significantly less bone than both the full-wedge and stepped implants. This implant shape preserves the most bone, which may be important in considering the long-term outcomes and future requirements for revision surgeries. However, although less bone is removed, significant differences still exist in the density and porosity of the underlying bone in the anterior and posterior hemispheres of the implant, as with the other 2 augmented implants. These extreme differences in the density and porosity between the anterior and posterior regions may have implications with implant migration and subsidence. These concerns would be uniform across all B2 erosions.

The final placement of the implant was also dependent on the geometry of each individual glenoid. Because of the variation in implant shapes by manufacturer, certain augmented implants may more accurately reproduce the native glenoid geometry while reducing bone removal in each specific case. Ideally, to fully realize the best-fit glenoid implant for each specific patient, a computerized preoperative planning software making use of 3D CT-based models of the glenoid with properly sized implants would be best. For example, patients with gradual posterior erosion that involves most of the glenoid, having a very large neoglenoid with a thin rim of remaining paleoglenoid, may be better suited to a full-wedge implant as it will likely remove less overall bone than to seat a posterior-wedge. These preoperative planning tools may allow optimization of implant positioning and measurements to be taken that are not currently possible with traditional methods.

Although fixation devices were omitted in this study, it has been reported that excessive implant medialization
results in peg perforation in standard glenoid implants and also in augmented implants. Joint medialization was not explored in this study; instead, we focused on implant placement and underlying bone support, but it is also important to understand that implant medialization may result in peg perforation, compromising fixation. Also, additional bone removal is required to facilitate the fixation devices, which further compromises underlying bone support. It is therefore even more essential to ensure that the implant backside removes the least amount of bone so enough bone remains to ensure effective fixation and support.

The results of our study are consistent with the total volume of bone removed in surrogate models previously investigated by Roche et al. Their study presents important aspects as related to augmented glenoid component designs; however, we believe the results of our study may be more clinically relevant because we chose to examine patients with B2 erosion compared with surrogate models that simulate B2 erosion. Choosing patients with B2 erosions does, however, introduce a limitation of our study in that although the patients were classified by a fellowship-trained shoulder surgeon (G.S.A.), the patient group may not fully represent the full range of B2 erosion patients who typically require augmented glenoid components within the population.

A further limitation of this study was that we did not evaluate bone removal by fixation devices (i.e., pegs or keels). Because of the variations in size, shape, and style of fixation devices, we decided this would introduce a level of bias that could not be accounted for within the small volumes of bone removed. To further evaluate the effect of underlying bone support and the fixation of augmented glenoid components, future directions would be to assess optimally placed implants on the basis of strain induced to the bone under physiologic loading using finite element analysis. Another limitation with our study is that we did not examine the biomechanical effects of these various implant shapes. Iannotti et al studied the liftoff resistance of the full-wedge and the posterior-step implants in a glenoid model with homogeneous bone properties and found the posterior-step to be superior. Unfortunately, they tested the implants on a homogeneous glenoid model, which does not accurately represent the clinical scenario of variable bone density and porosity in the paleoglenoid and neoglenoid. It is conceivable that implant designs that test favorably on homogeneous models may fare differently on clinically relevant models with variable bone quality.

**Conclusion**

Augmented glenoid components provide a bone-preserving surgical option for the management of B2 erosions. Substantial variations in the volume of bone removal and the quality of the remaining glenoid bone were found between 3 different designs of augmented implants. Simulations with the posterior-wedge implant resulted in substantially less glenoid bone removal, with the remaining supporting glenoid bone being of better quality.

**Disclaimer**

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**References**


