Comparison of Glenohumeral Contact Pressures and Contact Areas After Posterior Glenoid Reconstruction With an Iliac Crest Bone Graft or Distal Tibial Osteochondral Allograft

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Background: Posterior glenoid bone deficiency in the setting of posterior glenohumeral instability is typically addressed with bone block augmentation with iliac crest bone grafts (ICBGs). Reconstruction with fresh distal tibial allograft (DTA) is an alternative option, with the theoretical advantages of restoring the glenoid articular surface, improving joint congruity, and providing the biological restoration of articular cartilage loss.

Hypothesis: Reconstruction with an ICBG and DTA would more effectively restore normal glenoid contact pressures, contact areas, and peak forces when compared with the deficient glenoid.

Study Design: Controlled laboratory study.

Methods: Eight fresh-frozen human cadaveric shoulders were tested in 4 conditions: (1) intact glenoid, (2) 20% posterior-inferior defect of the glenoid surface area, (3) 20% defect reconstructed with a flush ICBG, and (4) 20% defect reconstructed with a fresh DTA. For each condition, a 0.1 mm–thick dynamic pressure-sensitive pad was placed between the humeral head and glenoid. A compressive load of 440 N was applied for each condition in the following clinically relevant arm positions: (1) 30° of humeral abduction, (2) 60° of humeral abduction, and (3) 90° of flexion–45° of internal rotation (FIR). Glenohumeral contact pressures (kg/cm^2), contact areas (cm^2), and joint peak forces (N) were compared.

Results: Glenoid reconstruction with DTA resulted in significantly higher contact areas than the 20% defect model at 30°, 60°, and FIR at the time of surgery ($P < .01$ in all cases). The intact state exhibited significantly higher contact areas than the defect in all positions, significantly higher contact areas than the ICBG in all positions, and significantly higher contact areas than the DTA at 30° ($P < .05$ in all cases). The intact state experienced significantly lower contact pressures than the defect at 60° and FIR, while reconstruction with both a DTA and ICBG resulted in significantly lower contact pressures than the defect at 60° ($P < .05$ in all cases). There were no differences in contact pressures when comparing both the DTA and ICBG to the intact glenoid ($P > .05$ in all cases). There were no differences in peak forces between the groups, for any of the conditions, in any of the positions ($P > .05$ in all cases).

Conclusion: Reconstruction of posterior glenoid bone defects with DTA conferred similar contact mechanics as reconstruction with ICBGs at the time of surgery.

Clinical Relevance: This study supports posterior glenoid reconstruction with fresh DTA as a viable alternative solution, with the potential advantage of improving joint congruity via an anatomic reconstruction, resulting in a cartilaginous, congruent articulation with the humeral head. Further studies are required to determine potential clinical effects of the glenohumeral joint contact mechanics reported here.

Keywords: glenoid bone loss; instability; distal tibial allograft; biomechanical

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Posterior glenohumeral instability is rare, accounting for less than 3% of all shoulder dislocations[25-27] and approximately 5% of all cases of shoulder instability.[15,22,25] As in

cases of anterior instability associated with glenoid bone loss, a 1-time traumatic event or, more commonly, multiple recurrent instability events, can lead to posterior glenoid bone loss, disrupting the static restraints to the glenohumeral joint. Glenoid bone loss in the setting of anterior glenohumeral instability has been implicated as a significant potential factor in cases of failed stabilization.[3,13] Large defects, or those greater than 20% to 25% of the glenoid surface area, have been recognized as potential causes for clinical failure after isolated soft tissue repair, and glenoid bone augmentation procedures have been recommended in these cases. Unfortunately, very little is known about the amount of posterior glenoid bone loss associated with recurrent posterior instability or the amount of bone loss that would prohibit the success of a posterior soft tissue stabilization procedure for recurrent posterior instability.

While a variety of surgical techniques have been described for anterior glenoid bone augmentation, including iliac crest bone grafts (ICBGs), coracoid transfer (Latarjet, modified Bristow), and recently, distal tibial allografts (DTA),[23] the reconstructive options for posterior glenoid bone loss are substantially more limited. The most often reported augmentation technique for posterior glenoid bone loss is the placement of an ICBG as a posterior bone block.[1,8,12,14,17,28-30] This technique relies on the placement of an extra-articular, nonanatomic bone graft to act as a structural block to posterior humeral head translation. Long-term clinical results after this procedure have historically been disappointing, with high rates of patient dissatisfaction, inability to return to desired levels of activity, recurrence of instability, and glenohumeral arthritis.[1,8,12,14,17,28-30] Other described alternatives to ICBGs include augmentation with fresh osteochondral allografts, including glenoid allografts[16,20] and DTA.[16]

Glenoid augmentation with a DTA has been demonstrated as an effective surgical technique for the treatment of anterior glenoid bone loss both in reducing the rate of dislocations clinically[23,24] and restoring more normal contact pressures biomechanically.[2] To date, no biomechanical data are available regarding the biomechanical effects of DTA reconstruction. Therefore, the objectives were to quantify glenohumeral contact areas, contact pressures, and peak forces in the (1) intact glenoid, (2) glenoid with a 20% posterior-inferior bone defect from 6 o'clock to 10 o'clock (right shoulder), (3) glenoid with a 20% posterior-inferior bone defect reconstructed with a flush ICBG, and (4) glenoid with a 20% posterior-inferior defect reconstructed with a fresh DTA. The hypothesis was that reconstruction with an ICBG and DTA would more effectively restore normal glenoid contact pressures, contact areas, and peak forces when compared with the deficient glenoid.

MATERIALS AND METHODS

The methodology was adapted from the work of Ghodadra et al[7] and Bhatia et al.[2] A total of 8 fresh-frozen cadaveric shoulders (3 left shoulders, 5 right shoulders) from donors with a mean age of 62.8 ± 7.8 years were included. Donors were screened and excluded for any known osteoporosis, arthritis, or bone defects. The mean bone mineralization as determined by quantitative computed tomography (CT) of all specimens was 217.2 ± 48.9 HU (range, 162.1-288.5 HU). Each specimen was dissected free of soft tissue, and the capsule was excised to expose the glenohumeral joint. The proximal humerus was disarticulated from the glenoid for subsequent testing. Digital calipers were used to measure the anterior-posterior and superior-inferior diameters of each glenoid specimen. These measurements were taken based on viewing the glenoid surface as the face of a clock, with the most inferior position of the glenoid corresponding to 6 o'clock.

After anatomic measurements, the glenoid was separated from the remainder of the scapula by sawing from 1 cm below the infraglenoid ridge along the infraspinatus fossa in a medial direction and then cutting along the medial border of the scapula just under the spine. Each scapula was potted in a polyvinyl chloride (PVC) pipe using dental acrylic (Isocryl, Lang Dental), with the glenoid surface oriented parallel to the floor as determined with a gravity level. The corresponding humeral shaft for each specimen was also potted in dental acrylic such that 2 cm of the proximal humeral shaft was exposed to minimize diaphyseal bending moments. The humeral shaft was then placed in a custom jig and fixed to the platform of a materials testing machine (Insight 5, MTS Systems), with the bicipital groove facing anteriorly (see Appendix Figure A1, available in the online version of this article at http://ajsm.sagepub.com/supplemental). The potted glenoid for each specimen was also placed into a custom jig and fixed to the crosshead of the MTS machine.

A 0.1 mm–thick dynamic pressure-sensitive pad (sensor model 5051, Tekscan), with a 56 × 56–mm matrix and a density of 62 sensels/cm^2, was precalibrated with the MTS machine utilizing previously published methods.[2,7] A 2-point calibration was performed per the manufacturer's guidelines, applying loads of 20% and 80% of the maximum test load (440 N). During testing, the sensor was placed between the humeral head and glenoid

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articular surfaces, with the 4 quadrants marked on the pad to allow for identical pad positioning between trials. A new Tekscan sensor was utilized for each specimen.

Testing Conditions

A compressive load of 440 N was applied across the glenohumeral joint.[2,7] This load magnitude has been estimated as an approximate maximal load for the simulation of in vivo glenohumeral loading conditions throughout the course of normal shoulder motion during activities of daily living.[11] Testing included 4 conditions for each shoulder as follows: (1) intact glenoid, (2) glenoid with a 20% posterior-inferior bone defect from 6 o'clock to 10 o'clock (right shoulder), (3) glenoid with a 20% posterior-inferior bone defect reconstructed with a flush ICBG, and (4) glenoid with a 20% posterior-inferior defect reconstructed with a fresh DTA. The following clinically relevant arm positions were tested for each condition: (1) 30° of humeral abduction with a 440-N load, (2) 60° of humeral abduction with a 440-N load, and (3) 90° flexion–45° internal rotation (FIR) with a 440-N load. Such humeral positions of the arm were chosen on the basis of prior work with the hopes of simulating commonly encountered arm positions in a patient with shoulder posterior instability.[16,25]

Creation of Bone Defect

After testing in the intact glenoid state, osteotomies simulating 20% posterior-inferior diameter–based bone loss were then performed with a 10 × 0.5–mm high-speed sagittal saw set to 15,000 revolutions per minute to minimize unintended bone loss. As noted in the literature,[4,31] the amount of bone loss as defined by the width of the glenoid can be estimated by using the following formula: defect size = $(B - A)/2B \times 100\%$, where B is the radius of the glenoid's true-fit circle, and A is the distance from the circle center to the edge of the defect (Figure 1). As noted by Piasecki et al[21] and Sugaya et al,[32] for this formula to be applied for the percentage of glenoid surface area bone loss, a corrective factor must be applied to prevent overestimation errors. Because the defect size was known (in our case, 20%), the formula was rearranged to algebraically solve for A. For each specimen, the anterior-posterior diameter of the glenoid (2 times the radius, B) was precisely measured using digital calipers. The distance from the circle center to the osteotomy site (A) was then solved algebraically and the corrective factor applied using ratio modeling to guarantee that the appropriate proportions for a 20% defect could be precisely created.[2,21] A true-fit circular template was then created with the same diameter as the glenoid specimen and was cut A millimeters from the center to replicate the 20% osteotomy site. The template was then applied to the glenoid and oriented such that a clinically relevant osteotomy, one parallel to the long axis of the glenoid, could be created.

After each osteotomy, the template remained in place to ensure that 20% bone loss had been removed from the posterior-inferior portion of the glenoid. The length and width of the defect were recorded.

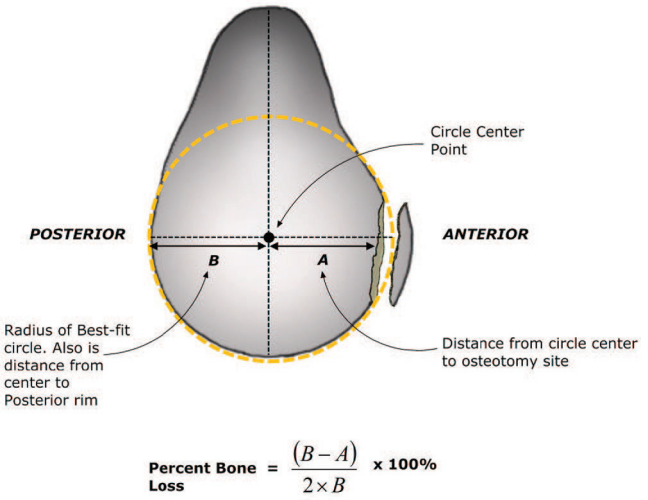

Figure 1. An osteotomy simulating at least 20% bone loss was performed based on a modification of the glenoid bone loss quantification techniques put forth by Sugaya et al[31] and Burkhart et al[5]. As noted in the literature, the amount of glenoid bone loss can be calculated by using the following formula: defect size = $(B - A)/2B \times 100\%$, where B is the radius of the glenoid's true-fit circle, and A is the distance from the circle center to the edge of the defect. Because the defect size was known (in our case, 20%), the formula was rearranged to algebraically solve for A. Reproduced with permission (Figure 3 in Bhatia et al[2]).

Graft Preparation

Specimens were assigned to undergo 1 of 2 testing protocols: (1) testing with DTA reconstruction, followed by testing in the defect state, followed by testing with ICBG reconstruction; or (2) testing with ICBG reconstruction, followed by testing in the defect state, followed by testing with DTA reconstruction. To perform glenoid augmentation with DTA, the fresh DTAs were prepared in accordance with the methods described by Provencher et al.[23] Donated DTAs (Joint Restoration Foundation) with a mean age of 24.5 ± 6.6 years were prepared (see Appendix Figure A2, available online). For each glenoid, a DTA of the same laterality was used (right DTA for right glenoid). Next, a graft with the same dimensions (width and length) as the glenoid defect was carefully cut from the lateral one third of the distal tibia (see Appendix Figure A3, available online). The length and width of the allograft were recorded (Table 1). The graft was appropriately contoured such that it could smoothly align with the natural arc of the glenoid when aligned flush to the articular surface. The DTAs were placed flush onto the glenoid defect location. Two 1.6-mm Kirschner wires drilled in a nonparallel fashion, consistent with the methodology utilized in a previous study[2] that served as a model for this study, were utilized to affix the bone block in place (Figure 2).

For ICBG reconstruction, donated iliac crests (Joint Restoration Foundation) with a mean age of 44.0 ± 12.8 years were prepared. From the iliac crest, a tricortical

TABLE 1
Demographics of Shoulder Specimens, ICBG Specimens, and DTA Specimens[a]

	Shoulder	ICBG	DTA
Age, y	62.8 ± 7.8	44.0 ± 12.8	24.5 ± 6.6
Sex, male/female, n	8/0	8/0	8/0
Side, left/right, n	3/5	4/4	3/5
Bone mineral density, HU	217.2 ± 48.9	N/A	N/A
Graft length, mm	22.7 ± 2.9	22.7 ± 2.4	22.4 ± 2.3
Graft width, mm	8.9 ± 0.8	9.1 ± 1.0	8.9 ± 0.9
Graft surface area, mm^2	208.3 ± 47.0	208.0 ± 41.1	199.8 ± 37.5

[a]Values are expressed as mean ± SD unless otherwise indicated. DTA, distal tibial allograft; ICBG, iliac crest bone graft; N/A, not applicable.

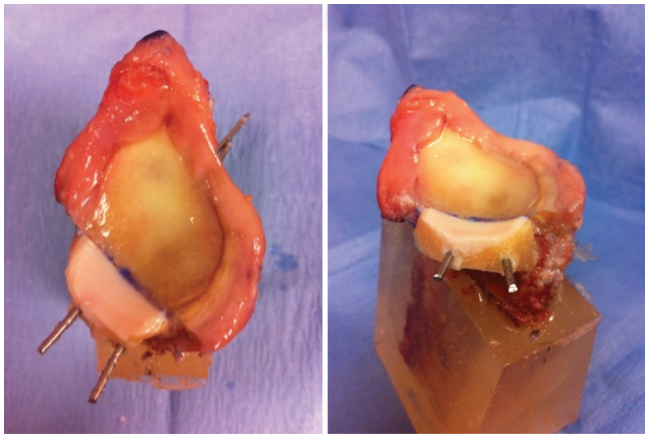

Figure 2. Posterior glenoid defect reconstruction with a distal tibial allograft.

graft with the same dimensions as the glenoid defect was harvested. The graft was placed flush onto the posterior glenoid defect location such that the superior cortical aspect of the iliac crest reconstructed the posterior rim of the glenoid, with the inner table of the iliac crest reconstructing the "articular surface" of the glenoid. Two 1.6-mm Kirschner wires, drilled in a nonparallel fashion,[2] were utilized to affix the bone block in place. The length and width of the crest graft were recorded (Table 1).

Each specimen was tested in the intact state, defect state, and after glenoid reconstruction both with a DTA and ICBG as described above (Figure 3). The defect state was tested between the reconstruction states such that the testing sequence for each of the 8 specimens was either (1) intact, DTA, defect, and ICBG or (2) intact, ICBG, defect, and DTA. With use of the Tekscan sensor and software, glenohumeral contact pressure (kg/cm^2), contact area (cm^2), and joint peak force (N) were recorded 3 times for each testing condition, with the mean used for data analysis. Contact pressure was defined as the force per unit area of the glenoid. Contact area was defined as the

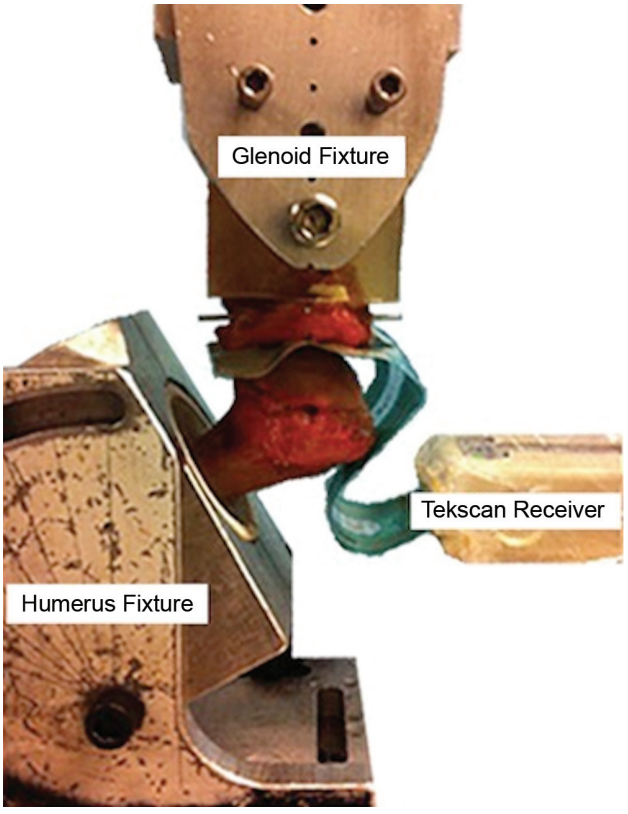

Figure 3. Setup of materials testing machine with Tekscan sensor in place.

area on which the humerus was able to articulate with the glenoid. Peak force was defined as the highest force recorded within the glenohumeral joint.

Statistical Analysis

All data from the pressure measurement software (I-scan, Tekscan) were collected and utilized for statistical analysis. Specimen data were normalized with respect to each specimen's intact state to account for variability in anatomic specimens. To do this, the means of the 3 trials in each position and state were first calculated. Then, for each specimen, data for each state and position (eg, 20% defect for FIR) were divided by the corresponding mean value for the intact state of the same specimen and position. Both the raw and normalized data between different testing conditions and settings were analyzed with a repeated 1-way analysis of variance (ANOVA) with a Tukey post hoc test when indicated. All calculations were performed using GraphPad Prism 5 software (GraphPad Inc), and statistical significance was considered for $P < .05$. An a priori power analysis based on prior data[2] showed that 8 specimens (4 groups with 3 measurements per group) would provide 80% power to detect a significant difference in the mean contact area among the groups, with an effect size of 0.67 and significance level of $P < .05$ (G*Power version 3.1.7, Heinrich Heine University).

TABLE 2
Glenohumeral Contact Area, Contact Pressure, and Peak Force Obtained During Tekscan Mapping Trials at Various Humeral Positions (Raw Averaged Data)[a]

	30°			60°			FIR		
	Contact Area, cm^2	Contact Pressure, kg/cm^2	Peak Force, N	Contact Area, cm^2	Contact Pressure, kg/cm^2	Peak Force, N	Contact Area, cm^2	Contact Pressure, kg/cm^2	Peak Force, N
Intact	5.18 ± 0.95	4.15 ± 0.93	3.66 ± 1.42	5.08 ± 1.07	4.13 ± 0.30	3.51 ± 1.21	4.02 ± 0.91	4.53 ± 0.94	3.89 ± 1.37
Defect	3.78 ± 0.58	4.35 ± 1.13	3.88 ± 1.73	3.72 ± 0.47	4.38 ± 0.39	3.82 ± 1.57	2.72 ± 0.36	4.74 ± 1.15	4.19 ± 1.74
ICBG	4.31 ± 0.46	4.19 ± 0.95	3.79 ± 1.48	4.44 ± 0.62	4.29 ± 0.30	3.97 ± 1.46	3.35 ± 0.52	4.46 ± 0.88	3.90 ± 1.30
DTA	4.33 ± 0.55	4.22 ± 0.97	3.75 ± 1.49	4.67 ± 0.73	4.14 ± 0.34	3.62 ± 1.39	3.65 ± 0.78	4.58 ± 0.98	3.83 ± 1.53

[a]Values are expressed as mean ± SD. DTA, distal tibial allograft; FIR, 90° of flexion–45° of internal rotation; ICBG, iliac crest bone graft.

RESULTS

Demographics for the shoulder and graft specimens are presented in Table 1. The mean anterior-posterior diameter of the intact glenoid specimens was 32.2 ± 2.7 mm (range, 28.2-34.4 mm). The mean calculated glenoid defect width was 8.2 ± 0.7 mm (range, 7.2-8.7 mm). The mean width of the actual defects after osteotomy was 8.9 ± 0.8 mm (range, 7.9-10.6 mm). The mean width of the DTAs was 8.9 ± 0.9 mm (range, 7.6-10.3 mm). The mean width of the ICBGs was 9.1 ± 1.0 mm (range, 7.9-10.5 mm). Consistent with previous work,[3] Tekscan mapping of mean glenohumeral contact pressures and contact areas demonstrated equal or higher contact pressures and smaller contact areas in the defect group compared with the intact state (Table 2). Overall progression of both contact area and contact pressure from the intact state to the defect to the reconstruction stages with the arm in a neutral position is shown in Figure 4.

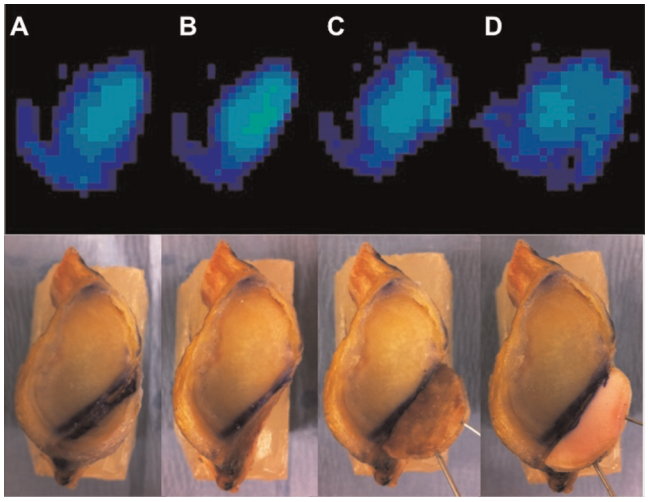

Figure 4. Representative Tekscan pressure map with the arm in neutral position. Higher pressures are signified by green/light blue and lower pressures by dark blue: (A) Intact glenoid, (B) glenoid with a 20% posterior-inferior bone defect (left shoulder), (C) glenoid after reconstruction with an iliac crest bone graft, and (D) glenoid after reconstruction with a distal tibial allograft.

Contact Area

After the creation of a 20% posterior-inferior glenoid defect, the contact area for the glenoid face decreased significantly in all 3 positions ($P < .01$). Glenoid reconstruction with a DTA resulted in a significantly higher contact area compared with the 20% defect model in all 3 positions ($P < .01$) (Tables 2 and 3). There were also significant differences in the contact area between the ICBG and the 20% defect at FIR ($P < .05$) (Table 2). The intact state exhibited a significantly higher contact area than the ICBG at all 3 positions ($P < .05$) and a significantly higher contact area than the DTA at 30° ($P < .05$) (Tables 2 and 3).

Contact Pressure

Creation of a 20% posterior-inferior glenoid defect resulted in a significantly increased mean glenoid contact pressure compared with the intact glenoid at 60° and FIR ($P < .05$) (Tables 2 and 3). Bony reconstruction with both a DTA and ICBG resulted in a significant improvement in contact pressure compared with the defect at 60° ($P = .0078$); in addition, DTA resulted in significant improvements at FIR ($P = .0099$) (Tables 2 and 3). There was no difference in contact pressures when comparing the reconstructed glenoid (both DTA and ICBG) to the intact glenoid (Tables 2 and 3).

Peak Force

Creation of a 20% posterior-inferior glenoid defect resulted in no significant differences ($P > .05$) in the mean glenohumeral peak force compared with the intact glenoid in all 3 positions (Tables 2 and 3). Peak forces after reconstruction with DTA were similar ($P > .05$) to those conferred by ICBGs in all 3 positions ($P > .05$) (Tables 2 and 3).

DISCUSSION

The principal findings of this study demonstrated that reconstruction of a posterior glenoid osteochondral defect with a fresh DTA resulted in a significantly higher contact

TABLE 3
Results of 1-Way ANOVA With Tukey Post Hoc Test[a]

	Intact vs Defect	Intact vs ICBG	Intact vs DTA	Defect vs ICBG	Defect vs DTA	DTA vs ICBG	*P* Value
Contact area							
30°	*	*	*	NS	*	NS	<.0001
60°	*	*	NS	NS	*	NS	<.0001
FIR	*	*	NS	*	*	NS	<.0001
Contact pressure							
30°	NS	NS	NS	NS	NS	NS	.0682
60°	*	NS	NS	*	*	NS	.005
FIR	*	NS	NS	NS	*	NS	.0145
Peak force							
30°	NS	NS	NS	NS	NS	NS	.304
60°	NS	NS	NS	NS	NS	NS	.106
FIR	NS	NS	NS	NS	NS	NS	.1229

[a]Asterisk indicates statistical significance (Tukey post hoc test). DTA, distal tibial allograft; FIR, 90° of flexion–45° of internal rotation; ICBG, iliac crest bone graft; NS, not significant.

area compared with the 20% defect model at 30°, 60°, and FIR at the time of surgery. The intact state exhibited a significantly higher contact area than the defect in all positions, a significantly higher contact area than the ICBG in all positions, and a significantly higher contact area than the DTA at 30°. In addition, the creation of a 20% posterior-inferior glenoid osteochondral defect decreased contact areas by a mean 25% to 32% compared with the intact state, establishing an effective scientific model for evaluating the loading properties of the glenoid in the setting of posterior glenoid deficiency.

Posterior glenohumeral instability is uncommon, accounting for approximately 3% to 5% of all cases of shoulder instability.[15,22,25] Given the overall low occurrence of posterior instability in general, the true incidence of bone deficiency in the setting of recurrent posterior instability is unknown. Unlike cases of anterior instability in which the general consensus is that bone defects greater than 20% should be treated with a bone augmentation procedure, indications for soft tissue–only versus bony augmentation procedures in the setting of posterior stabilization are unclear. Smith and colleagues[30] have suggested that general indications for bony augmentation (with soft tissue repair) include posterior instability with bony Bankart lesions, posterior glenoid erosion, insufficient or weak posterior capsulolabral tissue, posterior glenoid dysplasia, and failed previous stabilization surgery. Levigne and colleagues[12] described similar indications, including persistent pain and subluxations or dislocations in the setting of posterior instability after guided rehabilitation. Further, these authors noted that patients with recurrent posterior dislocations after an initial traumatic event as well as patients with involuntary recurrent posterior subluxations are most suitable for bone block augmentation.

The surgical management of patients with posterior shoulder instability is variable, ranging from soft tissue procedures including posterior capsulolabral repair,[18] capsulorrhaphy, and subscapularis transfer (McLaughlin procedure) to bony procedures, including autograft/allograft reconstruction and glenoid and humeral head osteotomy procedures. Posterior bone block augmentation with an ICBG is the most often reported bone grafting technique,[1,8,12,14,17,28-30] but long-term outcomes have been inconsistent, often with discouraging results including the development of glenohumeral arthritis.

First described by Hindenach[10] in 1947, posterior bone augmentation with ICBGs has been described as an extra-articular reconstruction that acts to extend the glenoid surface and serve as an actual block to posterior humeral head translation. While this may provide a physical barrier to further posterior instability events, bone block reconstruction does not provide anatomic restoration of the articular surface of the glenoid, and thus, the glenohumeral joint remains incongruent. Several different techniques, including the utilization of extra-articular tricortical, bicortical, and unicortical ICBGs, have been described with varying results (Table 4).

In the techniques described in Table 4, nonanatomic reconstruction of the posterior glenoid does not allow for true reconstitution of the glenoid chondral surface, which may predispose to early degenerative changes of the glenohumeral joint. Further, as shown biomechanically by Ghodadra and colleagues,[7] glenoid joint contact pressures are improved when grafts are placed flush, with significantly increased peak forces and altered joint loading patterns with proud grafts. While the Ghodadra et al[7] study examined specifically anterior glenoid bone loss and subsequent reconstruction with an iliac crest or coracoid transfer, the results can be extrapolated and applied to the posterior glenoid. In the present study, we utilized a tricortical graft with the same dimensions as the glenoid defect, placed flush onto the posterior glenoid defect location, such that the superior cortical aspect of the iliac crest reconstructed the posterior rim of the glenoid, with the inner table of the iliac crest reconstructing the "articular surface" of the glenoid. Our technique is different from the majority of techniques describing posterior ICBG augmentation, which typically utilize an extra-articular reconstruction that acts to extend the glenoid surface and serve as an actual block to posterior humeral head translation. Currently,

TABLE 4
Literature Review of Posterior Bone Block Surgical Techniques and Outcomes[a]

Study (Year)	No. of Shoulders	Follow-up	ICBG Harvest Technique	ICBG Fixation Technique	Outcomes
Smith et al[29] (2012)	8	n.a.	Tricortical graft from the ipsilateral anterior iliac crest, measuring 2.5-3 × 1 × 1 cm	Arthroscopic fixation such that the graft is extension of the glenoid itself	Results not given
Meuffels et al[13] (2010)	11	18.3 y	Tricortical graft from the posterior aspect of the iliac crest	Graft did not protrude lateral to the posterior labrum	36% recurrent dislocations; 45% would not repeat surgery; 100% with OA
Levigne et al[11] (2005)	n.a.	n.a.	Ipsilateral bicortical iliac crest, 2-3 cm from the upper cortex, 3-4 cm long	Cancellous aspect faces anteriorly, extending 5 mm from the posterior labrum and 10 mm over the posterior glenoid rim	Technique only
Sirveaux et al[28] (2004)	9	13.5 y	n.a.	n.a.	Duplay score of 70 (of 100); 2 with OA
Servien et al[27] (2007)	21	6 y	Ipsilateral bicortical iliac crest, 2-3 cm from the upper cortex, 3-4 cm long	Cancellous aspect faces anteriorly, extending 5 mm from the posterior labrum and 10 mm over the posterior glenoid rim	3 failures (recurrent instability); 2 with OA
Barbier et al[1] (2009)	8	34 mo	Unicortical ICBG, ~25 mm long, ~10 mm wide, and ~10 mm thick	Extension of the glenoid cavity as opposed to creating a blocking effect	ER limited in 3; reoperations in 3; return to sport in 4; Constant score of 96.25; Duplay score of 90
Mowery et al[16] (1985)	5	2.5-8 y	Posterior superior iliac crest harvested for a 2 × 3–cm graft	Cancellous screw fixation to the glenoid, extends ~1.5 cm laterally over the humeral head	4 excellent and 1 good; no recurrences
Gosens et al[7] (2001)	11	72 mo	Tricortical ICBG from the posterior iliac crest, ~3 cm in length	Fixed with 2 A-screws at the posterocaudal glenoid rim, so that it did not protrude laterally from the posterior labrum	Higher recurrence rate in patients with MDI; 2 with arthrodesis; Rowe: 2 poor, 2 fair, 2 good, and 5 excellent; 3 with bone block resorption (1 total and 2 partial)

[a]ER, external rotation; ICBG, iliac crest bone graft; MDI, multidirectional instability; n.a., not available; OA, osteoarthritis.

there are no published data on the outcomes of posterior glenoid reconstruction with ICBGs placed flush to the glenoid. Thus, while future arthritis is certainly a possibility given the noncartilaginous reconstruction provided by ICBGs (despite being placed flush to the glenoid), more research is needed on this technique and any potential association with the future development of glenohumeral arthritis.

Other described surgical alternatives to iliac crest bone blocks include augmentation with fresh osteochondral allografts, including glenoid allografts[16,20] and DTA.[9,16] Specifically, Petrera and colleagues[20] published a case report on their technique and 2-year results after open posterior glenoid reconstruction with fresh osteochondral glenoid allografts and noted excellent clinical outcomes in a 54-year-old male patient with chronic posttraumatic posterior instability. In 2013, Millett et al[16] described their 2-year results in 2 patients (15-year-old male and 16-year-old male patients) after open posterior shoulder stabilization with fresh DTA and noted successful outcomes with CT evidence of good bony incorporation of the graft in both cases. More recently, Gupta and colleagues[9] described the surgical technique for an arthroscopic approach to posterior glenoid augmentation with fresh DTA; however, no clinical outcomes are yet available. Certainly, the benefits of fresh allografts in overall healing are numerous, with an increase in chondrocyte viability when compared with frozen allografts or those preserved in other ways.[19]

In theory, reconstruction with a fresh DTA offers the same benefits of bone block reconstruction in preventing recurrent posterior glenohumeral instability while offering the advantages of biologically restoring the glenoid articular surface and providing congruency to the glenoid-humeral head articulation throughout the entire range of motion.[6,23] Recently, anterior glenoid augmentation with

a DTA has been proposed as an effective surgical technique for the treatment of anterior shoulder instability associated with anterior glenoid bone loss both in reducing the rate of dislocations clinically and restoring more normal contact pressures biomechanically.[23,24] Initial laboratory work has demonstrated a nearly identical radius of curvature between the distal tibia and the glenoid, even among nonmatched cadaveric specimens, allowing for unimpeded motion due to its congruency with the humeral head (see Appendix Figure A4 and Video Supplement, available online). The results from the present study apply these findings to the posterior glenoid, demonstrating DTA to provide anatomic osteoarticular repair with at least equivalent contact areas within the glenohumeral joint at multiple positions compared with the "gold standard" of glenoid reconstruction with ICBGs. Certainly, this technique is novel, and clinical studies are needed to describe the effects that these mechanical properties may have on postoperative outcomes after glenoid reconstruction. Of utmost importance is gaining a better appreciation of the potential for graft resorption, with further clinical work including follow-up imaging studies.

Overall, this is the first biomechanical study to determine the glenohumeral loading mechanics in a clinically relevant posterior glenoid bone loss model and compare those to glenohumeral loading mechanics after allograft reconstruction. In addition to this established study design, strengths of this study include a standardized testing protocol, similar bone densities among the specimens, and glenoid augmentation with clinically relevant techniques applied in clinically relevant arm positions. This study is not without some inherent limitations. As with any cadaveric study, this is a "time zero" ex vivo model, and there was no opportunity for bone healing to occur. Thus, the results from this study may differ from what occurs in an in vivo setting. The mean age of our specimens was somewhat older than that of the patient population that might undergo instability repair. There are limitations to the Tekscan system itself, with pressure measurements experiencing variability over time and based on the environment.[11] Finally, as noted by Ghodadra et al[7] and Bhatia et al[2] in establishing this model, this study design utilizes a static model of the glenohumeral joint, devoid of any dynamic soft tissue restraints, including the capsule and rotator cuff. Also of note, the ICBG reconstructive technique utilized in this study placed ICBGs flush with the glenoid defect in an attempt to replicate the technique utilized for DTA reconstruction. We chose this methodology, as opposed to extra-articular graft placement,[12,28] as we felt that this would facilitate a reliable comparison to DTA reconstruction with regard to the loading properties in this experimental model.

Current reconstructive techniques, including the use of an extra-articular, nonanatomic ICBG, aim to decrease posterior shoulder translation and the clinical sense of instability, but the concern for the development of early, symptomatic glenohumeral arthritis remains. At minimum, posterior glenoid reconstruction with a fresh DTA offers an alternative, viable surgical option that potentially restores both mechanics and biology for what is historically an extremely difficult problem. Specifically, reconstruction of posterior glenoid bone defects with DTA may allow for improved joint congruity with an osteoarticular construct, which demonstrates similar contact mechanics compared with reconstruction with ICBGs. While these mechanical properties may translate into clinical differences, further studies are needed to understand the long-term fate of these osteochondral grafts around the glenoid.

CONCLUSION

Reconstruction of posterior glenoid bone defects with DTA demonstrated at least equivalent biomechanical properties compared with reconstruction with ICBGs at the time of surgery. Given the concern over the association of the extra-articular, nonanatomic ICBG reconstruction technique with the development of early, symptomatic glenohumeral arthritis, this study suggests that posterior glenoid reconstruction with a fresh DTA is a viable alternative solution, with the potential advantage of improving joint congruity via an anatomic reconstruction that includes a cartilaginous, congruent articulation with the humeral head.

A Video Supplement for this article is available in the online version or at http://ajsm.sagepub.com/supplemental.

REFERENCES

1. Barbier O, Ollat D, Marchaland JP, Versier G. Iliac bone-block autograft for posterior shoulder instability. *Orthop Traumatol Surg Res*. 2009;95(2):100-107.
2. Bhatia S, Van Thiel GS, Gupta D, et al. Comparison of glenohumeral contact pressures and contact areas after glenoid reconstruction with Latarjet or distal tibial osteochondral allografts. *Am J Sports Med*. 2013;41(8):1900-1908.
3. Burkhart SS, De Beer JF. Traumatic glenohumeral bone defects and their relationship to failure of arthroscopic Bankart repairs: significance of the inverted-pear glenoid and the humeral engaging Hill-Sachs lesion. *Arthroscopy*. 2000;16(7):677-694.
4. Burkhart SS, De Beer JF, Barth JR, Cresswell T, Roberts C, Richards DP. Results of modified Latarjet reconstruction in patients with anteroinferior instability and significant bone loss. *Arthroscopy*. 2007;23(10):1033-1041.
5. Burkhart SS, Debeer JF, Tehrany AM, Parten PM. Quantifying glenoid bone loss arthroscopically in shoulder instability. *Arthroscopy*. 2002;18(5):488-491.
6. Frank RM, Provencher MT, Romeo AA. Comment on ''Reconstruction of posterior glenoid deficiency using distal tibial osteoarticular allograft'' [published online October 22, 2013.] *Knee Surg Sports Traumatol Arthrosc*. doi:10.1007/s00167-013-2722-6.
7. Ghodadra N, Gupta A, Romeo AA, et al. Normalization of glenohumeral articular contact pressures after Latarjet or iliac crest bone-grafting. *J Bone Joint Surg Am*. 2010;92(6):1478-1489.
8. Gosens T, van Biezen FC, Verhaar JA. The bone block procedure in recurrent posterior shoulder instability. *Acta Orthop Belg*. 2001;67(2):116-120.
9. Gupta AK, Chalmers PN, Klosterman E, Harris JD, Provencher MT, Romeo AA. Arthroscopic distal tibial allograft augmentation for posterior shoulder instability with glenoid bone loss. *Arthrosc Tech*. 2013;2(4):e405-e411.
10. Hindenach JC. Recurrent posterior dislocation of the shoulder. *J Bone Joint Surg Am*. 1947;29(3):582-586.
11. Jansson KS, Michalski MP, Smith SD, LaPrade RF, Wijdicks CA. Tekscan pressure sensor output changes in the presence of liquid exposure. *J Biomech*. 2013;46(3):612-614.

12. Levigne C, Garret J, Walch G. Posterior bone block for posterior instability. *Tech Shoulder Elbow Surg*. 2005;6(1):26-35.
13. Lo IK, Parten PM, Burkhart SS. The inverted pear glenoid: an indicator of significant glenoid bone loss. *Arthroscopy*. 2004;20(2):169-174.
14. Meuffels DE, Schuit H, van Biezen FC, Reijman M, Verhaar JA. The posterior bone block procedure in posterior shoulder instability: a long-term follow-up study. *J Bone Joint Surg Br*. 2010;92(5):651-655.
15. Millett PJ, Clavert P, Hatch GF, Warner JJ. Recurrent posterior shoulder instability. *J Am Acad Orthop Surg*. 2006;14(8):464-476.
16. Millett PJ, Schoenahl JY, Register B, Gaskill TR, van Deurzen DF, Martetschlager F. Reconstruction of posterior glenoid deficiency using distal tibial osteoarticular allograft. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(2):445-449.
17. Mowery CA, Garfin SR, Booth RE, Rothman RH. Recurrent posterior dislocation of the shoulder: treatment using a bone block. *J Bone Joint Surg Am*. 1985;67(5):777-781.
18. Nho SJ, Frank RM, Van Thiel GS, et al. A biomechanical analysis of shoulder stabilization: posteroinferior glenohumeral capsular plication. *Am J Sports Med*. 2010;38(7):1413-1419.
19. Pallante AL, Bae WC, Chen AC, Görtz S, Bugbee WD, Sah RL. Chondrocyte viability is higher after prolonged storage at 37 degrees C than at 4 degrees C for osteochondral grafts. *Am J Sports Med*. 2009;37(Suppl 1):24S-32S.
20. Petrera M, Veillette CJ, Taylor DW, Park SS, Theodoropoulos JS. Use of fresh osteochondral glenoid allograft to treat posteroinferior bone loss in chronic posterior shoulder instability. *Am J Orthop (Belle Mead NJ)*. 2013;42(2):78-82.
21. Piasecki DP, Verma NN, Romeo AA, Levine WN, Bach BRJ, Provencher MT. Glenoid bone deficiency in recurrent anterior shoulder instability: diagnosis and management. *J Am Acad Orthop Surg*. 2009;17(8):482-493.
22. Provencher MT, Bhatia S, Ghodadra NS, et al. Recurrent shoulder instability: current concepts for evaluation and management of glenoid bone loss. *J Bone Joint Surg Am*. 2010;92(Suppl 2):133-151.
23. Provencher MT, Ghodadra N, LeClere L, Solomon DJ, Romeo AA. Anatomic osteochondral glenoid reconstruction for recurrent glenohumeral instability with glenoid deficiency using a distal tibia allograft. *Arthroscopy*. 2009;25(4):446-452.
24. Provencher MT, LeClere LE, Ghodadra N, Solomon DJ. Postsurgical glenohumeral anchor arthropathy treated with a fresh distal tibia allograft to the glenoid and a fresh allograft to the humeral head. *J Shoulder Elbow Surg*. 2010;19(6):e6-e11.
25. Provencher MT, LeClere LE, King S, et al. Posterior instability of the shoulder: diagnosis and management. *Am J Sports Med*. 2011;39(4):874-886.
26. Robinson CM, Aderinto J. Posterior shoulder dislocations and fracture-dislocations. *J Bone Joint Surg Am*. 2005;87(3):639-650.
27. Robinson CM, Aderinto J. Recurrent posterior shoulder instability. *J Bone Joint Surg Am*. 2005;87(4):883-892.
28. Servien E, Walch G, Cortes ZE, Edwards TB, O'Connor DP. Posterior bone block procedure for posterior shoulder instability. *Knee Surg Sports Traumatol Arthrosc*. 2007;15(9):1130-1136.
29. Sirveaux F, Leroux J, Roche O, Gosselin O, De Gasperi M, Mole D. [Surgical treatment of posterior instability of the shoulder joint using an iliac bone block or an acromial pediculated bone block: outcome in eighteen patients]. *Rev Chir Orthop Reparatrice Appar Mot*. 2004;90(5):411-419.
30. Smith T, Goede F, Struck M, Wellmann M. Arthroscopic posterior shoulder stabilization with an iliac bone graft and capsular repair: a novel technique. *Arthrosc Tech*. 2012;1(2):e181-e185.
31. Sugaya H, Kon Y, Tsuchiya A. Arthroscopic repair of glenoid fractures using suture anchors. *Arthroscopy*. 2005;21(5):635.
32. Sugaya H, Moriishi J, Dohi M, Kon Y, Tsuchiya A. Glenoid rim morphology in recurrent anterior glenohumeral instability. *J Bone Joint Surg Am*. 2003;85(5):878-884.