Normalization of Glenohumeral Articular Contact Pressures After Latarjet or Iliac Crest Bone-Grafting

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Background: Multiple bone-grafting procedures have been described for patients with glenoid bone loss and shoulder instability. The purpose of this study was to investigate the alterations in glenohumeral contact pressure associated with the placement and orientation of Latarjet or iliac crest bone graft augmentation and to compare the amount of glenoid bone reconstruction with two coracoid face orientations.

Methods: Twelve fresh-frozen cadaver shoulders were tested in static positions of humeral abduction (30°, 60°, and 60° with 90° of external rotation) with a 440-N compressive load. Glenohumeral contact pressure and area were determined sequentially for (1) the intact glenoid; (2) a glenoid with an anterior bone defect involving 15% or 30% of the glenoid surface area; (3) a 30% glenoid defect treated with a Latarjet or iliac crest bone graft placed 2 mm proud, placed flush, or recessed 2 mm in relation to the level of the glenoid; and (4) a Latarjet bone block placed flush and oriented with either the lateral (Latarjet-LAT) or the inferior (Latarjet-INF) surface of the coracoid as the glenoid face. The amount of glenoid bone reconstructed was compared between the Latarjet-LAT and Latarjet-INF conditions.

Results: Bone grafts in the flush position restored the mean peak contact pressure to 116% of normal when the iliac crest bone graft was used (p < 0.03 compared with the pressure with the 30% defect), 120% when the Latarjet-INF bone block was used (p < 0.03), and 137% when the Latarjet-LAT bone block was used (p < 0.04). Use of the Latarjet-LAT bone block resulted in mean peak pressures that were significantly higher than those associated with the iliac crest bone graft (p < 0.02) or the Latarjet-INF bone block (p < 0.03) at 60° of abduction and 90° of external rotation. With the bone grafts placed in a proud position, peak contact pressure increased to 250% of normal (p < 0.01) in the anteroinferior quadrant and there was a concomitant increase in the posterosuperior glenoid pressure to 200% of normal (p < 0.02), indicating a shift posteriorly. Peak contact pressures of bone grafts placed in a recessed position revealed high edge-loading. Augmentation with the Latarjet-LAT bone block led to restoration of the glenoid articular contact surface from the 30% defect state to a 5% defect state. Augmentation of the 30% glenoid defect with the Latarjet-INF bone block resulted in complete restoration to the intact glenoid articular surface area.

Conclusions: Glenohumeral contact pressure is optimally restored with a flush iliac crest bone graft or with a flush Latarjet bone block with the inferior aspect of the coracoid becoming the glenoid surface. Bone grafts placed in a proud position not only increase the peak pressure anteroinferiorly, but also shift the articular contact pressure to the posterosuperior quadrant. Glenoid bone augmentation with a Latarjet bone block with the inferior aspect of the coracoid as the glenoid surface resulted in complete restoration of the 30% anterior glenoid defect to the intact state. These findings indicate the clinical utility of a flush iliac crest bone graft and utilization of the inferior surface of the coracoid as the glenoid face for glenoid bone augmentation with a Latarjet graft.

Glenoid bone loss resulting from either an acute shoulder dislocation or chronic osseous erosion due to recurrent episodes of instability has been shown to decrease the intrinsic stability of the glenohumeral joint[1]. Although long-term studies have demonstrated favorable results, in terms of stability and function, after autologous bone-grafting procedures

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such as the Latarjet[2-9] procedure, arthritis remains a concern[8,10,11]. Nonoptimal positioning (either too proud or too recessed) of the glenoid bone block has been identified as a potential cause of arthritis and shoulder pain following bone graft reconstruction of the glenoid[1,7,12].

Several autologous bone-grafting procedures, including the Latarjet (and modified Bristow) procedure as well as the use of iliac crest bone graft, have been described[7,13-15]. However, neither method has been identified as clearly superior in the setting of recurrent instability and glenoid bone loss. Proponents of the iliac crest bone graft technique, which utilizes the inner table of the iliac crest, identify a theoretical advantage over the Latarjet procedure in terms of improved congruity of the glenoid as well as a limitless bone-graft size[14]. Advocates of the Latarjet procedure have argued that glenoid conformity is not the most important factor in the treatment of glenoid bone loss[7,15]. The original Latarjet procedure[13] involves fixation of the coracoid to the glenoid so that the lateral edge of the coracoid becomes juxtaposed to the glenoid surface (Latarjet-LAT procedure). However, this traditional method of performing the Latarjet procedure was challenged by De Beer and Burkhart[3], who modified the technique by affixing the coracoid to the glenoid in a rotated position so that the inferior (deep) coracoid surface became contiguous with the glenoid surface (Latarjet-INF procedure). Proponents of that technique (the coracoid positioned with its inferior surface as the glenoid face) argue that it allows better articular surface congruity by matching the glenoid concavity, similar to the way that the concavity of the inner table of the iliac crest bone graft matches the glenoid concavity[4,14].

Articular conformity after bone-grafting procedures for the treatment of glenoid deficiency remains poorly defined, as does the bone-grafting solution that is optimal for restoration of glenohumeral contact pressures. We investigated the alterations in glenohumeral articular contact pressures in a glenoid bone-loss model to determine the optimal graft choice, orientation, and placement.

The purposes of our study were to determine changes in the magnitude and location of contact pressure after (1) creation of clinically relevant 15% and 30% anterior glenoid defects; (2) subsequent glenoid bone augmentation procedures with iliac crest bone graft or a Latarjet bone block; and (3) flush, proud, or recessed placement of each glenoid bone graft. In addition, we sought to determine the amount of glenoid bone reconstruction after use of either the Latarjet-LAT or the Latarjet-INF bone block. We hypothesized that a clinically relevant defect involving 30% of the glenoid surface area would increase articular contact pressure in the antero-inferior quadrant of the glenoid and that bone augmentation with either the iliac crest bone graft or the Latarjet-INF bone block in a flush position would best normalize articular contact pressures. We also hypothesized that augmentation with the Latarjet-INF bone block would provide glenoid bone reconstitution that was greater (closer to the intact state) than that provided by the Latarjet-LAT bone block.

Materials and Methods

Twelve fresh-frozen human cadaver shoulders (six left shoulders and six right shoulders from donors with a mean age of forty-five years [range, thirty-two to fifty-four years] at the time of death) were dissected free of all soft tissues, and the capsule was excised to expose the humerus and the osseous glenoid with the labrum. Prior to potting of the scapula, digital
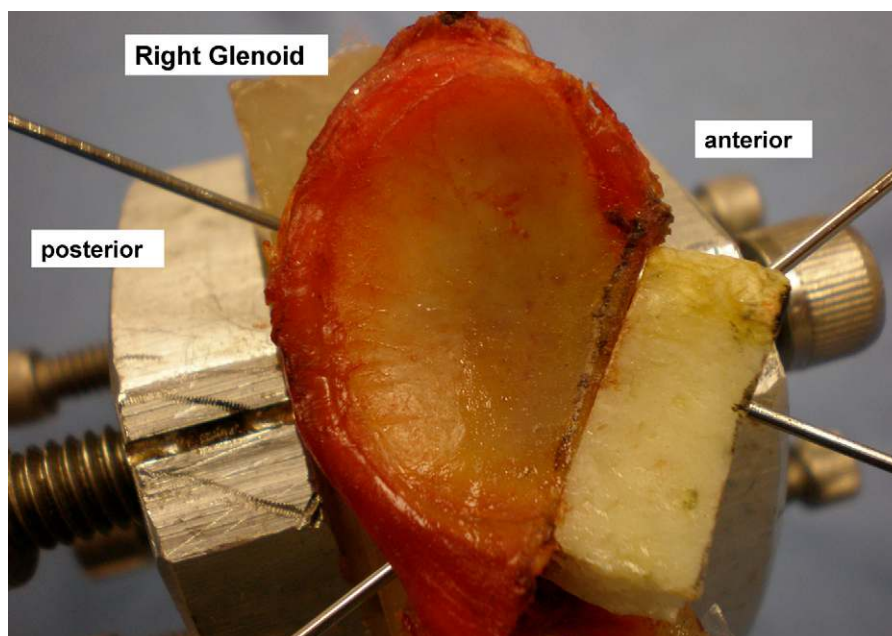

Fig. 1

En face view of a right cadaver glenoid with an iliac crest bone graft placed onto its anterior aspect.

calipers were used to measure the anterior-posterior and superior-inferior diameters of the glenoid with the labrum attached. The diameter measurements were based on viewing the glenoid *en face* as a clock with the superior portion of the glenoid equaling twelve o'clock (Fig. 1). The diameters measured from twelve o'clock to six o'clock and from three o'clock to nine o'clock were recorded for each specimen. The average anterior-posterior diameter was 26 mm (range, 22 to 30 mm), and the average superior-inferior diameter was 34 mm (range, 32 to 35 mm).

To determine the amount of simulated glenoid bone loss, the entire glenoid surface was digitized with a 10.0-megapixel digital camera mounted parallel to the glenoid face. A 30-mm sizing marker was placed flush against the glenoid rim to serve as a reference for the digitizing software. The digitized images of each glenoid were then loaded into a personal computer digitizer, and a best-fit circle of the inferior two-thirds of each glenoid was determined with commercial software (Adobe Photoshop [Adobe Systems, San Jose, California] and the Universal Ruler [PC Industries, Gurnee, Illinois])[16,17]. The area of the best-fit circle was determined after it

was digitally calibrated with the sizing marker with use of Universal Ruler software. The total area of the inferior two-thirds of each glenoid served as the starting point from which two sequential osteotomies would be calculated[18]. The inferior two-thirds of the glenoid is a well-conserved circle, and bone loss measurements were based on the relative percentage of the surface area lost from the intact circle[19].

Once the area of the glenoid was determined, the scapula was potted in epoxy cement with the glenoid oriented parallel to the floor with a gravity-level so that loads across the joint would be compressive. Two perpendicular 0.45-in (11.4-mm) Kirschner wires were placed through the glenoid neck from the six o'clock to the twelve o'clock position and from the three o'clock to the nine o'clock position to act as reference points to divide the glenoid into four quadrants.

The humeral shaft was potted in epoxy cement and was placed in a custom fixture that was mounted on an MTS closed-loop servohydraulic testing machine (MTS Systems, Eden Prairie, Minnesota). The exposed length of the proximal part of the shaft was 5 cm to minimize diaphyseal bending
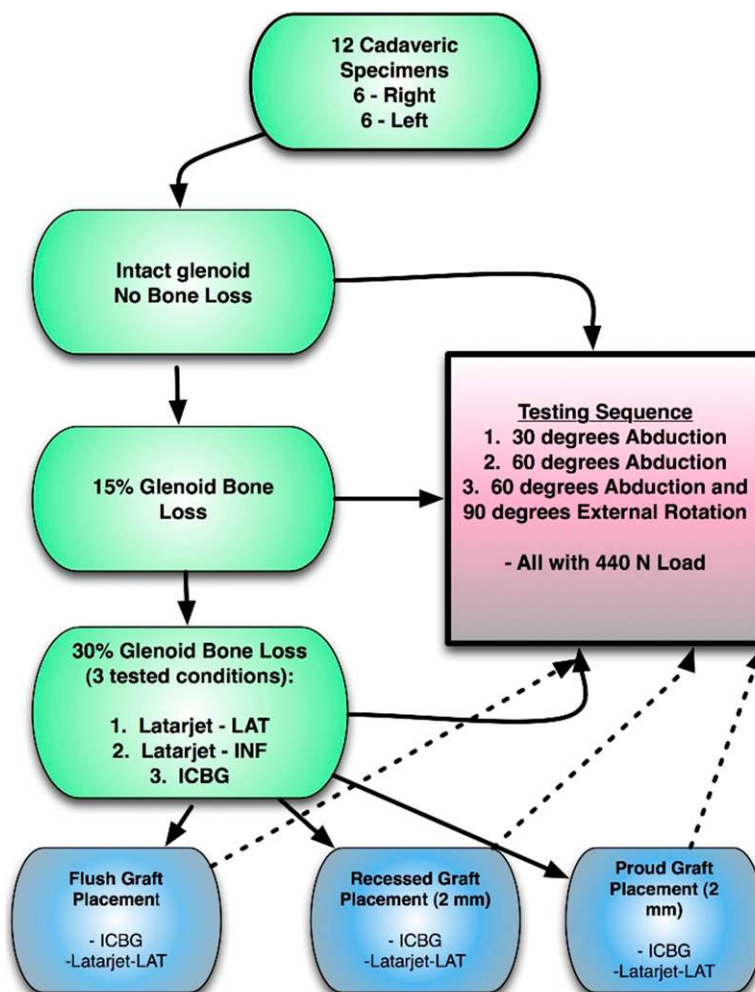

Fig. 2

Flow chart depicting all testing conditions. ICBG = iliac crest bone graft.

moments and interference by the testing apparatus during abduction. The neutral axis was defined by placing the bicipital groove anteriorly and externally rotating the humerus 10° with a goniometer with no abduction or flexion[20].

A 0.1-mm-thick dynamic pressure-sensitive pad (Tekscan 5051 pad; Tekscan, Boston, Massachusetts), with a 56 × 56-mm matrix and a density of 62 sensels/cm^2, was precalibrated with loaded MTS machine weights similar in size to the average glenoid. The manufacturer's guidelines and recommendations were followed for calibration, which was performed with loads that were 20% and 80% of the maximum test load (440 N) applied across the glenohumeral joint. The pressure pad was placed between the humerus and glenoid and was marked so that the pad could be placed in an identical position with staples during each sequential trial.

Testing Conditions

The MTS machine was used to apply a compressive load of 440 N, and the glenohumeral contact pressure, contact area, shift in the center of pressure, and edge-loading were determined with a Tekscan sensor. A load of 440 N was chosen on the basis of prior work and served as an approximate maximal load for simulation of in vivo glenohumeral loading conditions during the range of motion of the shoulder during activities of daily living[21]. The testing sequence included ten conditions (Fig. 2): an intact glenoid (condition 1), a glenoid with a clinically relevant 15% (condition 2) or 30% (condition 3) defect from two o'clock to six o'clock, a 30% glenoid defect with a Latarjet-LAT bone block placed 2 mm proud (condition 4), placed flush (condition 5), and recessed 2 mm (condition 6) in relation to the level of the glenoid (Fig. 3), a 30% glenoid defect with an iliac crest bone
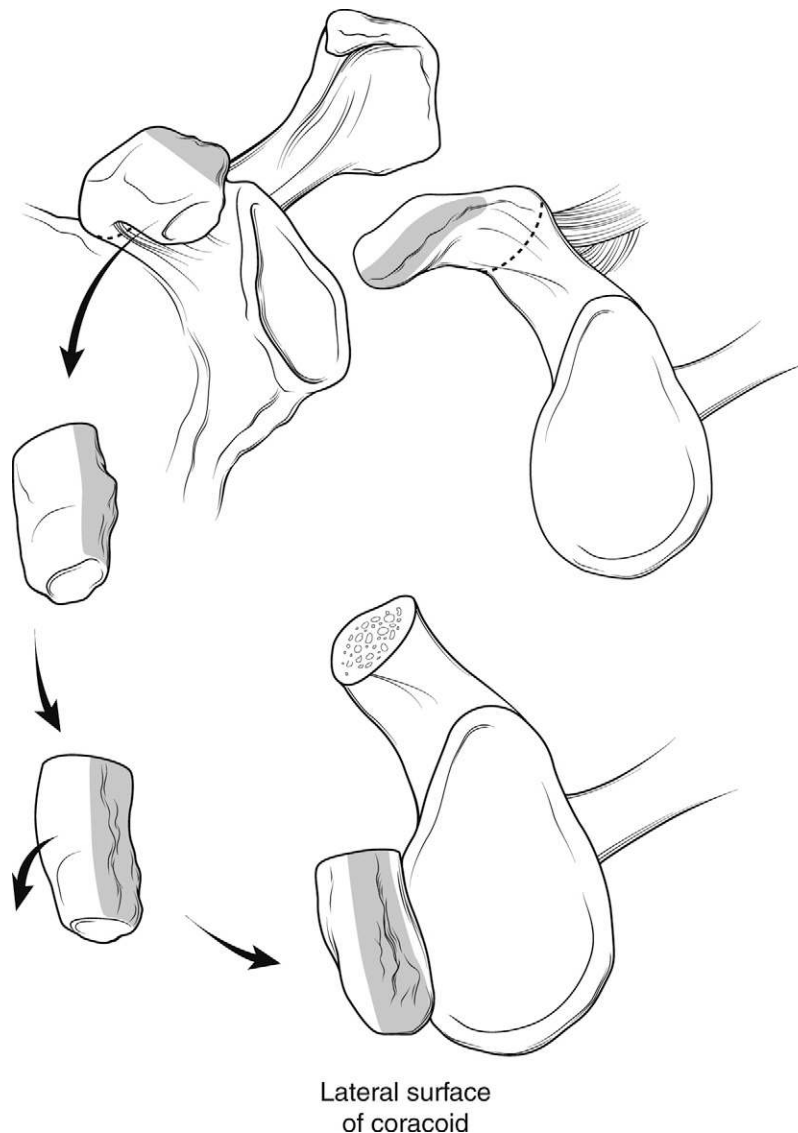

Lateral surface
of coracoid

Fig. 3

Illustration showing placement of the Latarjet graft so that the lateral surface of the coracoid becomes the face of the glenoid (Latarjet-LAT).

graft (Fig. 1) placed 2 mm proud (condition 7), placed flush (condition 8), and recessed 2 mm (condition 9) in relation to the level of the glenoid, and a Latarjet-INF bone block placed flush with the glenoid (condition 10) (Figs. 4-A and 4-B). The Latarjet-INF bone block was tested in only the flush position because of financial restrictions and technical difficulties, including deterioration of bone quality after repeated testing that led to an inability to maintain fixation throughout loading.

The custom fixture allowed positioning of the humerus relative to the glenoid for the following testing positions for each condition (Fig. 2): (1) 30° of humeral abduction with a 440-N load, (2) 60° of humeral abduction with a 440-N load, and (3) 60° of humeral abduction and 90° of humeral external rotation with a 440-N load.

After each measurement, the pressure sensor was removed and then repositioned and affixed with staples. Care was taken to ensure that each mark on the sensor pad was positioned according to the Kirschner wires placed into the glenoid. A new Tekscan sensor was utilized for each specimen as our pretesting of Tekscan sensors showed a decrease in sensitivity and the ability to detect contact pressure after approximately ninety-five consecutive loads of 440 N. Thus, a new sensor was utilized well below the threshold of any potential decrease in sensitivity due to potential creep from repeated testing and handling of the sensor.

Bone Defects
Two sequential osteotomies simulating 15% and 30% bone loss were performed on the basis of the area calculation of the best-fit circle[18]. After calculating the exact area of the loss in square millimeters corresponding to 15% and 30% of the circle, the digitizer was used to print a template for each "clinical" osteotomy, defined by Sugaya et al.[17] and Saito et al.[16] as an osteotomy line parallel to the long axis of the glenoid. This line is different from that used in prior cadaver studies[21] but is more consistent with clinical bone loss as it occurs more parallel to the long axis of the glenoid[16-18]. Each glenoid osteotomy was made with use of a 0.5-mm-diameter high-speed circular saw set to 15,000 revolutions per minute to minimize bone loss. The template remained in place after each osteotomy to ensure that the correct amount of bone had been removed. Prior to testing, the anterior-posterior diameter of the glenoid was measured in line with the glenoid bare spot and recorded. After each osteotomy, the testing sequence was repeated from neutral to the abducted and externally rotated position and pressure measurements were recorded as described above.

Bone Augmentation Procedures
After the osteotomy that resulted in 30% anterior glenoid bone loss, each of the twelve cadaver specimens was randomly assigned to first undergo either a Latarjet autograft procedure or an iliac crest bone autograft procedure. For the Latarjet procedure, a mean of 2.0 cm of the length of the coracoid process was harvested from the cadaver specimen to the elbow of the coracoid base and stripped of all soft-tissue attachments. The Latarjet bone block was rotated 90° so that the lateral aspect of the coracoid became the face of the glenoid and the inferior
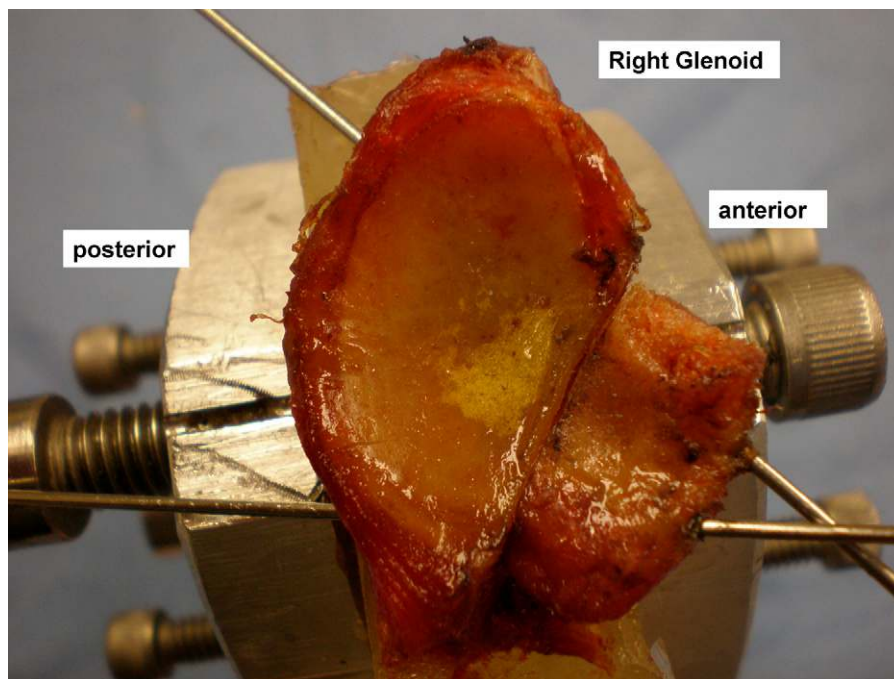

Fig. 4-A

En face view of a right cadaver glenoid with the coracoid of the Latarjet graft placed with its inferior surface juxtaposed to the face of the glenoid (Latarjet-INF). The inferior aspect of the coracoid is the glenoid face in this testing orientation.

surface of the coracoid was apposed to the glenoid neck[9,15] (Fig. 3). Three 2.0-mm threaded Kirschner wires, drilled in parallel fashion, were utilized to affix the bone block in place. A reduction clamp (Synthes, West Chester, Pennsylvania) was used to provide compression across the construct. Each specimen was also treated with the modified Bristow-Latarjet method described by Burkhart et al.[4]. The coracoid was affixed to the glenoid with Kirschner wires, as described above, with the inferior surface of the coracoid serving as the face of the glenoid and the medial surface of the coracoid apposed to the glenoid neck (Figs. 4-A and 4-B).

Prior to loading, the anterior-posterior diameter of the glenoid was measured in line with the bare spot to determine the degree to which the Latarjet-LAT and Latarjet-INF configurations restored the glenoid bone to the intact state. These measurements were not conducted for the iliac crest bone graft, as multiple sizes of that graft can be obtained for glenoid bone augmentation.

To obtain the iliac crest bone graft, a freeze-dried cadaveric iliac crest specimen was cut to the same size as the Latarjet graft (mean, 2.0 × 1.8 cm). The iliac crest bone graft was placed onto the glenoid as described by Warner et al.[14]. The inner table of the iliac crest served as the glenoid face, and the graft was affixed to the glenoid in the same fashion as the coracoid was affixed to it (Fig. 1).

Each specimen was tested after both the Latarjet and the iliac crest bone graft procedure, with randomization used to determine which bone-grafting procedure would be tested first for each specimen. With each of the bone-grafting procedures, the testing sequence was repeated from neutral to the abducted and externally rotated position and pressure measurements were
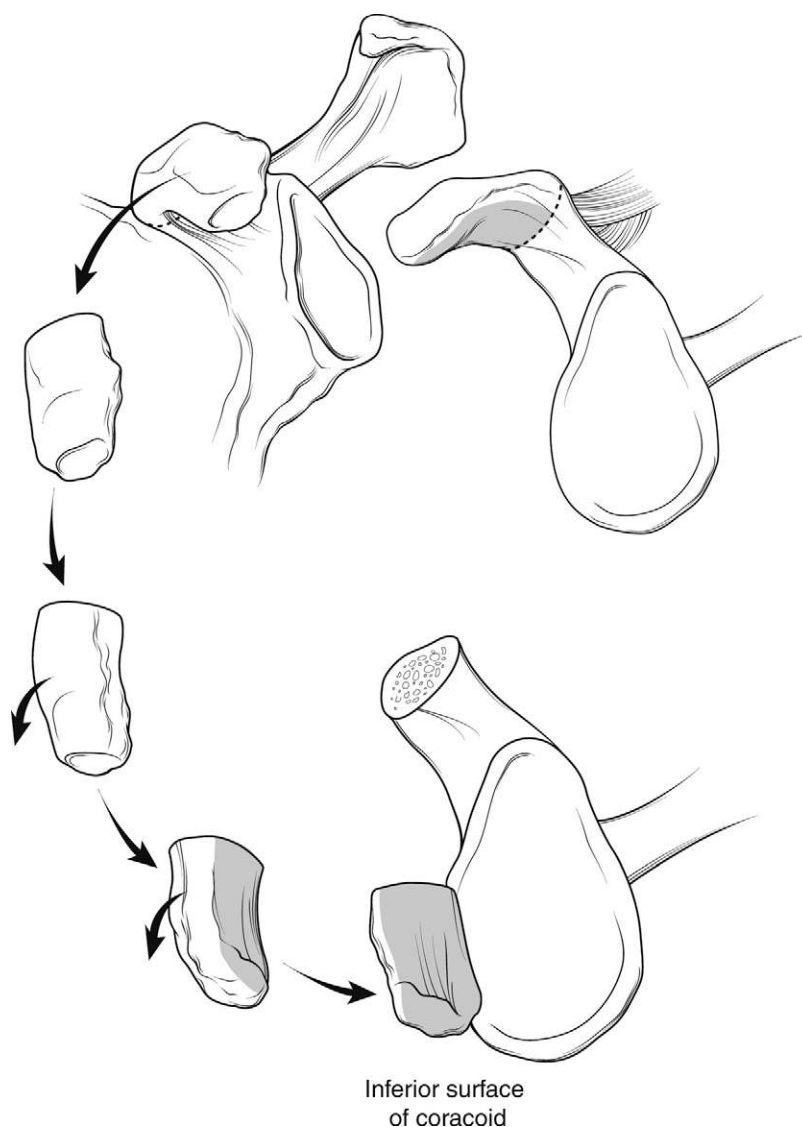

Fig. 4-B

Illustration showing placement of the Latarjet graft so that the inferior surface of the coracoid becomes the face of the glenoid (Latarjet-INF).

TABLE I Mean Anteroinferior Glenoid Contact Area and Pressure in 60° of Abduction and 90° of External Rotation with 2-mm Proud, Flush, and 2-mm Recessed Graft Locations ➤

	2 mm Proud				Flush	
	Contact Area		Contact Pressure		Contact Area	
	Mean ± Stand. Dev. (cm²)	% of Intact	Mean ± Stand. Dev. (MPa)	% of Intact	Mean ± Stand. Dev. (cm²)	% of Intact
Iliac crest bone graft	1.91 ± 0.20†§	54 ± 10	4.04 ± 0.32†§	245 ± 20	2.90 ± 0.20†§	82 ± 6
Latarjet-LAT*	1.80 ± 0.21†	51 ± 12	4.20 ± 0.40†§	254 ± 24	2.58 ± 0.12§	73 ± 5
Latarjet -INF†	Not applic.	Not applic.	Not applic.	Not applic.	2.83 ± 18§	80 ± 6

*The coracoid bone block is oriented and affixed to the glenoid such that the lateral aspect of the coracoid is the glenoid face. †The coracoid bone block is oriented and affixed to the glenoid such that the inferior aspect of the coracoid is the glenoid face. ‡P < 0.05 compared with the intact specimen. §P < 0.05 compared with the 30% defect.

recorded. Pressure measurements were recorded three times for each testing condition, and the mean was used for data analysis.

Graft-Placement Conditions

The Latarjet-LAT bone blocks and the iliac crest bone grafts were each tested in three positions: (1) flush with the level of the glenoid, (2) 2 mm medial (recessed) in relation to the level of the glenoid, and (3) 2 mm lateral (proud) in relation to the level of the glenoid (Fig. 5).

Each testing condition from neutral to abduction and external rotation was repeated for each graft position. Before and after testing, the height of the bone graft relative to the native glenoid was recorded at the upper, middle, and lower third of the graft.

Statistical Analysis

Data from the pressure software were analyzed with descriptive statistics, and analysis of variance was performed to compare the values between the testing conditions. For comparison between the data sets, the Wilcoxon rank-sum test was used with p values adjusted for multiple comparisons. Post hoc corrections were utilized to confirm differences between the testing conditions. In addition, analysis of variance and post hoc testing were used to compare the bone grafts. A pre hoc power analysis based on prior data indicated that twelve specimens would be necessary with a beta of 0.8 to detect a 20% difference in contact pressure[21].

Source of Funding

There were no external sources of funding for this project. All iliac crest bone graft specimens were provided by AlloSource.

Results

Contact Pressure at 30° and 60° of Abduction, and 60° of Abduction with 90° of External Rotation

The largest changes in contact pressure were seen with the humerus in 60° of abduction and 90° of external rotation. Creation of a 15% glenoid defect increased the mean peak contact pressure of the glenoid-labral complex by 25% to 30% (mean, 28%; p < 0.05) and a 30% glenoid defect increased the mean peak contact pressure by 85% to 105% (mean, 94%, p < 0.03) as compared with the pressure in the intact condition.

After creation of a 30% defect, the measured peak contact pressure in the anteroinferior quadrant increased by a mean (and standard deviation) of 390% ± 29% (p < 0.01) at 60° of abduction and 90° of external rotation. At all testing angles, flush bone grafts resulted in significant (p < 0.05) normalization of contact pressure as compared with the pressure associated with the 30% defect condition (Fig. 6). The flush iliac crest bone graft restored the mean peak contact pressure to 116% (p < 0.03 compared with the pressure with the 30% defect) of that in the intact condition and the flush Latarjet-INF and Latarjet-LAT bone blocks restored it to 120% (p < 0.03) and 137% (p < 0.04), respectively, at 60° of abduction and 90° of external rotation. There was no significant difference in the peak contact pressure between the graft types or the graft orientations at 30° or 60° of abduction. At 60° of abduction and 90° of external rotation, there was a significant difference between the Latarjet-LAT and iliac crest bone grafts and between the Latarjet-LAT and Latarjet-INF bone blocks (p < 0.02 and p < 0.03, respectively) (Table I). There were no significant differences between the Latarjet-INF and iliac crest bone grafts with regard to their ability to restore
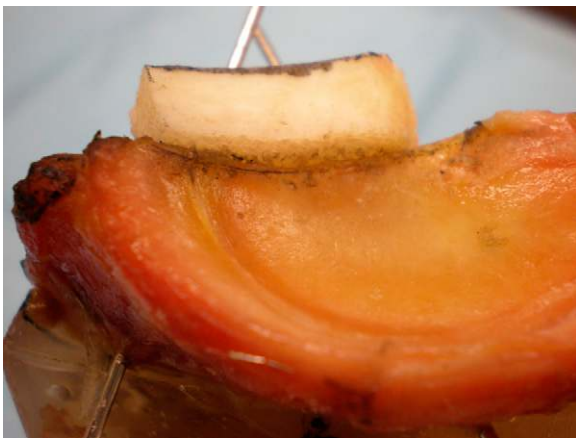

Fig. 5

View of a left glenoid with a 30% anterior defect and placement of the iliac crest bone graft 2 mm proud.

TABLE I (continued)

Flush		2 mm Recessed			
Contact Pressure		Contact Area		Contact Pressure	
Mean ± Stand. Dev. (MPa)	% of Intact	Mean ± Stand. Dev. (cm²)	% of Intact	Mean ± Stand. Dev. (MPa)	% of Intact
1.91 ± 0.14§	116 ± 9	1.56 ± 0.18†	44 ± 12	6.25 ± 0.34†	379 ± 22
2.26 ± 0.10†§	137 ± 6	1.49 ± 0.13†	42 ± 9	6.35 ± 0.28†	385 ± 17
1.98 ± 0.11§	120 ± 7	Not applic.	Not applic.	Not applic.	Not applic.

contact pressures to the intact state at 60° of abduction and 90° of external rotation.

When the Latarjet-LAT and iliac crest bone grafts were placed 2 mm proud in relation to the glenoid articular surface and the testing was performed at 60° of abduction and 90° of external rotation, there was a significant increase in the anteroinferior peak contact pressure to 254% ± 24% ($p < 0.02$)

and 245% ± 20% ($p < 0.02$), respectively, of the pressures in the intact specimens (Table I) and the contact pressures in the posterosuperior quadrant increased to 191% ± 5% and 204% ± 13%, respectively, of the pressures in the intact specimens (see Appendix). Proud placement of both the Latarjet-LAT bone block and the iliac crest bone graft led to a significant shift in the center of pressure to the posterosuperior quadrant
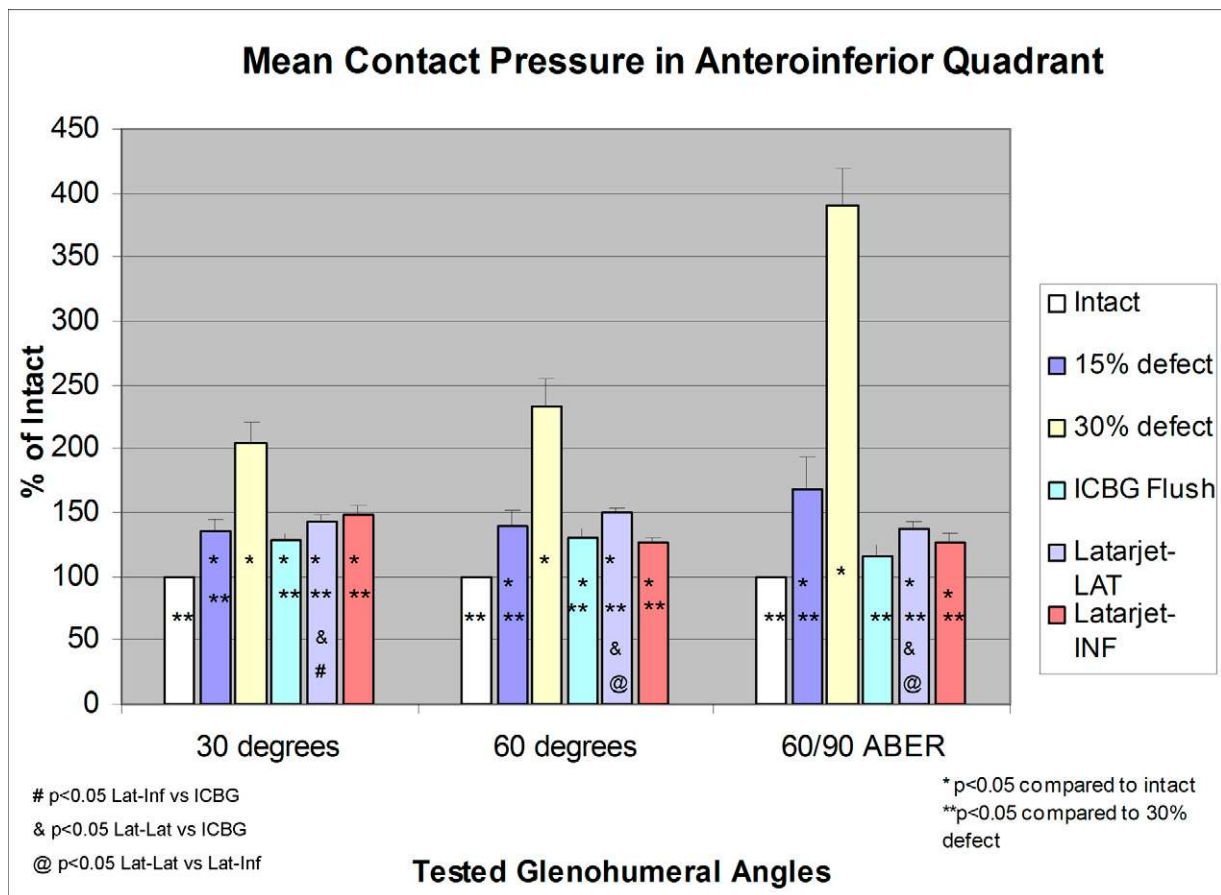

Fig. 6

Mean contact pressure data for the anteroinferior quadrant of the glenoid at all tested angles under a 440-N load. Results are presented in relation to the intact condition. 60/90 ABER = 60° of abduction and 90° of external rotation, ICBG = iliac crest bone graft, Lat-Inf = Latarjet-INF, and Lat-Lat = Latarjet-LAT.
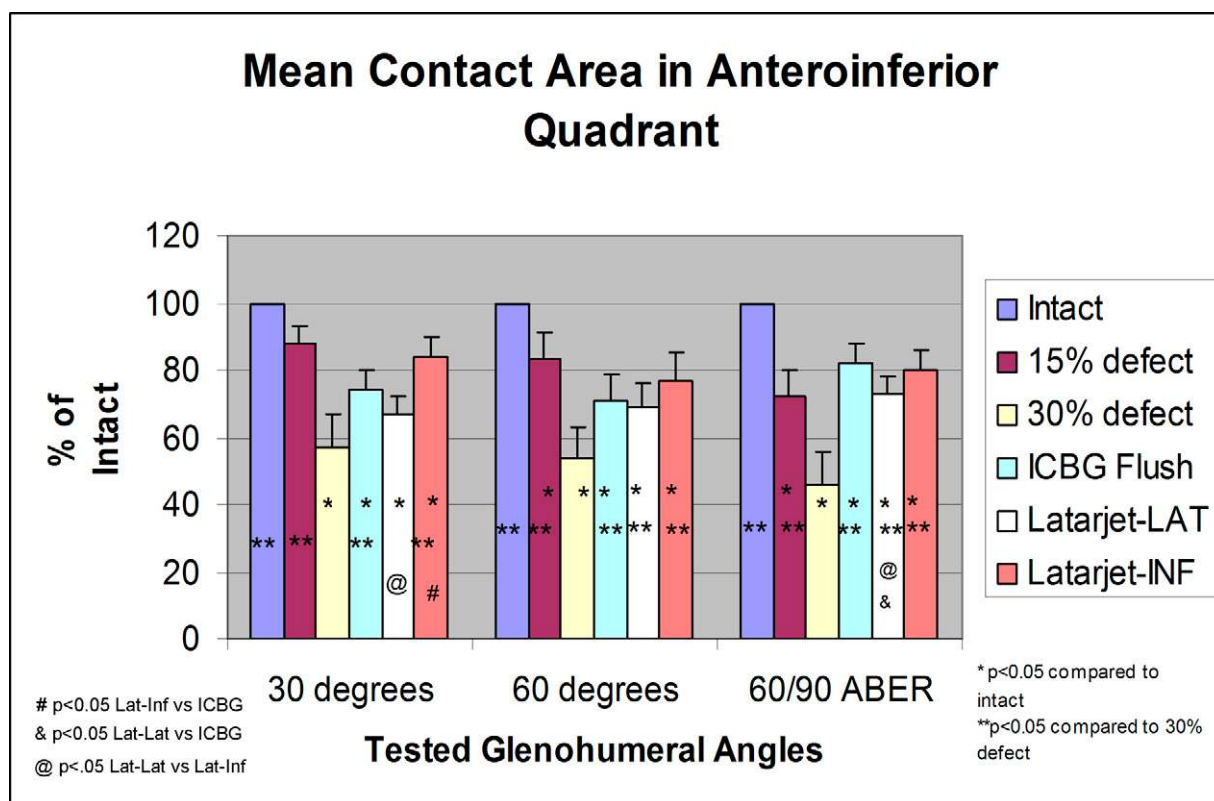
Fig. 7

Mean contact area data for the anteroinferior quadrant of the glenoid at all tested angles under a 440-N load. Results are presented in relation to the intact condition. 60/90 ABER = 60° of abduction and 90° of external rotation, ICBG = iliac crest bone graft, Lat-Inf = Latarjet-INF, and Lat-Lat = Latarjet-LAT.

of the glenoid at 60° of abduction and 90° of external rotation. With the Latarjet-LAT and iliac crest bone grafts placed in a recessed position (2 mm medial to the glenoid articular surface), there was no significant difference in the magnitude or location of the contact pressure compared with the values associated with the 30% glenoid defect (see Appendix). There was no significant difference between the Latarjet-LAT and iliac crest bone grafts, in either the recessed or the proud position, with regard to the restoration of the peak contact pressure to the intact state.

There was an increase in the mean peak contact pressure with progressive bone loss in three of the four quadrants (anteroinferior, anterosuperior, and posteroinferior) as well as a decrease in the mean contact pressure in the posterosuperior quadrant. There was a shift of the center of pressure to the posterosuperior quadrant of the glenoid in specimens with proud placement of the bone graft (see Appendix). At 60° of abduction and 90° of external rotation, Tekscan mapping revealed a significant ($p < 0.05$) anteroinferior shift of the center of pressure of specimens with a defect. A 30% glenoid defect increased the peak contact pressure significantly in the anterosuperior quadrant by a mean of 86% when compared with the pressure in the intact condition at 60° of abduction and 90° of external rotation. Flush placement of the Latarjet-LAT, Latarjet-INF, and iliac crest bone grafts resulted in significant increases in anterosuperior mean

contact pressure of 31%, 22%, and 18%, respectively, compared with the values in the intact state (see Appendix).

Contact Area at 30° and 60° of Abduction, and 60° of Abduction with 90° of External Rotation

Changes in the mean contact area in the intact, defect, and optimally placed graft conditions were most notable in the anteroinferior quadrant (Fig. 7). After creation of a 30% defect, the measured contact areas in the anteroinferior quadrant decreased significantly. At 60° of abduction and 90° of external rotation, specimens with a defect had increased edge-loading at the cut surface. In the same testing position, the flush bone grafts led to a significant restoration of the contact area to the intact condition as compared with the 30% defect condition ($p < 0.05$) (Table I).

Latarjet and iliac crest bone grafts placed 2 mm proud in relation to the glenoid articular surface did not restore the contact area to the intact state. Proud placement of both the Latarjet and the iliac crest bone grafts led to a significant shift in the contact area to the posterosuperior quadrant of the glenoid at 60° of abduction and 90° of external rotation (see Appendix). When the Latarjet and iliac crest bone grafts were recessed 2 mm in relation to the glenoid articular surface, neither the contact area nor the contact location differed significantly from those in the 30% glenoid defect state.

Glenoid Bone Reconstruction

The measured anterior-posterior diameter of the glenoid was 27.7 ± 1.6 mm in the intact state, 18 ± 1.3 mm after creation of a 30% anterior glenoid defect, 25.3 ± 1.1 mm after glenoid bone augmentation with the Latarjet-LAT bone block, and 27.9 ± 1.4 mm after augmentation with the Latarjet-INF bone block. Reconstruction with the Latarjet-LAT bone block restored the anterior-posterior diameter of the glenoid bone to within 5% of the intact value, whereas placement of the Latarjet-INF bone block resulted in complete restoration of the diameter to the intact state.

Discussion

The principal findings in this study confirm our hypothesis that, compared with the Latarjet-LAT bone block, the Latarjet-INF and iliac crest bone grafts, placed in a flush position, are better able to restore glenohumeral loading mechanics to the intact condition. However, the Latarjet-LAT procedure led to significant restoration of contact pressure and area compared with the values found with the clinically relevant 30% anterior glenoid defect. In addition, our goal to determine whether variations in placement of a glenoid bone graft can alter glenohumeral mechanics was met as our data show that grafts placed 2 mm lateral to the glenoid face increased contact pressure in the posterosuperior quadrant as the humeral head strikes the bone block. Grafts placed in a recessed position resulted in no significant difference in contact pressure or edge-loading compared with the values in the defect state. In addition, we confirmed our hypothesis that augmentation of glenoid bone with the Latarjet-INF bone block provides greater restoration of the glenoid diameter (closer to the intact state) than does the Latarjet-LAT bone block. To our knowledge, this is the first study reported in the literature to demonstrate the changes in glenohumeral loading mechanics in a clinically relevant anterior instability and glenoid reconstruction model.

The observed changes in glenohumeral loading mechanics in this study can be attributed to the anatomical variations in graft type and placement. The fact that the Latarjet-LAT bone block resulted in less restoration of pressure to the intact state than did the Latarjet-INF and iliac crest bone grafts is likely due to the osseous incongruity and decreased surface area of the lateral aspect of the coracoid. With the Latarjet-LAT procedure, the lateral portion of the coracoid is juxtaposed to the face of the glenoid and the rough osseous incongruity of the lateral coracoid surface leads to increased contact pressure during glenohumeral loading. The lateral surface area of the coracoid is 24% smaller than the inferior surface area, which corresponds to our data showing an approximately 25% decrease in contact area between the Latarjet-LAT and Latarjet-INF conditions. When the arm is in a position of abduction and external rotation, there is increased contact pressure in the anteroinferior quadrant[21]. The bone block, when placed in a proud position, does not allow proper seating of the humeral head on the glenoid and pushes the humeral head to the posterosuperior aspect of the glenoid during arm abduction and external ro-

tation. With a graft placed only 2 mm medial to the glenoid face, there is no reconstruction of the glenoid articular surface and no osseous block to anterior glenohumeral translation during arm abduction and external rotation. Our results confirm this finding as there were no significant differences in contact pressure and edge-loading between the defect and recessed-graft states.

To our knowledge, there has been no study in the literature that has demonstrated the degree to which the Latarjet procedure restores the anterior-posterior diameter of the glenoid bone to the intact state. Our findings show that the Latarjet-INF graft position completely restores the anterior-posterior glenoid bone diameter to the intact state, whereas the Latarjet-LAT position restores it to within 5% of the intact state. These results indicate that the greater surface area provided by the inferior surface of the coracoid, compared with that provided by the lateral coracoid surface, leads to better restoration of glenoid bone area. The complete restoration of the anterior-posterior glenoid diameter after the Latarjet-INF procedure suggests that that procedure has greater potential clinical utility than the Latarjet-LAT procedure.

Reconstruction with a Latarjet or iliac crest bone graft is currently recommended for addressing glenoid bone deficiency[13,22-24]. The reported clinical results of these two procedures do not indicate that either provides a clear advantage over the other and do not delineate the optimal orientation of these grafts[2,3,6,7,25-27]. In a recent biomechanical study of reconstruction of large anteroinferior glenoid defects, Wellmann et al. showed that the Latarjet procedure outperformed a contoured iliac crest bone graft in terms of reducing translation[28]. They also demonstrated an advantage of the Latarjet procedure compared with an iliac crest bone graft at 60° of glenohumeral abduction. Montgomery et al. documented the degrees of restoration of glenohumeral stability with variations in the placement of the bone graft on the glenoid[29]. Our data, which show an increase in posterior glenoid contact pressure with lateral placement of the bone graft, confirmed the results of the study performed by Montgomery et al. This posterior shift of glenohumeral contact pressure can have important clinical implications in terms of compromised stability and an increased risk of osteoarthritis. Montgomery et al. also demonstrated that a 6-mm-thick bone block is necessary to restore osseous stability in the repair of a clinically relevant defect. Thus, the mean 7-mm thickness used in our study is greater than the minimal thickness required to restore osseous stability and helps to validate our results in this glenoid cavity compression model of glenohumeral instability.

In addition to providing stability, bone-grafting allows normalization of contact pressures to those in the intact state[21]. In a study of contact pressure changes in an anteroinferior glenoid bone-loss model, Greis et al. reported that a 30% glenoid defect increased anteroinferior contact pressures 300% to 400%[21]. These results suggest that a potential long-term consequence of shoulder instability is osteoarthritis, further highlighting the importance of delineating the optimal graft choice and orientation during glenoid reconstruction. The

changes in glenohumeral loading mechanics that we observed with glenoid bone defects in the present study were similar to those previously reported by Greis et al. Our measurements of contact areas and contact pressure at 30° and 60° of abduction of the glenolabral complex with a 440-N load were comparable with the values recorded by Greis et al. In addition, the increase in edge-loading and the anteroinferior shift of glenohumeral contact pressure after the creation of a glenoid defect were consistent with the findings of Greis et al. It is important to emphasize that our biomechanical study differs from previous studies in that we tested a clinically relevant anterior glenoid defect in addition to glenoid reconstruction with a Latarjet graft or an iliac crest bone graft placed in various positions.

There were several limitations to this study. The shoulder instability model, which has been used in previous studies[21,30,31], does not allow dynamic evaluation of muscles and ligaments involved in shoulder stability. Although our data suggest that certain constructs can lead to a shift in peak pressure from the anteroinferior quadrant to the posterosuperior quadrant, these conditions may differ substantially in patients with an intact glenohumeral capsule. While glenohumeral instability can result from glenoid defects of many sizes, we studied only 15% and 30% glenoid defects. Although our reconstructions were randomized, we used the same specimen to perform the Latarjet and iliac crest bone graft reconstructions. Secondary to financial limitations and to a decrease in bone stock—leading to an inability to maintain fixation—with repetitive use of the coracoid, the Latarjet-INF bone block was tested in only a flush position. In addition, we performed the Latarjet procedure without transfer of the conjoined tendon with the coracoid, which would have allowed the tendon to act as a sling to help prevent shoulder dislocation.

In conclusion, placement of a Latarjet-INF or iliac crest bone graft in a flush position was the best technique for normalizing glenohumeral contact pressures. Compared with the Latarjet-LAT bone block, the Latarjet-INF graft provided greater surface area and increased congruity to the native glenoid as well as better restoration of the anterior-posterior glenoid diameter. Grafts placed in a proud position led to increased contact pressure in the posterosuperior quadrant, whereas grafts placed in a recessed position led to increased pressure and edge-loading in the anteroinferior quadrant. Thus, our findings indicate the clinical utility of flush placement of an iliac crest bone graft and utilization of the inferior surface of the coracoid of a Latarjet graft as the glenoid face for glenoid bone augmentation.

Appendix

eA A table showing the center of glenohumeral contact pressure in 60° of abduction and 90° of external rotation with the grafts 2 mm proud, flush, or recessed 2 mm is available with the electronic version of this article on our web site at jbjs.org (go to the article citation and click on "Supporting Data"). ■

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