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The ability of massive osteochondral allografts from the medial tibial plateau to reproduce normal joint contact pressures after glenoid resurfacing: the effect of computed tomography matching

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Background: Current techniques for resurfacing of the glenoid in the treatment of arthritis are unpredictable. Computed tomography (CT) studies have demonstrated that the medial tibial plateau has close similarity to the glenoid. The purpose of this study was to assess contact pressures of transplanted massive tibial osteochondral allografts to resurface the glenoid without and with CT matching.

Methods: Ten unmatched cadaveric tibiae were used to resurface 10 cadaveric glenoids with osteochondral allografts. Five cadaveric tibiae and glenoids were CT matched and studied. An internal control group of 4 matched pairs of glenoids, with the contralateral glenoid transplanted to the opposite glenoid, was also included as a best-case scenario to measure the effects of the surgical technique. All glenoids were tested before and after grafting at different abduction and rotation angles, with recording of peak contact pressures.

Results: Peak contact pressures were not different from the intact state in the autografted group but were increased in both allografted groups. CT-matched tibial grafts had lower peak pressures than unmatched grafts. Peak pressures were on average 24.8% (range [18.3%, 29.6%]) greater than in the native glenoids for unmatched allografts, 21.8% ([17.0%, 25.5%]) greater for the matched allografts, and 4.9% ([3.8%, 5.5%]) greater for matched autografts.

Conclusion: Osteochondral grafting from the medial tibial plateau to the glenoid is feasible but results in increased peak contact pressures. The technique is reproducible as defined by the autografted group. Contact pressures between native and allografted glenoids were significantly different. The clinical significance

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remains unknown. Peak pressures experienced by the glenoid seem highly sensitive to deviations from the native glenoid shape.

Level of evidence: Basic Science, Biomechanics.

Keywords: Shoulder osteoarthritis; cartilage restoration; osteochondral grafting; CT matching; medial tibial plateau

Treatment of shoulder arthritis in patients younger than 50 years remains controversial. Total shoulder arthroplasty has limitations in this age group and is frequently avoided because of concerns of premature glenoid component failure. Therefore, a number of joint-preserving, biologic procedures have been attempted, the majority of which have involved nonanatomic soft tissue interpositions to resurface the glenoid. The results of these procedures are generally inconsistent and have not been durable, leading researchers to consider more anatomic reconstruction options.[1,2,5,6,8,19,22]

Anatomic cartilage resurfacing procedures, such as osteochondral grafting, have had good results in the knee, elbow, and shoulder and have demonstrated re-creation of native biomechanics when graft placement is flush.[14,17] However, osteochondral grafting is not as well studied or established in the shoulder. This is, in part, due the large defect sizes often encountered in glenohumeral osteoarthritis that necessitate massive grafts and the difficulty in obtaining glenoid allografts due to limited supply and the considerable risk of infection during procurement. Therefore, alternative graft sources have been used. Rios et al[23] and Gupta et al[15] have shown that the medial tibial plateau is similar in size and curvature to the glenoid when it is assessed with computed tomography (CT) scans, and thus this could be a potential source for osteochondral grafts for glenoid reconstruction. Despite a lack of preclinical data, some surgeons have been using single allograft plugs from the medial tibial plateau or lateral tibial plafond for local glenoid resurfacing.[16] In a study by Gobezie et al,[12] fresh tibial plateau grafts were used to resurface the glenoid as part of a biologic total shoulder replacement, although the grafts were not size and curvature matched to the glenoid and only partially resurfaced the glenoid. Clinical follow-up was also limited to only 1 month, so the longevity of the grafts and the long-term clinical outcomes of this procedure are unknown. Furthermore, it remains unknown whether osteochondral grafting of the glenoid could compromise subsequent glenoid prosthetic replacement. Small plugs may be insufficient to treat the cartilage loss in many cases, and there have been no reports of resurfacing of the entire glenoid with hyaline cartilage.

The purpose of this study therefore was to assess contact pressures of transplanted massive osteochondral allografts harvested from the medial tibial plateau to resurface the glenoid. In addition, CT matching was used to determine if this would improve biomechanical results. Intact glenoids were compared with glenoids grafted with unmatched medial tibial plateaus and CT-matched medial tibial plateau grafts. The precision of the surgical technique was assessed by transferring the contralateral glenoid as the donor to the opposite glenoid as the recipient in a right and left matched pair to serve as an internal control. The principal outcome measure was peak contact pressures relative to the native intact state. Secondarily, we evaluated the stability of the grafts by qualitative measures.

Materials and methods

Specimen preparation

Nonmatched allografts (group 1)

Ten fresh frozen shoulders (6 female, 4 male) with a mean age (standard deviation [SD], range) of 56.6 years (10.2, 33-65) without evidence of osteoarthritis were dissected free of all soft tissue. An oscillating saw was used to osteotomize the scapulae perpendicular to the glenoid surface, 5 cm distal to the glenoid. The humeri were osteotomized 15 cm distal to the surgical neck. The scapulae and humeri were then potted in polymethyl methacrylate (Fricke Dental International Inc., Streamwood, IL, USA) with use of cylindrical molds. The glenoid surfaces were aligned parallel to the base. The humeri were potted 2 cm proximal to the surgical neck to minimize bending moments. Ten medial tibial plateaus (3 female, 7 male) with a mean age (SD, range) of 51.5 years (9.6, 28-62) were dissected free of all soft tissue and matched to each glenoid on the basis of macroscopic observations of similar size and curvature. Two specimens were later excluded because of fracture of the humerus during biomechanical testing (Table I).

CT-matched allografts (group 2)

On the basis of prior CT studies,[15,23] matching of the radius of curvature was performed to minimize the incongruencies of the surfaces. By use of three-dimensionally (3D) reconstructed CT scans (Aquilion Premium; Toshiba America Medical Systems, Inc., Tustin, CA, USA), the surface curvatures of 8 glenoids and 12 tibial plateaus were assessed according to the method described by Rios et al[23] (Fig. 1). The 5 best matching pairs of glenoids and medial tibial plateaus were selected and prepared as described before. The mean age (SD, range, gender) was 44.8 years (13.0,

Table I Group distribution and surgical setting, graft matching, and configuration

Groups	Nonmatched allografts	CT-matched allografts	Matched autografts
Setting	Glenoid–tibial plateau (unmatched)	Glenoid–tibial plateau (CT matched)	Glenoid–glenoid (CT matched)
Graft configuration	2-plug–snowman	2-plug–snowman	2-plug–snowman
No. of specimens	10	5	4

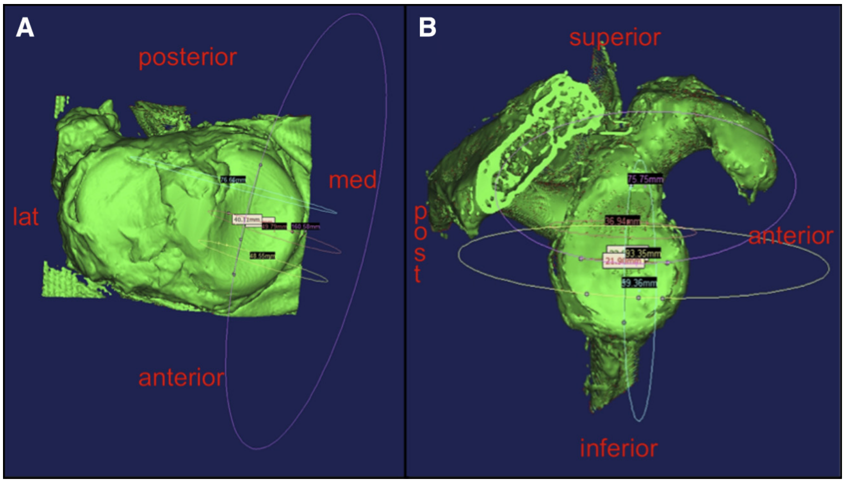

Figure 1 The 3D reconstructed CT scans and measurements (radii of curvature) of the medial tibial plateau (**A**) and the glenoid (**B**).

23-57, 5 male) for the glenoid specimens in group 2 and 55.6 years (6.4, 50-66, 4 male) for the tibia specimens.

Matched, paired glenoid autografts (glenoid to glenoid)—internal control (group 3)

Four matched pairs of glenoids with a mean age (SD, range, gender) of 48 years (6.9, 37-54, 4 female) were used to assess the limits of the surgical technique. This arm of the study was performed to simulate the ideal graft surface and to determine the effects of the surgical technique. To ensure that each pair was similar in geometry, 3D reconstructed CT scans were obtained of those 8 specimens, and the radii of curvature at appropriate surface regions were compared.

CT matching process

For groups 2 and 3, CT scans representing slices of 0.5-mm thickness with a resolution of 512 × 512 pixels were obtained for all specimens (glenoids and medial tibial plateaus), and 3D geometries were reconstructed with Mimics version 16.0 software for Windows (Materialise, Leuven, Belgium). Geometric measurements were performed, as described by Rios et al.[23] For the glenoids, length was measured from the most superior to the most inferior onset of the cartilage, and width was measured from the most posterior to the most anterior onset of the cartilage. For the medial tibial condyles, length was measured from the most anterior to the most posterior onset of the cartilage, and width was measured from the most lateral to the most medial onset of the cartilage. Lines were drawn for all length and width measurements. Accordingly, parallel lines were then drawn at 25% and 75% of the total length. The radii of curvature were calculated with 3 points on each created line to form a circle: the 2 highest (most prominent) points on the articular surface and the deepest point in between. Thus, every surface was systematically defined through 6 measurements (Fig. 1). For group 2, the 5 best matching pairs of glenoids and tibiae were chosen empirically by minimizing the mean square difference between the tibia and glenoid measurements.

Surgical technique

The sizing guide from the osteochondral autograft transfer system (OATS; Arthrex, Naples, FL, USA) was used to select an appropriately sized plug to fit the inferior aspect of the glenoid, ensuring a 2-mm rim of native bone for stability of the grafts. For the nonmatched allograft specimens (group 1), a 20-mm sizer was appropriate in all but 1 specimen, for which a 15-mm sizer was used. For the CT-matched allograft group (group 2), a 20-mm sizer was used for all specimens. Finally, for the matched, paired autografts (group 3), a 15-mm sizer was used for all specimens. A guide pin was drilled parallel to the articular surface through the sizing guide. The corresponding reamer was then placed on the guide pin, and a recipient site was reamed to a depth of 10 mm of subchondral bone. The corresponding harvesting reamer was then used to harvest an osteochondral plug from the posterior medial tibial plateau. The depths of 4 sides of the recipient site and donor graft were matched to within 1-mm increments. The plugs were placed into the glenoid recipient site according to the positions from which they were harvested and secured with a combination of manual pressure and light mallet taps. The following orientations were used:

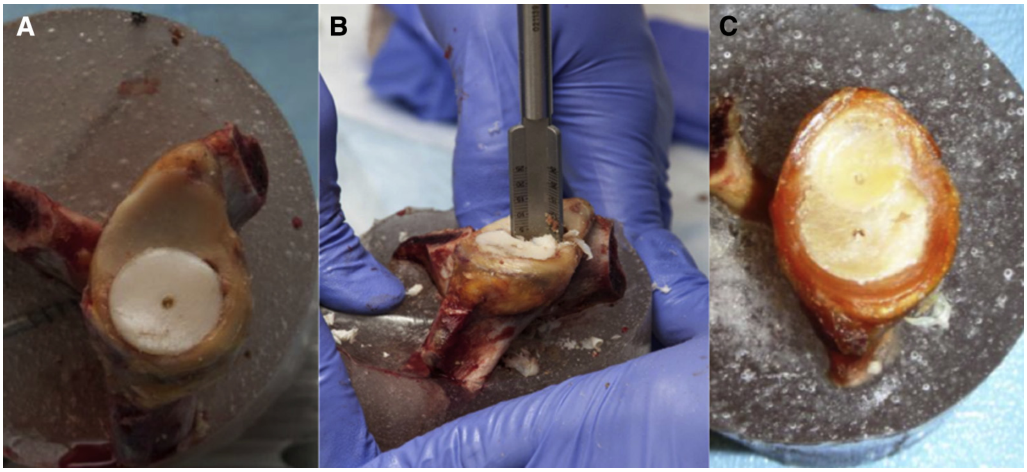

Figure 2 (**A**) Initial placement of the larger plug into the inferior glenoid. (**B**) Subsequent reaming into the graft to create the multiplug ''snowman'' configuration. (**C**) Final appearance of the multiplug snowman grafted glenoid.

Glenoid superior » tibia posterior
Glenoid inferior » tibia anterior
Glenoid posterior » tibia lateral
Glenoid anterior » tibia medial

This procedure was then repeated to resurface the superior aspect of the glenoid. A smaller plug (15 mm) was used in all cases. Because of the elliptical shape of the glenoid, adequate resurfacing required overlap of the osteochondral plugs. The larger plug and the native glenoid were reamed to accommodate the smaller plug (Fig. 2). In the matched autograft group (group 3), the same technique was used. The inferior graft was implanted with the following orientation:

Donor superior » recipient inferior
Donor inferior » recipient superior
Donor anterior » recipient posterior
Donor posterior » recipient anterior

The superior graft was then harvested and transplanted, oriented in the exact same manner.

Biomechanical testing

All glenoids were tested with their corresponding humeri. A custom-made fixture secured the humerus to the base of the test frame (ElectroPuls E10000; Instron, Norwood, MA, USA) and allowed external rotation and abduction angles to be accurately selected and locked into place while also allowing freedom of motion in the sagittal plane to settle the humeral head into the glenoid by sliding on linear bearing plates (Fig. 3). Glenoids were rigidly fixed to the load actuator of the test frame, with the face of the glenoid parallel to the base. Pressure sensors (Model 4000; Tekscan, Inc., South Boston, MA, USA) were positioned between the glenoid and humeral head. A new sensor was used for each glenoid and was calibrated with a single point load using a jig with the same surface area and stiffness as anticipated with the glenohumeral joint with 400 N of force under load for 30 seconds.

A 10 N axial compressive load was first applied to center the humeral head in the concavity of the glenoid. The load was then increased to 440 N during 10 seconds and held for 30 seconds, at which point the contact pressure was recorded. This load mimics the maximum compressive loads experienced by the shoulder during activities of daily living.[11,13] This was performed at abduction angles of 0°, 30°, 60°, and 90° with the shoulder in −45°, 0°, and 45° of external rotation (Fig. 3). The angles were tested in random order for each specimen, and the same order was repeated after the OATS procedure. The testing was performed on the native glenoids first. Osteochondral grafts were then transplanted, and testing was repeated following the same protocol.

Statistical analysis

For each treatment group, a linear mixed-effects model was constructed with 3 repeated measures variables as explanatory factors of peak pressure—status (intact vs. graft), abduction angle, and rotation angle. This method allowed pooling of evidence across abduction and rotation angles for our primary comparison of interest, peak pressure observed in intact vs. grafted glenoids. Pairwise comparisons of levels within each factor were made post hoc with a Bonferroni correction. Residual diagnostics were performed to check the validity of model assumptions. *P* values $< .05$ were deemed significant. All statistical analyses were performed with SPSS Statistics, version 20 (IBM, Armonk, NY, USA).

Results

All 19 glenoids [mean age (SD, range, gender), 49.8 years (11.5, 23-65, 7 female, 12 male)] underwent testing with and without multiplug snowman osteochondral grafts. In group 1, 2 of the humeri fractured during testing at lower abduction angles from increased bending stresses. The data from the fractured specimens were excluded. In group 3, 1 pair of glenoids turned out to appear severely osteoarthritic after dissection. This pair was also excluded.

For all 3 models, the effect of glenoid grafting on peak pressure did not depend on the combination of abduction and rotation angle (insignificant interaction terms). Thus, the effect of grafting on peak pressure could be estimated as a single constant value across all angle conditions. Mean

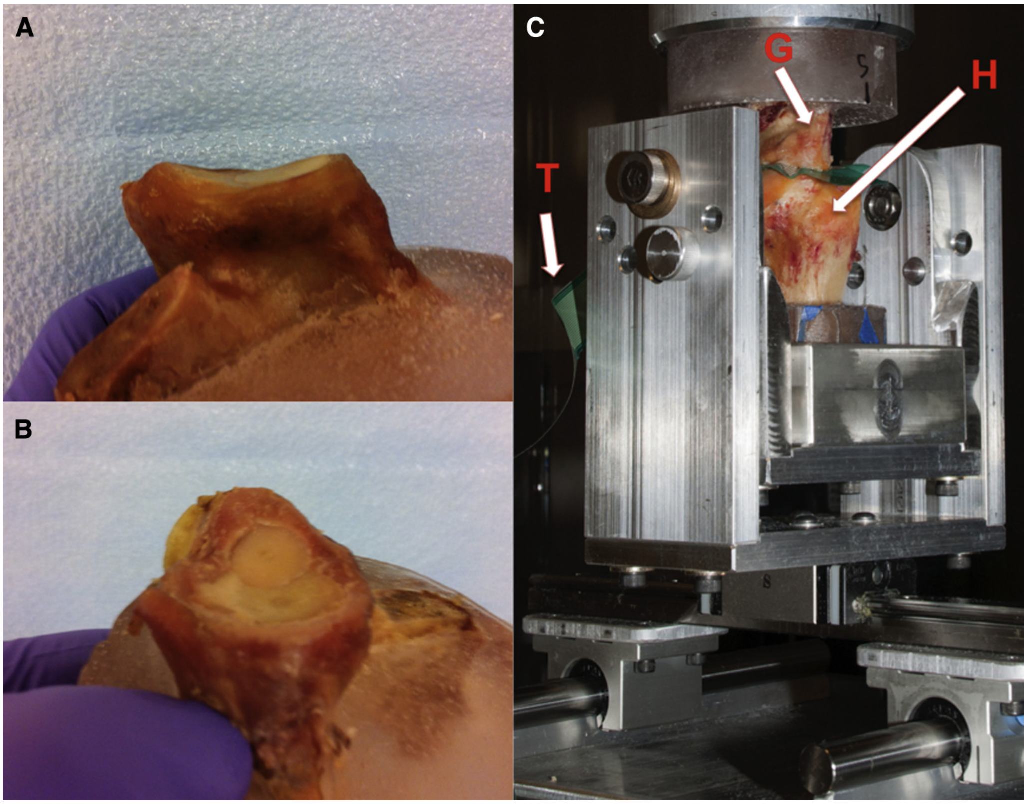

Figure 3 Example of the multiplug "snowman" technique for a glenoid osteochondral allograft showing 2 overlapping grafts with views from medial (**A**) and lateral (**B**). **C**, Test setting with the humerus (*H*) mounted in the fixture, glenoid (*G*) placed atop the humeral head in 90° of abduction, and Tekscan (*T*) in between.

peak pressure values for each group along with 95% confidence intervals (CIs) are presented in Figure 4, stratified by status, abduction angle, and rotation angle.

Status

For the nonmatched allografts (group 1), the grafted glenoid produced significantly higher peak pressure than the paired intact specimen (effect estimate = 79.0 N/mm^2; P = .004; 95% CI [26.6, 131.4]). Among the 12 rotation/abduction angle combinations, this effect estimate corresponds to a median 24.8% increase in peak pressure (range [18.3, 29.6]) over the intact glenoid. The CT-matched allografts (group 2) performed better with lower peak pressures but also had increased peak pressures relative to the intact glenoid (effect estimate = 72.0 N/mm^2; P = .004; 95% CI [25.9, 117.9]). Among the 12 rotation/abduction angle combinations, this corresponds to a median 21.8% increase (range [17.0, 25.5]). Meanwhile, the matched, paired autografts (group 3) performed best and had peak pressures similar to those of their paired intact glenoids (effect estimate = 18.7 N/mm^2; P = .336; 95% CI [−20.8, +58.1]), a median increase of 4.9% (range [3.8, 5.5]) over the intact glenoid among all rotation/abduction angle combinations. Percentage increases in peak pressure measurements between intact and grafted glenoids are presented in Table II.

Abduction and rotation angle

Abduction angle significantly affected peak pressure in the nonmatched allografts and CT-matched autografts (groups 1 and 3). In both cases, 0° abduction produced higher peak pressures than 30°, 60°, and 90°, with effect estimates ranging from 63 to 124 N/mm^2 (Bonferroni post hoc comparisons, all $P < .05$). No significant abduction angle effect was observed for the CT-matched allografts (group 2).

Rotation angle also significantly affected peak pressure in the nonmatched allografts and CT-matched autografts (groups 1 and 3). In the nonmatched allografts (group 1), internal rotation produced significantly lower peak pressures than the neutral or externally rotated positions (Bonferroni post hoc comparisons, each $P < .001$). Among the matched, paired autografts (group 3), external rotation exhibited higher peak pressures than the neutral position (Bonferroni post hoc comparison, P = .034). These significant rotation angle effect estimates ranged between 33 and 51 N/mm^2. No significant rotation angle effect was observed for the CT-matched allografts (group 2).

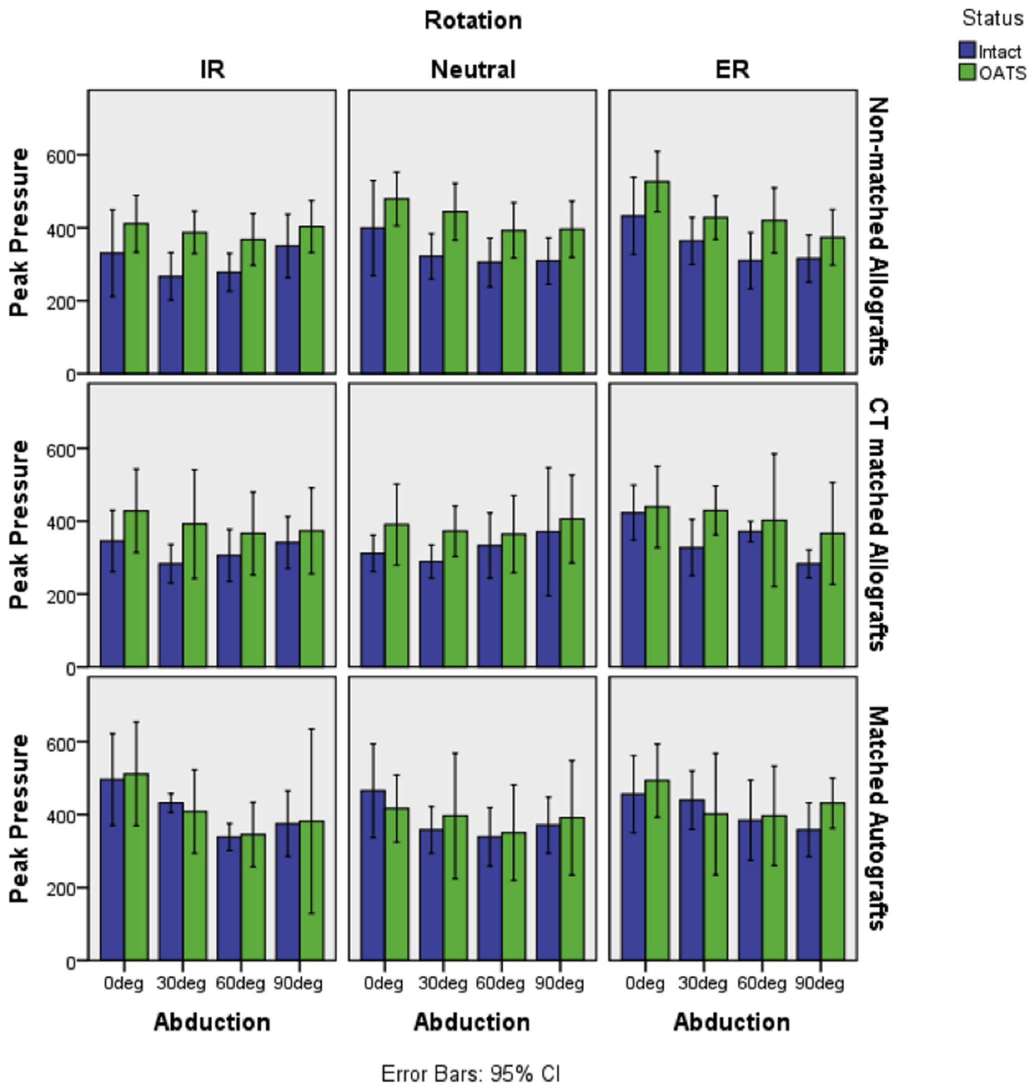

Figure 4 Mean peak pressure (N/mm^2) for intact and OATS glenoids and for each of the 3 graft type groups, stratified by abduction and rotation angle. *Error bars* represent the 95% confidence interval (*CI*) of the mean. *IR*, internal rotation; *ER*, external rotation.

CT match optimization results

The optimal matching of glenoid-tibia pairs for group 2 produced mean differences of 0.78 mm and 2.20 mm in the width at 50% and radius width at 75%, respectively. Pearson correlation between glenoid surface and tibia transplant shape measurements of the 5 glenoid-tibia pairs was 0.96 and 0.99 for the same 2 measurements, respectively.

Discussion

The most important findings of this study were that peak contact pressures after the osteochondral *auto*grafting procedure did not differ from the intact state in matched, paired glenoids with similar surface topography (group 3) and that CT-matched medial tibial osteochondral *allo*grafts had lower peak pressures than unmatched grafts, but the differences were not statistically different. Qualitatively, resurfacing of the glenoid by transplanting massive osteochondral allografts from the medial tibial plateau was technically feasible and resulted in stable grafting. Harvesting of the graft from the tibial plateau, both with visual matching and with CT matching, increased peak contact pressures by 24.8% and 21.8%, respectively. Grafting of the glenoid with a graft from the contralateral side did restore the biomechanics to nearly normal. These results suggest that whereas the surgical technique works well, use of the medial tibial plateau as an allograft increases peak contact pressures. Whether this is clinically relevant is unknown. Perhaps improved surface matching techniques or new graft harvest sites should be investigated, particularly when massive osteochondral grafts are used.

On average, there were increases in peak pressures for both nonmatched and CT-matched allografted glenoid groups compared with the intact state (groups 1 and 2). The

Table II Mean percentage increase in peak pressure between intact and OATS grafted glenoid, stratified by graft type, rotation angle, and abduction angle

Percentage increase in peak pressure after OATS graft	Internal rotation			Neutral rotation			External rotation		
	Mean % increase	95% CI of mean		Mean % increase	95% CI of mean		Mean % increase	95% CI of mean	
		LB	UB		LB	UB		LB	UB
Nonmatched allografts (n = 8)									
Abduction = 0°	33.2	6.3	60.2	32.9	−7.6	73.3	31.3	−9.7	72.3
Abduction = 30°	50.9	23.0	78.8	40.0	19.4	60.5	19.2	3.3	35.1
Abduction = 60°	35.2	10.7	59.7	31.4	7.7	55.1	39.2	15.4	63.0
Abduction = 90°	23.3	−10.3	57.0	31.5	5.6	57.3	22.5	−1.8	46.8
CT-matched allografts (n = 5)									
Abduction = 0°	26.6	−6.8	60.0	25.1	−3.2	53.4	4.3	−18.0	26.6
Abduction = 30°	37.4	−0.5	75.2	30.2	−1.1	61.5	34.3	1.6	67.1
Abduction = 60°	23.5	−24.4	71.5	11.3	−19.2	41.8	9.9	−46.2	66.0
Abduction = 90°	12.5	−31.0	56.0	21.0	−38.1	80.2	30.6	−21.8	82.9
Matched autografts (n = 4)									
Abduction = 0°	3.7	−21.9	29.2	−8.2	−44.7	28.3	10.4	−28.8	49.6
Abduction = 30°	−5.7	−29.6	18.2	14.1	−56.9	85.1	−7.3	−51.3	36.6
Abduction = 60°	2.5	−26.0	31.0	7.3	−55.6	70.1	4.5	−28.9	37.8
Abduction = 90°	−2.5	−35.3	30.2	6.6	−37.9	51.2	22.8	−17.1	62.7

LB, lower bound of 95% confidence interval of the mean; *UB*, upper bound of 95% confidence interval of the mean.

matched, paired autografted glenoids (group 3) had similar peak pressures in native and grafted states.

One possible explanation for the increases in peak pressures after allografting might be geometric differences in the shape of the graft compared with the shape of the native intact glenoid. Another possible cause could be the differences in cartilage thickness. Cartilage thickness of the glenoid has been reported to be around 1.5 to 2 mm on average, and it is thicker peripherally and thinner centrally at the bare area.[27] The cartilage thickness of the tibial plateau is relatively uniform and demonstrates a thickness around 2.5 to 3 mm.[3] In our study, we did not measure cartilage thickness. However, implantation of a thicker layer of cartilage from the graft in the region where the bare area of the glenoid is typically located may have contributed to the differences in peak pressures and may be a potential reason for the differences that were measured.

Treatment of glenohumeral osteoarthritis in the active, young patient remains controversial. Total shoulder arthroplasty is not ideal as there are concerns about durability and risk of premature failure of the glenoid component.[20] Hemiarthroplasty is also not ideal, as less favorable clinical results and higher revision rates have been seen, often due to pain from residual osteoarthritis on the unresurfaced glenoid.[4] For this reason, nonarthroplasty treatment options for glenoid osteoarthritis have been investigated.[20]

Several techniques have been described for resurfacing of the glenoid.[9,16,18,22,24,25] The majority of these techniques have used some type of soft tissue interposition, with limited reports on osteochondral grafting.[16,25] Krishnan et al[18] reported on 2- to 15-year results of 36 shoulders treated with hemiarthroplasty with soft tissue resurfacing of the glenoid with interposition of capsule, Achilles allograft, or fascia lata autograft. The average American Shoulder and Elbow Surgeons score at final follow-up was 91 with a 90% satisfaction rate. Conversely, Elhassan et al[9] described 13 patients younger than 50 years who underwent treatment with glenoid soft tissue, interposition grafts, and humeral prosthetic replacements. Poor results were the norm, with 10 of the 13 patients requiring revision to total shoulder arthroplasty at an average of 14 months after surgery. They concluded that soft tissue resurfacing was an unreliable procedure to treat glenohumeral arthritis in the young patient. Similarly poor results have been reported by others with similar techniques, emphasizing the need for alternative biologic, joint-preserving techniques.[9,16,22,24]

The ideal graft source for massive glenoid resurfacing would be an allograft glenoid with bone and articular cartilage. Complete glenoid resurfacing with an allograft glenoid has been biomechanically evaluated in a sheep model and has shown stability with press-fit fixation.[10] In addition, the present study demonstrated biomechanically that autografts taken from the contralateral shoulder restore peak contact pressures to intact levels. However, fresh glenoid allografts are not widely available in the United States.[23] In fact, in our experience, it has been nearly impossible to obtain a fresh osteochondral glenoid allograft for clinical use. The suppliers of these osteochondral grafts cite an unacceptably high contamination rate with harvest due to the proximity to the axilla and the chest wall. Therefore, we proposed a new technique to resurface the entire glenoid surface, using two osteochondral plugs placed in the "snowman" configuration from the medial tibial plateau. We chose the medial tibial plateau because the medial tibial plateau is readily available, is offered as a fresh allograft, and has been shown from previous work using 3D CT scans from our laboratory and others to have a shape that is similar in size and curvature to the glenoid.[15,23] Furthermore, the technique of osteochondral allograft transplantation is widely used and allowed us to use readily available, reliable, familiar, and precise instrumentation. Finally, a single-plug technique with fresh osteochondral medial tibial plateau allografts is already being used clinically to partially resurface the glenoid, although before this study there had been no biomechanical data to support this approach.[12]

This experiment has substantiated previous reports that glenohumeral conformity and contact patterns vary with changes in abduction and rotation.[7,26] In our study, however, there was appreciable variability across specimens. This has been reported in native shoulders and possibly played a role in our results.[7] Our study has shown that the glenoid has sufficient bone stock to support massive, osteochondral grafting and that the grafts were qualitatively stable with press-fit fixation. It took considerable effort to remove the osteochondral plugs after testing. Removal of the grafts necessitated drilling into the grafts to a depth deeper than the width of the graft and using a tool to pry the grafts loose. A clinical scenario that mimics this type of pullout force is almost inconceivable. In addition, the normal concavity-compression force seen in the shoulder joint would actually enhance stability. It is unknown, however, how such grafts would perform in an arthritic shoulder, in a shoulder with bone loss, or in one in which there has been an acquired dysplasia or retroversion of the glenoid—all important and relatively common clinical scenarios.

Despite their stability, the medial tibial plateau grafts did not consistently restore native peak contact pressures under a load similar to that observed with activities of daily living. Although CT matching did improve results, higher peak contact pressures were observed, even when the medial tibial plateaus were CT matched for radius of curvature with the glenoids. Possible reasons for the observed differences between the native and medial tibial plateau grafted glenoids include very small graft height mismatches at the interface between the 2 snowman grafts, shape or curvature differences between the glenoid and the medial tibial plateau, or both. Even with 3D CT matching to minimize differences in shape or curvature (group 2), there were still elevations in peak contact pressures. However, the clinical implications of this are unknown, and whether grafts could tolerate such pressure differences is unknown. From a qualitative surgical visual and tactile perspective, the grafts looked and felt good. According to previous described matching techniques,[21,23] the articular surface of every specimen was constituted by means of 6 different measurements with 3D reconstructed CT scans and therefore made comparable. CT scans can be acquired easily, are not complex procedurally, and are not time-consuming. Furthermore, measurements can be conducted with common software. Of a pool of 8 glenoids and 12 tibial plateaus, the 5 best matching pairs were assembled. We believe the method used was reliable as the generated pairs appeared to match very well by visual and tactile inspection. However, this study was not designed to compare various graft types, and this should therefore be investigated further as there may be other better osteochondral allograft sources.

As for surgical technique, we believe this was optimized. A standardized method was used in all cases. We do not believe technical issues influenced our results adversely as our technique was highly reproducible, measurements of graft depth were meticulous and to the millimeter, and all of the grafts appeared flush, being confirmed visually and with direct palpation. These observations were also confirmed biomechanically, with the inclusion of the matched, paired group (group 3), where grafts were taken from the contralateral glenoid and implanted into the recipient glenoid to isolate the influence of the technique. In this arm, test specimens exhibited similar peak pressures compared with their native intact controls. This arm demonstrated the small and relatively negligible effects of the surgical procedure itself. The senior surgeon has experience performing osteochondral allografting clinically and thought that the technical aspects of the procedure were similar to what was being performed routinely in other joints, such as the knee, elbow, and humeral head. All grafts from the study, once implanted, would have been acceptable clinically and were not dissimilar from what would be acceptable in standard clinical practice at present.

The strengths of our study include the clinical applicability, the rigorous design, the testing at multiple shoulder positions, and the 3D CT-based matching of the medial tibial plateaus with the glenoids. The procedure was also highly reproducible and technically feasible. The limitations and weaknesses of this study were the testing setup without any labral or tendinous stabilization tissue attached to the bones and the lack of a quantitative way to measure graft stability. Although no quantitative measure of graft stability was used, we believe that the grafts demonstrated excellent qualitative stability, certainly similar to what is being achieved in other clinical applications of osteochondral grafting. Also, because there were no prior studies, a pre hoc power analysis could not be performed to determine sample size. On the basis of prior CT studies[15,23] and clinical studies[12] that support unmatched grafting, the radius of curvature was matched only qualitatively by visual and tactile inspection in group 1. The 3D reconstructed CTs were used in group 2 to see if biomechanical performance could be improved with more sophisticated 3D CT matching, as opposed to the process of simply using a qualitative assessment.[21,23] Whereas results were improved slightly with CT matching, the geometry of the graft seems more important, given the differences between medial tibia plateau grafts and contralateral glenoid grafts.

Because this is a time zero biomechanical study, the effects of healing and the effects of differences in cartilage thickness or peak pressure differences are completely unknown. It appears that an unmatched medial tibial plateau transplanted to the glenoid produces higher variable differences in contact pressure compared with prior CT-matched constructs. However, as the shoulder is a non–weight-bearing joint, these differences may not be of clinical significance. We make an assumption that restoring peak pressures to normal is ideal, but there may be a threshold below which it is acceptable and above which it is detrimental. Further investigation is certainly needed to determine the clinical implications. On the basis of the results of this study, it certainly seems reasonable to suggest that procurement methods be adapted to allow more availability of fresh glenoid grafts.

Conclusion

The average peak contact pressures were significantly different between the native glenoids and the multiplug, snowman grafted glenoids, and peak pressures increased by 24.8% without CT matching and 21.8% with CT matching. These differences could be the result of multiple factors but seem to be related to microanatomic differences in the structure of the medial tibial plateau and the native glenoid. CT matching of pairs improved the results but did not reduce peak contact pressures to normal levels, and pressures remained highly variable. Multiplug, snowman, massive osteochondral grafting from the medial plateau to the glenoid, by conventional techniques and instrumentation, produced stable grafts that qualitatively resurfaced the glenoid cartilage.

Overall, it is clear that the glenoid contact pressure is sensitive to deviations from the native glenoid architecture. Therefore, if the goal of glenoid restoration is to create a normal biomechanical environment, the size and curvature of the donor tissue, be that medial tibial plateau, allograft glenoid, or some other osteochondral tissue, should match the recipient glenoid as closely as possible. We speculate that optimizing biomechanics and restoring them as close to the native intact state as possible will result in the greatest durability of the grafts with the least cartilage wear. Improved matching may produce a more normal biomechanical environment and should be considered if this technique is used clinically.

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