Feasibility of an osteochondral allograft for biologic glenoid resurfacing

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Background: Concerns regarding insufficient press fit and glenoid vault cortical blowout make glenoid osteochondral allografting uncommon. We used 3-dimensional computed tomography modeling to test glenoid osteochondral allografting feasibility.

Materials and methods: Sixteen cadaveric shoulders without osteoarthritis underwent computed tomography scans to create 3-dimensional models. The diameter of circular center-based reaming reaching the medial endosteal surface at depths of 4, 6, and 8 mm and the clock face position of the most shallow points were calculated. Demographic factors associated with graft diameter were analyzed by step-wise multiple regressions.

Results: Shallower graft depths allowed larger graft diameters ($P < .001$). With a graft depth of 4 mm, 56% of glenoids allowed 20-mm-diameter grafts and 94% accommodated 16-mm grafts versus 31% and 75%, respectively, for a graft depth of 6 mm and 13% and 38%, respectively, for a graft depth of 8 mm. Increasing graft depth decreased graft glenoid coverage: mean coverage was $51.9\% \pm 12.2\%$, $36.3\% \pm 12.9\%$, and $23.8\% \pm 14.2\%$ for 4-, 6-, and 8-mm depths, respectively. The glenoid's most shallow point was between the 1:30 clock face position and 3-o'clock position in reference to a right shoulder in 69%, 75%, and 44% of glenoids for 4-, 6-, and 8-mm depths, respectively. Although female gender, patient height, and glenoid height and width were associated with graft diameter, multiple regression analysis showed that patient height was the only independent variable associated with accommodated graft diameter at depths of 4, 6, and 8 mm ($P = .001$, $P = .001$, and $P = .003$, respectively).

Conclusion: Most glenoids support center-based grafts of 16 to 20 mm in diameter at a depth of 4 mm, covering an average of 51.9% of the glenoid. Accommodated graft size decreases as reaming depth increases.

Level of evidence: Basic Science Study, Anatomy, Cadaver Imaging.
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Keywords: Glenoid; osteochondral allograft; cadaveric study; computed tomography; glenoid-chondral lesion; 3-dimensional

Shoulder pathology such as isolated chondral defects, chondrolysis, osteoarthritis, post-traumatic arthritis, and instability arthropathy can cause shoulder pain and disability in young active patients.[1] Glenoid cartilage loss is discovered in 5% to 17% of diagnostic arthroscopies, although in

many cases the contribution of the glenoid lesion to patient symptomatology is unclear.[7,9,17] In the young active patient, surgical management of symptomatic glenoid chondral lesions is controversial, with outcomes poorly reported in the literature. Management may depend on multiple factors including the presence or absence of bipolar disease, patient age, activity level, expectations, and concomitant shoulder pathology.

For patients unresponsive to nonoperative management including activity modification, physical therapy, nonsteroidal anti-inflammatory medications, and corticosteroid injections,[1,7] surgical treatment can be considered. Although total shoulder arthroplasty has predictable outcomes in older patients, younger patients have up to a 38% incidence of glenoid component failure within 10 years of follow-up.[21] Non-arthroplasty options for young active patients are limited to debridement, capsular release, microfracture, ream and run, autologous chondrocyte implantation, and osteoarticular grafting procedures.[1,2,8,13,18,23] Biologic glenoid resurfacing using anterior capsule, autogenous fascia lata, and lateral meniscal allograft[16] and Achilles tendon allograft can also be considered.[14]

Osteochondral allograft transplantation to the glenoid may be a viable alternative to current treatment methods. Though successful in other joints, press-fit osteochondral allografting of the glenoid has been described only in a few cases.[2,13,18] Concern exists as to whether adequate depth to achieve a stable press fit may result in cortical blowout during reaming. The purpose of this study was to use 3-dimensional (3D) computed tomography (CT) modeling of cadaveric glenoids to determine the maximum graft diameter possible based on a given reamer depth. We elected to study depths of 4, 6, and 8 mm based on a recent biomechanical study that showed glenoid osteochondral allograft press-fit stability with a reaming depth of 4 mm.[10] We hypothesized that as the depth of glenoid reaming increased, the corresponding osteochondral allograft diameter size would become significantly smaller.

Materials and methods

Computed tomography

Nineteen fresh-frozen cadaveric shoulders (Anatomical Service, Schiller Park, IL, USA) were obtained. Demographic data including patient height, weight, age, cause of death, race, and gender were available for each cadaver. Each cadaveric shoulder underwent CT scanning in a General Electric Bright Speed 16 scanner (General Electric Healthcare USA, Waukesha, WI, USA). Raw axial images were obtained in 0.625-mm increments with the following settings: 120 kV, 260 mA, and 512 × 512 matrix. After inspection of the CT images, 3 samples were excluded from further analyses: 2 for radiographic signs of degenerative joint disease and 1 for evidence of widely metastatic blastic lesions. For each of the remaining 16 scans, a combination of thresholding using pixel intensity, region growing, and manual mask manipulation was used

to create a mask for the scapula by use of Mimics (Materialise, Plymouth, MI, USA) (Fig. 1). Automated reconstruction of this mask created a freestanding 3D volumetric image of the scapula, on which a plane was fit to the face of the glenoid as previously described.[4] New "anatomic" axial, coronal, and sagittal slices were created perpendicular to this plane (Fig. 2).

Sample measurement

All measurements were taken from the anatomic slices. By use of the best-fit circle method,[4,11] the 3D location (axial, coronal, and sagittal coordinates) of the center of the glenoid best-fit circle was measured. In addition, we measured the width of the glenoid (in millimeters), as measured on the axial image at the level of the glenoid center; the height of the glenoid (in millimeters), as measured on the coronal image at the level of the glenoid center; the 3D location of most inferior point on the glenoid; and the 3D location of the most superior point on the glenoid.

To simulate reaming for an osteoarticular graft, two sets of 4-, 6-, and 8-mm-long lines were drawn perpendicular to the plane of the glenoid on each slice. These lines were drawn at the anterior and posterior aspects of the glenoid with the medial aspect intersecting the subchondral bone and the lateral aspect intersecting the endosteal surface of the glenoid vault. The 3D location of the subchondral intersection was recorded for each slice, resulting in 6 data points for each slice (Fig. 3, A). These data were then plotted on the en face glenoid view (Fig. 3, B).

All 3D data point analyses was performed in Excel X (Microsoft, Redmond, WA, USA). The radial distance between the glenoid center and the subchondral location of each depth measurement was then calculated. The clock face location of each of these points was also calculated based on a right glenoid as our reference, with 12 o'clock set as the most superior aspect of the glenoid as visualized on the en face view. These data were used to determine the location at which a center-based coring reamer would violate the back wall of the glenoid and the size of reamer with which this violation would occur. In addition, for each sample, the largest size of reamer that could be used to obtain graft depths of 4, 6, and 8 mm based on the reamer sizes available in one commonly used commercially available operative instrument set (Osteoarticular Allograft Set; Arthrex, Naples, FL, USA) was determined. The chondral surface area of a graft of this size was then compared with the surface area of the glenoid for each patient as determined by use of a best-fit circle method to calculate the percent of the articular surface covered by the largest available graft.

Statistical analysis

All statistical analyses were performed in SPSS 18 (IBM, Armonk, NY, USA). Kolmogorov-Smirnov testing confirmed nonnormal data distribution, and thus nonparametric tests were used. Kruskal-Wallis tests were used to compare glenoid width, glenoid height, patient age, patient height, and patient weight between genders. Friedman 2-way analysis-of-variance testing was performed step-wise to determine the effect of changing depth on the shortest radial distance. Step-wise multiple regression analyses were used to determine the correlation between glenoid height, glenoid width, patient age, patient weight, and patient height and the shortest radial distance at a depth of 4, 6, and 8 mm.
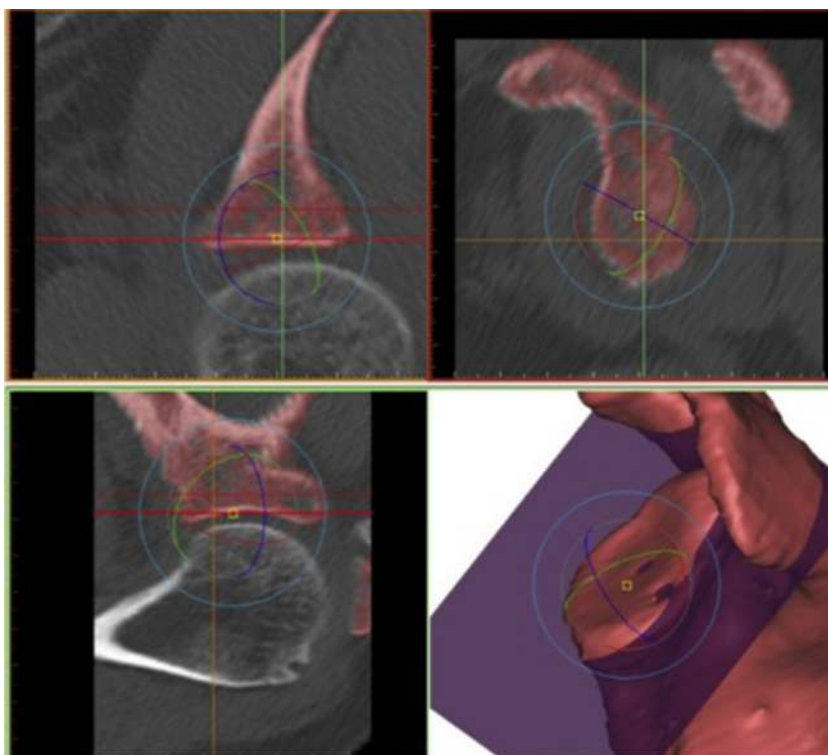
Figure 1 Images of the glenoid showing the application of a ''mask'' in red to the glenoid covering the entirety of the osseous surface. By use of Mimics, this mask can then be used to reconstruct a freestanding 3D model of the scapula (Fig. 2, *A*).

Results

Our cohort included 8 male and 8 female glenoids. All specimens were from white cadavers. Our cohort had a mean age of 46 ± 9.8 years (range, 28-65 years), a mean height 168 ± 11 cm (range, 155-191 cm), and a mean weight of 124 ± 31.2 kg (range, 75-180 kg). Five of our patients died of neurologic conditions: two died of spinocerebellar ataxia, one died of Huntington disease, one died of amyotrophic lateral sclerosis, and one died of subarachnoid hemorrhage. Eleven died of oncologic causes: four died of lung cancer, two died of rectal cancer, two died of esophageal cancer, one died of endometrial cancer, one died of colon cancer, and one died of melanoma.

Four-millimeter depth analysis

At a graft depth of 4 mm, the mean reamer diameter accommodated was 20.5 ± 3.7 mm (range, 11.4-25.6 mm). Fifty-six percent of glenoids could allow for a graft with a 20-mm-diameter, and 94% of the samples would accommodate a 16-mm-diameter graft (Table I). When each glenoid was fitted with the largest reamer available at a depth of 4 mm, the mean coverage was 51.9% ± 12.2% (range, 31.6%-80.1%). In 69% of cases, the most shallow point of glenoid depth lay anterosuperiorly between the 1:30 clock face position and 3-o'clock position, and in 31%, it lay posterosuperiorly between the 7:30 clock face

position and 9-o'clock position. No specimen had its shallowest point anteroinferiorly or posteroinferiorly.

Six-millimeter depth analysis

At a graft depth of 6 mm, the mean reamer diameter accommodated was 17.9 ± 3.9 mm (range, 8.0-23.4 mm). Thirty-one percent of the glenoids could allow for a graft with a 20-mm-diameter, and 75% of the samples would accommodate a 16-mm-diameter graft (Table I). When each glenoid was fitted with the largest reamer available at a depth of 6 mm, the mean coverage was 36.3% ± 12.9% (range, 13.5%-58.4%). In 75% of cases, the most shallow point of glenoid depth lay anterosuperiorly between the 1:30 clock face position and 3-o'clock position; in 13%, it lay posterosuperiorly between the 7:30 clock face position and 9-o'clock position; and in 13%, it lay posteroinferiorly between the 9-o'clock position and 10:30 clock face position. No specimen had its shallowest point anteroinferiorly.

Eight-millimeter depth analysis

At a graft depth of 8 mm, the mean reamer diameter accommodated was 14.4 ± 3.8 mm (range, 7.3-20.7 mm). Thirteen percent of the glenoids could allow for a graft with a 20-mm-diameter, and 38% of the samples would accommodate a 16-mm-diameter graft (Table I). When each glenoid was fitted with the largest reamer available at
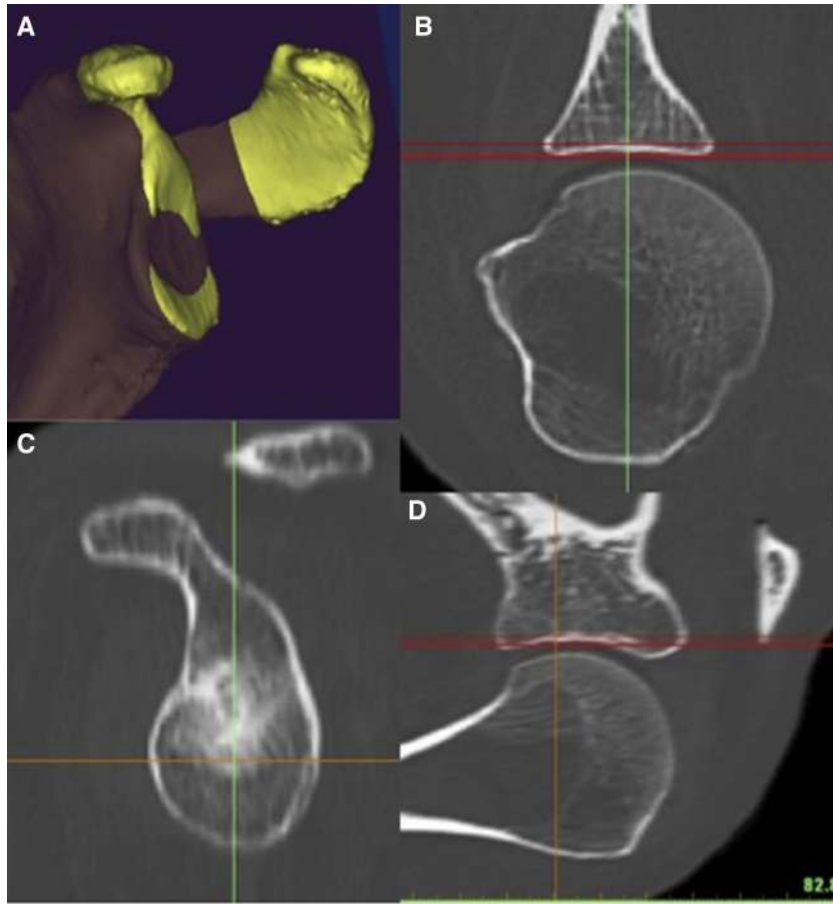
Figure 2   (**A**) A 3D volumetric representation of the glenoid was used to create an en face view of the glenoid, and a plane was fit to the face of the glenoid using the best-fit circle method. Anatomic axial (**B**), coronal (**C**), and sagittal (**D**) slices were created perpendicular to this plane.

a depth of 8 mm, the mean coverage was 23.8% ± 14.2% (range, 3.4%-55.7%). In 44% of cases, the most shallow point of glenoid depth lay anterosuperiorly between the 1:30 clock face position and 3-o'clock position; in 6%, it lay posterosuperiorly between the 7:30 clock face position and 9-o'clock position; and in 44%, it lay posteroinferiorly between the 9-o'clock position and 10:30 clock face position. No specimen had its shallowest point anteroinferiorly.

Demographic analysis

Statistical analyses of specimen demographic characteristics and glenoid measurements showed that female glenoids accommodated smaller-diameter grafts than male glenoids at depths of 4 mm ($P = .003$), 6 mm ($P = .003$), and 8 mm ($P = .005$) (Fig. 4). Female glenoids were smaller than male glenoids in height (32 ± 2.0 mm vs 36.3 ± 3.7 mm, $P = .034$) and width (24.6 ± 2.2 mm vs 29.0 ± 2.2 mm, $P = .011$). Compared with male cadavers in this study, female cadavers had a smaller overall height (157 ± 5 cm vs 176 ± 9 cm, $P = .004$), although there were no significant differences in age (46.0 ± 9.4 years vs 45.3 ± 10.9

years, $P = .474$) or weight (117.4 ± 40.0 kg vs 127 ± 22.1 kg, $P = .494$). Multiple regression analysis showed that patient height was the only independent variable associated with glenoid width ($R = 0.612$, $P = .012$) and glenoid height ($R = 0.663$, $P = .005$).

Multiple regression analysis showed that patient height was the only independent variable associated with accommodated graft diameter at depths of 4, 6, and 8 mm ($R = 0.751$, $R = 0.726$, and $R = 0.690$, respectively, and $P = .001$, $P = .001$, and $P = .003$, respectively) (Fig. 5). At a graft depth of 4 mm, patient height in cm could be used to calculate graft size in mm by use of the following equation: Graft radius = Patient height × 0.122 − 10.2. At a graft depth of 6 mm, patient height in cm could be used to calculate graft size in mm by use of the following equation: Graft radius = Patient height × 0.124 − 11.9. At a graft depth of 8 mm, patient height in cm could be used to calculate graft size in mm by use of the following equation: Graft radius = Patient height × 0.113 − 11.7. Friedman repeated-measures analysis of variance showed a significantly greater graft radius at lesser depths; that is, the 4-mm depth allowed a greater graft radius than the 6-mm depth,
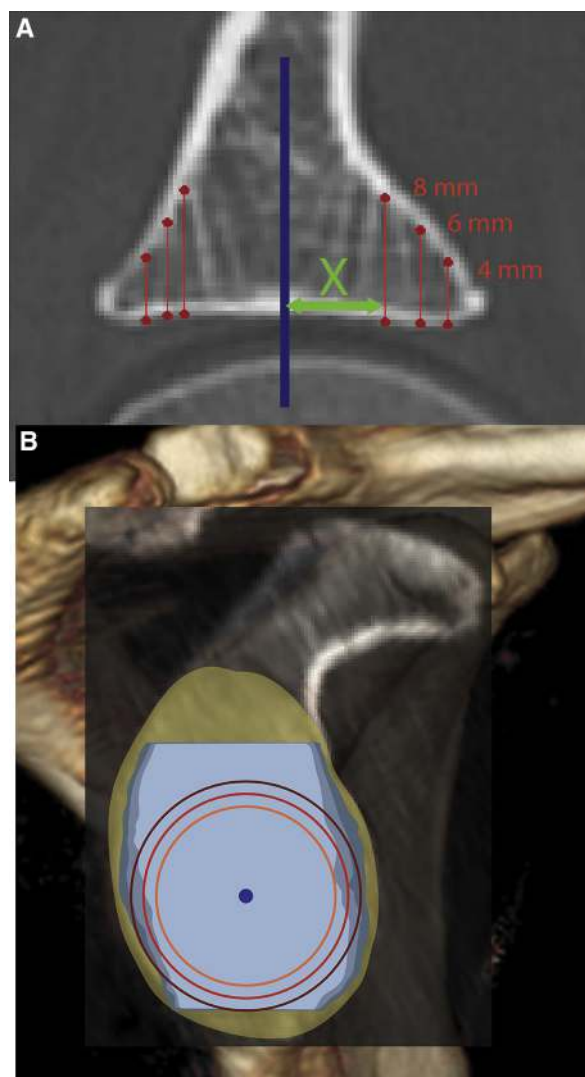
Figure 3 (**A**) By use of axial CT, 4-, 6-, and 8-mm lines were drawn from the subchondral surface to the medial glenoid endosteal surface. For a depth of 8 mm, X is the radius of accommodated graft. (**B**) Three-dimensional CT scan showing glenoid center point and circles indicating accommodated graft diameter for 4-, 6-, and 8-mm depths.

the 6-mm depth allowed a greater graft radius than the 8-mm depth, and so on ($P < .001$ for all comparisons).

Discussion

Glenoid chondral lesions can be a cause of shoulder pain and disability in young patients, with glenoid cartilage loss discovered in 5% to 17% of diagnostic arthroscopies, although in many cases the contribution of the glenoid lesion to patient symptomatology is unclear.[7,9,17] Currently, there are few to no non-arthroplasty treatment options with proven effective long-term outcomes. Most reports of surgical management of isolated glenoid chondral lesions to date have used microfracture, although there have been a few reports of osteochondral allografting.[8,13,18] Although

osteoarticular grafting has been widely used with relatively good success for symptomatic chondral lesions of the knee, the treatment of glenoid chondral lesions with osteoarticular grafting procedures has been limited in part by concerns about the depth of the glenoid as compared with the depth of subchondral bone on the graft necessary to achieve a press fit. To our knowledge, this was the first study to use 3D CT modeling of cadaveric glenoids to determine the feasibility of osteoarticular glenoid grafting based on center-based grafts of 4-, 6-, and 8-mm depths. We found that in the majority of shoulders studied, the glenoid can support center-based grafts of 16 to 20 mm in diameter at a depth of 4 mm. The anterosuperior 1:30 clock face position to 3-o'clock position is the most common limiting location in center-based glenoid grafting. Factors associated with smaller accommodated grafts include female gender, decreased patient height, and decreased glenoid height and width. Although most glenoids studied could support center-based grafts with dimensions as described earlier, the grafts would only cover an average of 51.9% of the glenoid surface. Thus, although our results suggest that glenoid osteoarticular grafting would be feasible for isolated glenoid chondral lesions, use for diffuse glenoid cartilage loss in cases of chondrolysis might not be appropriate given that it provides incomplete coverage.

Most glenoids support center-based grafts of 16 to 20 mm in diameter at a depth of 4 mm, covering an average of 51.9% of the glenoid.

Most studies of glenoid anatomy have focused on anteroposterior width and superoinferior height.[6,15] Few data exist regarding glenoid depth despite its importance for osteoarticular grafting and for placement of glenoid components for total shoulder arthroplasty.[22] In a recent study, Jung et al[12] used 3D CT reconstructions to measure the glenoid penetration depth in nonarthritic glenoids to provide information relevant to screw placement for glenoid replacement. They found that the glenoid depth was least at the posterior and inferior aspects, especially in female patients, and concluded that care should be taken when placing screws in this location. Whereas Jung et al found that the glenoid depth was most limited in the posteroinferior region, we found that the anterosuperior 1:30 clock face position to 3-o'clock position is the most common limiting location in center-based glenoid grafting. This difference may reflect a difference in methodology because Jung et al determined glenoid penetration depth at points on a glenoid grid whereas we determined the diameter of center-based grafts that could be accommodated by the glenoid for 4-, 6-, and 8-mm depths. Thus, our findings could reflect that the anterosuperior portion of the glenoid is closer to the glenoid center point. Our use of the best-fit circle method may have contributed to the differences between our results and those of Jung et al. We believe that the best-fit circle method best represents the surgical technique of osteochondral grafting because we use circular graft harvesting reamers. Nevertheless, many of our

Table I Summary data for included specimens

| Specimen No.	Shortest distance (mm) from center to 4-mm depth	Shortest distance (mm) from center to 6-mm depth	Shortest distance (mm) from center to 8-mm depth	Glenoid measurements		Patient demographic characteristics			
				Width (mm)	Height (mm)	Gender	Age (y)	Height (cm)	Weight (kg)
1	5.7	4.0	3.7	21.8	28.8	F	28	157	90
2	8.2	7.2	6.0	26.0	30.6	F	46	160	120
3	8.9	7.6	5.3	24.6	34.8	F	46	155	75
4	8.9	7.7	5.2	23.3	31.2	F	46	155	75
5	9.4	8.1	6.1	28.5	34.0	F	49	155	127
6	9.4	8.5	5.8	23.4	32.4	F	60	168	175
7	9.5	8.2	7.1	24.8	32.0	F	47	155	160
8	10.3	9.2	8.2	29.9	36.8	M	38	175	122
9	10.5	8.6	6.8	25.6	32.5	F	54	178	160
10	10.7	10.1	8.8	26.2	35.2	M	48	168	120
11	11.8	9.2	6.5	28.5	34.0	M	65	170	120
12	11.9	11.6	10.3	28.0	31.9	M	48	168	120
13	12.1	11.5	8.5	33.4	44.3	M	49	188	180
14	12.1	10.2	8.8	29.5	34.7	M	38	175	122
15	12.1	10.0	7.3	29.6	37.5	M	48	173	107
16	12.8	11.8	10.4	26.8	35.8	M	28	191	125
Mean	10.3	9.0	7.2	26.9	34.2	8 M and 8 F	46	168	125

F, Female; *M*, male.
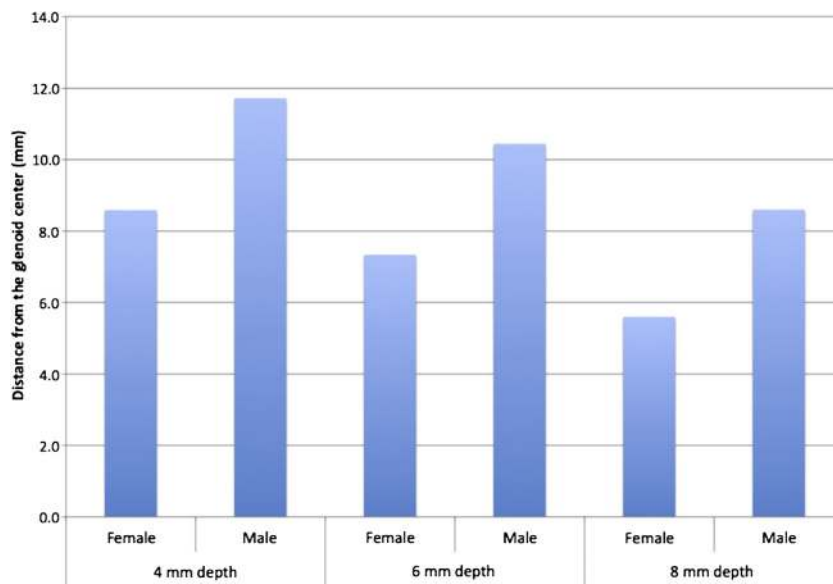
Figure 4 Shortest distance from center of glenoid to 4-, 6-, and 8-mm depth for female and male glenoids. Significant differences were seen between genders at all depths ($P = .003$ at 4 mm, $P = .003$ at 6 mm, and $P = .005$ at 8 mm).

cadavers had their most shallow point posteroinferiorly, including 44% of cases for the 8-mm depth.

This study provides important anatomic data that can be applied to advancing the technique of osteoarticular grafting of the glenoid. For instance, on the basis of our study, a surgeon performing this technique could use a 16-mm-diameter reamer to a depth of 4 mm and be 94% confident that this would not blow out the back of the glenoid in the setting of concentric glenoid chondral loss. Of note, the depths that we studied were selected based on previously published data showing press-fit stability with a depth of 4 mm in in vitro biomechanical models.[10] Gerber et al[10] used Sawbones models of glenoids (Pacific Research Laboratories, Vashon, WA, USA) as well as sheep glenoids to test the biomechanics of press-fit osteochondral glenoid allograft, finding in this biomechanical model that glenoid osteochondral allograft via the press-fit method is technically feasible with adequate in vitro stability. It is unclear
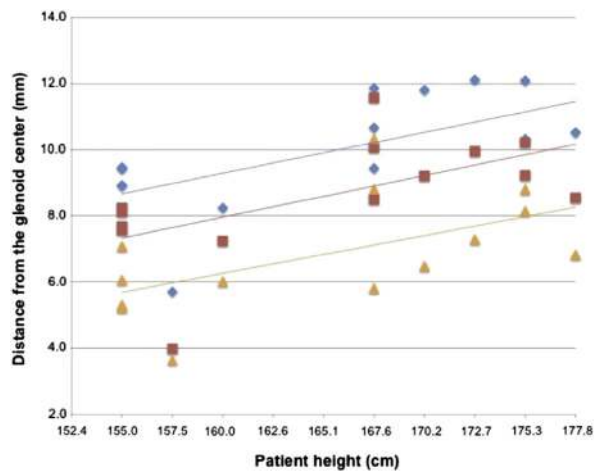
Figure 5 Correlation between patient height in centimeters and shortest distance to glenoid depth of 4 mm (*blue diamonds* and *blue trend line*), 6 mm (*red squares* and *red trend line*), and 8 mm (*orange triangles* and *orange trend line*).

whether the data from this study of Sawbones and sheep glenoids would also apply to human glenoids, and this will require further study.

In addition, our study found that the factors associated with smaller regions with a given glenoid depth include female gender, decreased patient height, and decreased glenoid height and width. This is consistent with prior published studies.[5,12,15] This implies that female patients and patients with smaller heights are likely to have smaller glenoids with decreased glenoid depths; one should plan screw placement or osteoarticular grafting procedures accordingly. Making preoperative measurements of glenoid dimensions could be used in such cases to reduce the risk of complication such as cortical blowout during reaming. On the basis of a study from the forensics literature, the association of female patients with smaller glenoids is most likely confounded by patient height, and the primary driver for a smaller glenoid is in fact patient height.[3] This is consistent with our finding that patient height was the only independent variable associated with accommodated graft diameter at depths of 4, 6, and 8 mm.

The strengths of the study include the use of a proven effective 3D point cloud creation instrument[20,24] and relevance of measurements to existing biomechanical models of osteoarticular grafting of the glenoid.[10] This study could have been strengthened by using more specimens. However, the associations observed in this study are sufficiently strong in that we achieved statistical significance in all observed comparisons with our current sample size. Another weakness is that the specimens with evidence of arthritis were excluded. Our clinical experience has been that glenoids with cartilage lesions tend to be found in young patients who do not have the osseous changes typical of degenerative joint disease such as posterior glenoid bony wear; thus, nonarthritic glenoids were selected to most accurately reflect the patient population in which osteochondral allografting

would be performed. However, osteoarthritic glenoids tend to have posterior wear that could alter the plane of the en face view and lead to significantly more glenoids with insufficient depth posteriorly.[19] Our data from this study of nonarthritic glenoids would have limited applicability to situations of glenoid bone loss and posterior wear. An additional potential limitation is that we did not account for variation in glenoid version among samples. However, because all measurements were based on an en face glenoid view with reformatted axial images perpendicular to the glenoid face, our measurements should represent an analysis of glenoid vault topology that is independent of version. Moreover, when one is placing a glenoid osteoarticular graft, altering glenoid version can be difficult. Therefore, it is technically easier to match the naive glenoid version, which should not be altered in these patients, as it is for osteoarthritis. Our simulations of osteoarticular allografting of the glenoid were based on the assumption that a circular press-fit technique would be used. It is also possible that headless screw fixation could be used in this application, although the topology of the back side of the glenoid might complicate this type of fixation. Finally, we made our measurements based on osseous data provided by CT and did not consider the labrum or residual cartilage, which could limit direct applications of our measurements to clinical glenoid osteoarticular grafting. Future studies will be necessary to replicate our findings using magnetic resonance images.

Future studies should focus on using similar 3D CT methodology to evaluate glenoid depth in shoulders with osteoarthritis and chondral lesions. Additional future studies should take glenoid depth data obtained by this 3D CT methodology and apply it to predict feasible areas for osteoarticular glenoid grafting, initially in cadaveric models and subsequently in clinical applications.

Conclusion

In the majority of shoulders, the glenoid can support center-based grafts of 16 to 20 mm in diameter at a depth of 4 mm, covering an average of 51.9% of the glenoid. Accommodated graft size decreases as reaming depth increases. The anterosuperior 1:30 clock face position to 3-o'clock position is the most common limiting location in center-based glenoid grafting. Factors associated with smaller accommodated grafts include female gender, decreased patient height, and decreased glenoid height and width.

Disclaimer

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