Review Article

Evaluating Bone Loss in Anterior Shoulder Instability

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ABSTRACT

Anterior shoulder instability is a common orthopaedic condition that often involves damage to the bony architecture of the glenohumeral joint in addition to the capsulolabral complex. Patients with recurrent shoulder dislocations are at increased risk for glenohumeral bone loss, as each instability event leads to the accumulation of additional glenoid and/or humeral head bone defects. Depending on the degree of bone loss, successful treatment may need to address bony lesions in addition to injured soft-tissue structures. As such, a thorough understanding of methods for evaluating bone loss preoperatively, in terms of location, size, and significance, is essential. Although numerous imaging modalities can be used, three-dimensional imaging has proven particularly useful and is now an integral component of preoperative planning.

Glenohumeral joint stability results from a complex interplay between dynamic and static restraints that function synergistically to keep the humeral head centered within the glenoid. Both soft-tissue and bony structures are critical in maintaining a concentric joint and preventing subluxation or dislocation. Traumatic anterior instability events involve disruption of the capsulolabral complex but can also lead to damage of the bony architecture of the glenoid and humerus. Bone loss after dislocation is common, with up to 90% of patients demonstrating either a glenoid or a humeral head defect during arthroscopic evaluation for recurrent instability.[1] Even first-time traumatic subluxation events have been associated with high rates of Hill-Sachs lesions (HSLs) and osseous Bankart lesions on MRI.[2]

Successful surgical treatment of shoulder instability often requires the surgeon to consider both bony defects of the glenohumeral joint and damage to the capsulolabral complex. Failure to address significant bone loss may lead to recurrent instability, despite robust soft-tissue repairs.[3–5] Recurrent instability after arthroscopic soft-tissue procedures can be as high as 17.8% among contact athletes, and there is currently no consensus regarding the amount of bone loss beyond which a soft-tissue repair cannot reliably restore stability.[3] Accordingly, accurate characterization of glenoid and humeral bone loss, in terms of location, size, and significance, is an important

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component of preoperative planning and essential to minimizing the risk of recurrent dislocation.

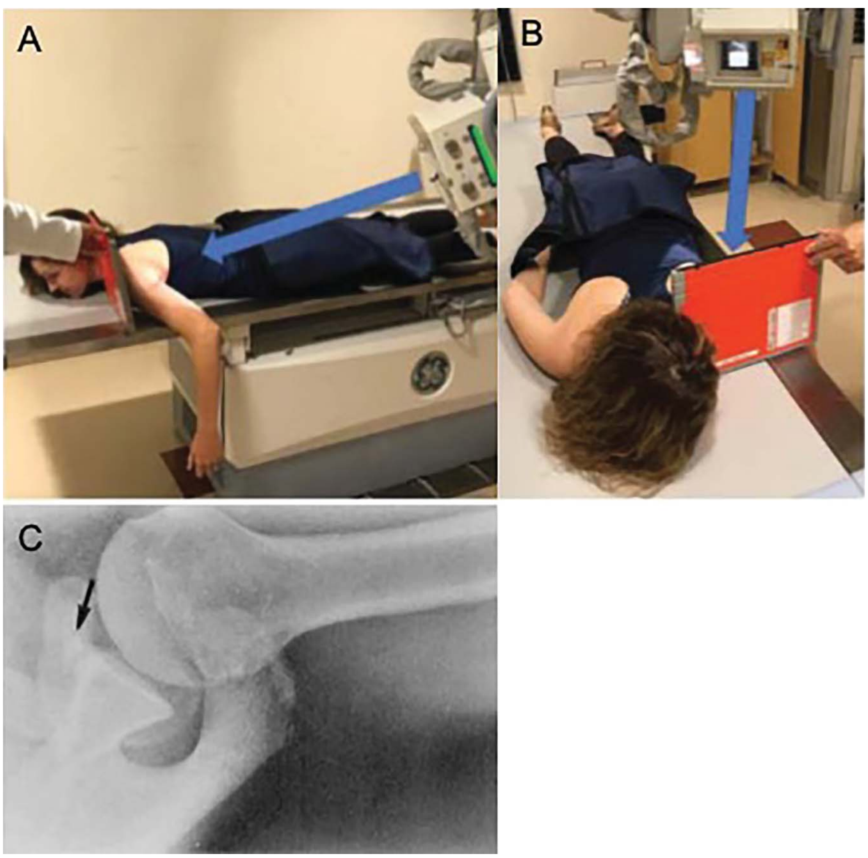
Assessment of Glenoid Bone Loss

Radiography

After an episode of traumatic anterior shoulder instability, standard radiographs of the glenohumeral joint including AP, Grashey, axillary, and scapular *y* views should be obtained. In addition to assessing for congruity of the glenohumeral joint, radiographs can be helpful in identifying glenoid and humeral bone loss. On the AP view, for instance, an intact anterior glenoid rim typically appears as a continuous sclerotic line. Jankauskas et al[6] demonstrated that loss of the sclerotic glenoid line on the AP radiograph was highly specific but only moderately sensitive for identifying anterior glenoid rim deficiencies compared with CT. Consistent with this finding, Auffarth et al asked six observers to review conventional radiographs (AP and axillary) of patients with a first-time shoulder dislocation and found that of the 10 patients who presented with a glenoid rim fracture (confirmed on CT), each investigator overlooked at least one fracture (range, 1 to 4) based on radiographs alone. Accordingly, the authors recommended CT evaluation in all patients after primary dislocation.[7] However, additional radiographic projections have also been devised to facilitate the identification and evaluation of glenoid bone.

The West Point view (Figure 1) is helpful for identifying osseous Bankart lesions of the anteroinferior glenoid rim. The West Point view is obtained with the patient lying prone, the shoulder slightly elevated, and the arm abducted to 90° hanging over the edge of the table. The radiograph tube is oriented inferosuperior, 25° medial, and 25° anterior so that it is tangential to the anteroinferior rim of the glenoid. Itoi et al conducted a cadaveric study that involved obtaining radiographs of progressively larger glenoid defects and found that

Figure 1



West point radiograph view demonstrating patient positioning. The patient is in the prone position with the forearm hanging off the table. The radiograph beam is centered on the axilla and aimed at 25° downward from the horizon (**A**) and 25° medial to the plate (**B**). Radiograph view (**C**) demonstrating a view of the anterior glenoid rim with an osseous lesion at the anterior-inferior glenoid (arrow). Figure modified from Rockwood and Green Fractures in Adults, 9th edition.

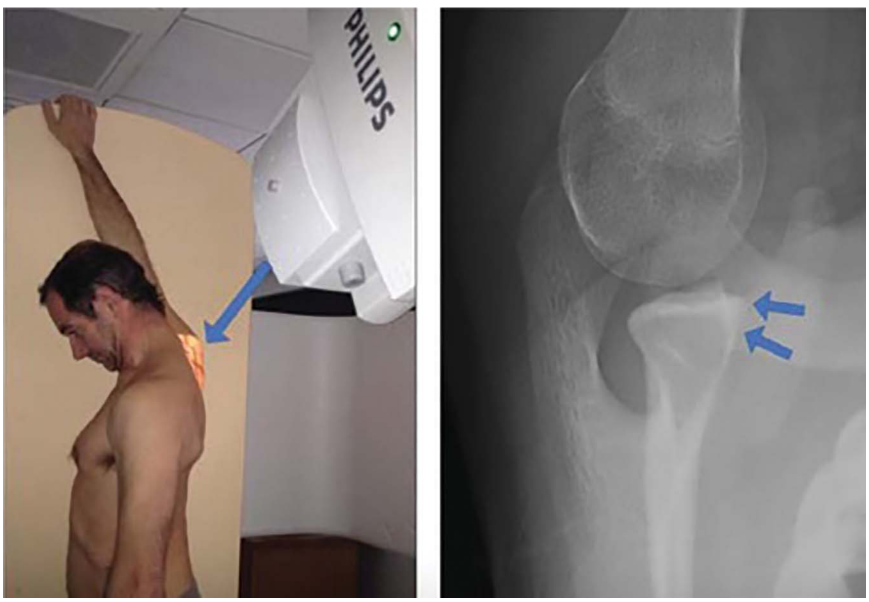
changes in the glenoid width were more appreciable on the West Point view compared with the axillary view. However, the West Point view was still less accurate than CT for evaluating anteroinferior bony Bankart lesions, leading the authors to conclude that although radiographs represent an acceptable screening tool, CT is notably more accurate for measuring bone loss.[8]

The Bernageau glenoid profile view (Figure 2) is another radiographic projection that can be used to assess for bony defects that are more anterior along the glenoid face.[9,10] For the Bernageau view, the patient is standing with the affected arm forward flexed to 160° and the thorax in contact with the cassette at an angle of 70°. The radiograph tube is centered over the scapular spine with a caudal inclination of 30°. Murachovsky et al compared the Bernageau view with three-dimensional (3D) CT for quantifying glenoid bone loss and found no difference between the two imaging modalities. Although the authors did not recommend radiographs in lieu of 3D CT for preoperative planning, the Bernageau view was identified as an accurate and reproducible technique for identifying and measuring glenoid bone loss.[11] Among patients undergoing surgical treatment of chronic anterior shoulder instability, Edwards et al[9] found osseous abnormalities of the glenoid in 78.8% of shoulders using the Bernageau view but noted that very inferior fractures can be difficult to visualize on this projection.

CT

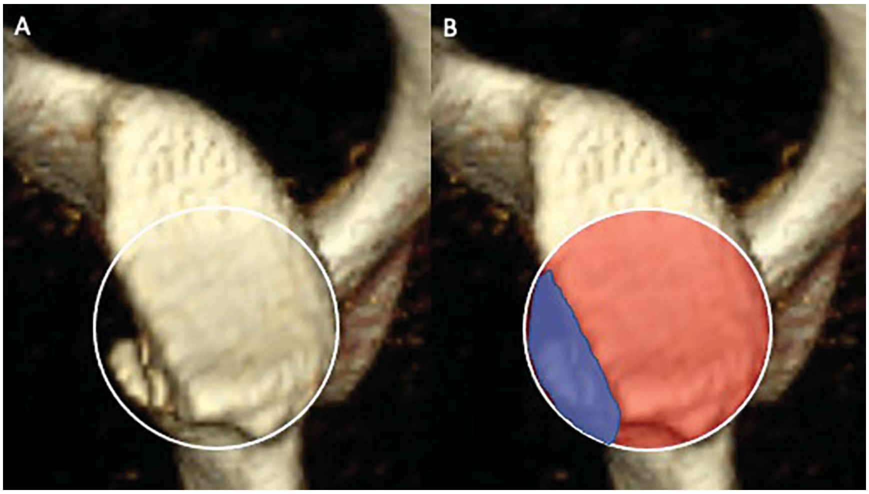
Given the overall difficulty of reliably identifying and measuring glenoid bony defects using radiographs alone, CT should be obtained in patients with evidence of bone loss on radiograph, patients who have experienced recurrent instability, and patients who have failed prior instability surgery.[12] A multitude of methods have been devised for quantifying glenoid bone loss based on both two-dimensional (2D) and 3D CT. A benefit of 3D CT is that the humerus can be subtracted from the digital reconstruction of the shoulder joint, allowing for a perfect en face sagittal view of the glenoid surface. Most methods of measuring glenoid bone loss use a "best-fit circle" technique, which is based on a cadaveric study by Huysmans et al[13] that found the inferior glenoid roughly constitutes a true circle. Viewing the glenoid articular surface en face, a circle is drawn centered about the glenoid bare area, using the intact posteroinferior glenoid as a reference (Figure 3, A). The area of the circle that does not overlap with the glenoid anteriorly is presumed to be bone loss and can be compared with the area of the entire circle to calculate percent bone loss (Figure 3, B).[14] The Pico method, developed by Baudi et al,[15] uses a 3D CT of the patient's contralateral uninjured glenoid to generate a best-fit circle, which is superimposed on the injured glenoid to determine percent bone loss. Barchilon et al[16] devised a relatively simple mathematical function to estimate glenoid bone

Figure 2



A: Patient positioning for taking the Bernageau view of the shoulder. B: Bernageau view demonstrating an intact anterior glenoid rim (blue arrows). Reference: Rockwood and Green Fractures in Adults, 9th edition.

Figure 3

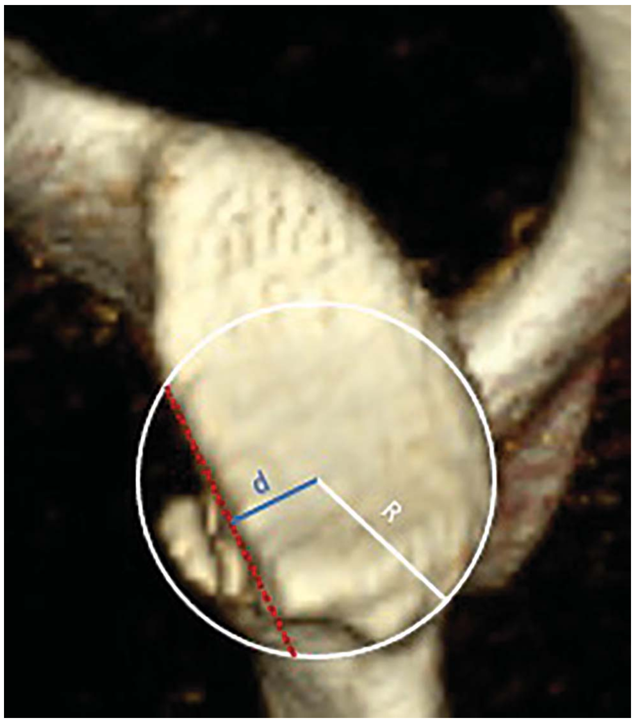


Sagittal oblique projection of the glenoid fossa from a three-dimensional CT reconstruction. The intact posteroinferior glenoid has been used as a template to overlay a "best-fit circle" centered over the glenoid bare area (**A**). The "best-fit circle" method (**B**) can be used to estimate glenoid bone loss (blue). Percent bone loss may be determined by dividing the area in blue by the entire area within the "best-fit circle" (blue + red). Image courtesy of Dr. Eric Makhni.

loss based on the ratio of the depth of the defect (a perpendicular line from the center of the best-fit circle to the anterior edge of the glenoid) and the radius of the best-fit circle (Figure 4). Similarly, Dumont et al[17] described a method for determining percent bone loss by measuring the arc angle that subtends the area of glenoid bone loss as defined by a best-fit circle (Figure 5).

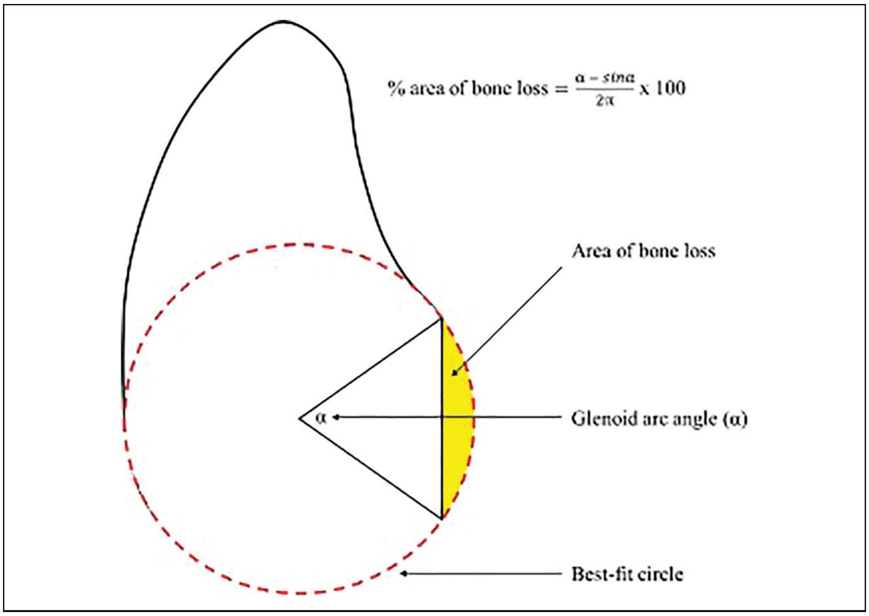
CT may also be beneficial in differentiating acute bony Bankart lesions amenable to repair from attritional glenoid bone loss with resorption of the bone fragments, which often requires grafting to reconstitute the bony architecture of the glenoid (Figure 6). When possible, incorporation of the bony Bankart fragment into the capsulolabral repair leads to improved patient-reported outcomes and lower rates of recurrence, particularly when the glenoid defect is large (>20%).[18] Nakagawa et al[19] examined serial CT scans of patients who underwent arthroscopic bony Bankart repair and found that larger fragments were more likely to unite and that union of the bony fragment decreased the glenoid defect from 18.6% to 4.7% on average. As expected, nonunion of the bony Bankart fragment was a positive predictor of recurrent instability. However, longitudinal assessment of bony Bankart fragments has demonstrated a correlation between bone loss and time from the initial trauma, with severe resorption observed at 1 year after primary dislocation.[20] Accordingly, timely treatment of acute bony Bankart lesions with incorporation of the bone fragment into the repair may decrease the risk of recurrent instability without the need for bone grafting.

Figure 4



Linear method of estimating glenoid bone loss as described by Barchilon et al.[14] A mathematical equation is used to measure the area of defect as a function of the ratio between the depth (d) to the glenoid defect margin (a perpendicular line from the erosion edge (red line) to the center of the "best-fit circle") and the radius (R) of the intact inferior glenoid rim, as defined by the "best-fit circle." This ratio is then used to determine the percent bone loss. Image courtesy of Dr. Eric Makhni.

Figure 5

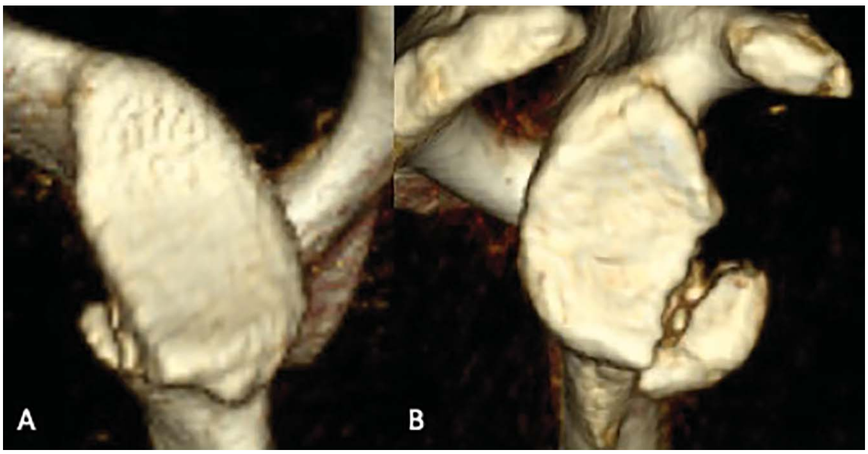


Arc angle method of calculating glenoid bone loss as described by Dumont et al. A circle is superimposed on a sagittal view of the glenoid, using the inferior border of the glenoid as a reference. The glenoid arc angle (α) that subtends the area of bone loss (shaded in yellow) is measured and used to calculate percent bone loss with the equation provided.[17]

MRI

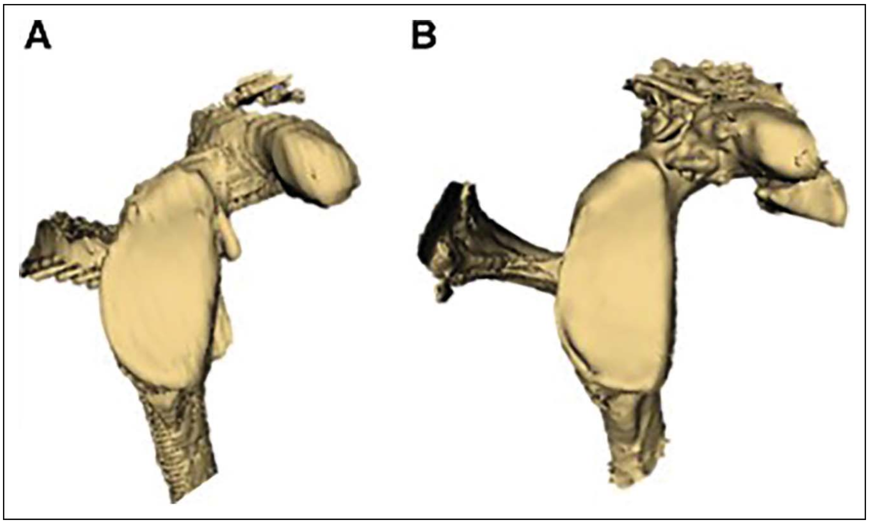
Although MRI is used to evaluate for soft-tissue injuries associated with shoulder instability, there is increasing evidence that MRI can also be used to reliably and accurately assess bone loss.[21] Lee et al[22] compared MR arthrography with CT in the evaluation of glenoid bone loss and found excellent correlation, with strong interobserver and intraobserver correlations of MR arthrography–derived measurements of bone loss. In addition to allowing for concomitant evaluation of soft tissues and bone, MRI does not involve ionizing radiation, and the introduction of 3 tesla(T) magnets has dramatically improved the acquisition speed, signal, and spatial resolution of MRI.[23] Moreover, it is now possible to generate 3D reconstructions using MRI, further increasing its utility in assessing glenohumeral bone loss. For all these reasons, MRI is now included in the basic workup of anterior shoulder instability for many orthopaedic surgeons.[23]

Figure 6



En face views of three-dimensional CT reconstructions of the glenoid. **A**, The glenoid of a patient suffering from recurrent instability demonstrating attritional bone loss with several small bone fragments. **B**, The glenoid of a patient who experienced a traumatic first-time dislocation event resulting in a large bony Bankart lesion. Image courtesy of Dr. Eric Makhni.

Figure 7



Views of three-dimensional reconstructions of the glenoid from the same patient using (**A**) CT versus (**B**) MRI. Reference: Lansdown DA, Cvetanovich GL, Verma NN, et al: Automated 3-Dimensional Magnetic Resonance Imaging Allows for Accurate Evaluation of Glenoid Bone Loss Compared With 3-Dimensional Computed Tomography. *Arthroscopy* 2019;35:734-740.

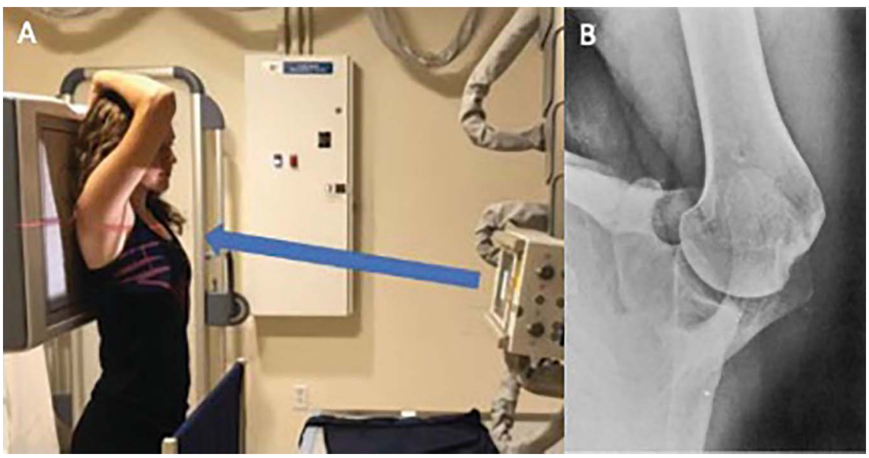
Gyftopoulos et al[21] described using 3T and 1.5T MRI with dedicated 16-channel shoulder array coils to produce an axial 3D dual echo time T1-weighted sequence with Dixon-based fat-water separation, which was then used to generate a 3D reconstruction of the glenohumeral joint. Glenoid bone loss was calculated from the 3D reconstruction using the best-fit circle method and found to be consistent with findings on arthroscopy. Using a similar imaging protocol with Dixon-based fat-water separation MRI, Lansdown et al[24] found a strong correlation between estimates of bone loss based on 3D MRI reconstructions and 3D CT reconstructions (Figure 7), further supporting the notion that CT may not be necessary if a 3D MRI will be obtained. However, 3D MRI is not yet widely available, and CT remains the benchmark for detecting significant bone loss in patients with anterior shoulder instability, with a sensitivity approaching 100% compared with 35.3% for standard 2D MRI.[25]

Assessment of Humeral Head Bone Loss

Radiography

A HSL is a compression fracture of the posterolateral humeral head that results from impaction of the

Figure 8



Patient positioning for a Stryker notch view radiograph (**A**) with radiograph demonstrating a Hill-Sachs lesion of the posterosuperior humeral head (**B**). Reference: Pavlov H, Warren RF, Weiss CB, Jr, Dines DM: The roentgenographic evaluation of anterior shoulder instability. *Clin Orthop Relat Res* 1985:153-158. Rockwood and Green Fractures in Adults, 9th edition.

Figure 9

Anteroposterior radiograph of the shoulder where the maximum depth of the Hill-Sachs lesion (P) is compared with the radius of the humeral head (R) to estimate percent bone loss. Reference: Maio M, Sarmento M, Moura N, Cartucho A: How to measure a Hill-Sachs lesion: a systematic review. *EFORT Open Rev* 2019;4:151- 157.

humerus on the anterior glenoid rim during an instability event. HSLs are common after anterior shoulder instability events, with an incidence nearing 100% in patients with recurrent instability.[1] In addition to a standard shoulder series, specialized radiographs of the posterolateral humerus may assist in the identification of HSLs. The Stryker notch view is one such projection commonly used for this purpose (Figure 8).[10] The patient is typically standing with the affected side rotated 30 to 45° toward the radiograph tube and the injured arm fully abducted and internally rotated. Although the size of a HSL can be approximated by comparing the depth of the lesion with the radius of the humeral head on an internal rotation radiograph, CT and MRI provide more accurate and reliable quantification (Figure 9).[26]

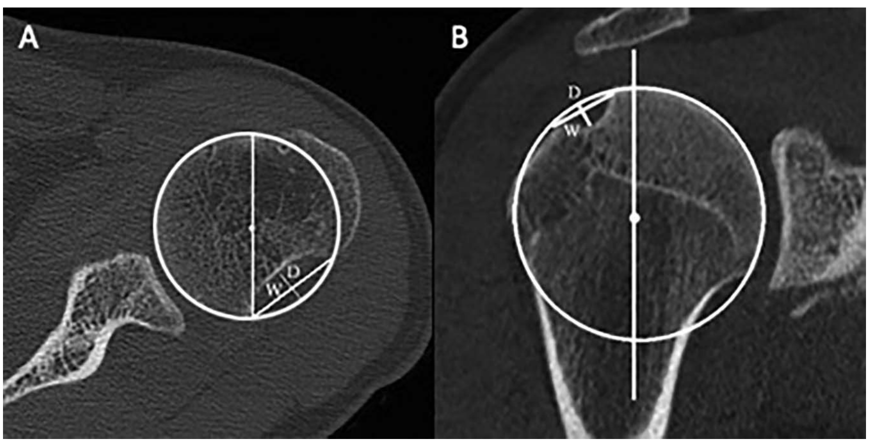
CT

As the contribution of humeral head bone loss to glenohumeral instability has been better elucidated, increased emphasis has been placed on using advanced imaging to quantify humeral head defects during the diagnostic workup for patients with shoulder instability. Similar to glenoid bone loss, CT is the current benchmark for localizing and measuring humeral head bone loss and is indicated in patients with recurrent instability, patients with large HSLs on radiographs, and patients who have failed prior shoulder stabilization procedures.[27] 3D CT, in particular, is a reliable, effective, and accurate method for measuring the size of HSLs.[27] Ozaki et al[28] compared humeral head bone loss identified on 3D CT with intraoperative findings and found a sensitivity and a specificity of 76.3% and 100%, respectively. Of the HSLs that were missed on 3D CT, all but one were either chondral lesions or osseous lesions with a depth of less than 6.5%. In addition, high intraobserver reliability was demonstrated with measurements of HSL length, width, and depth.

MRI

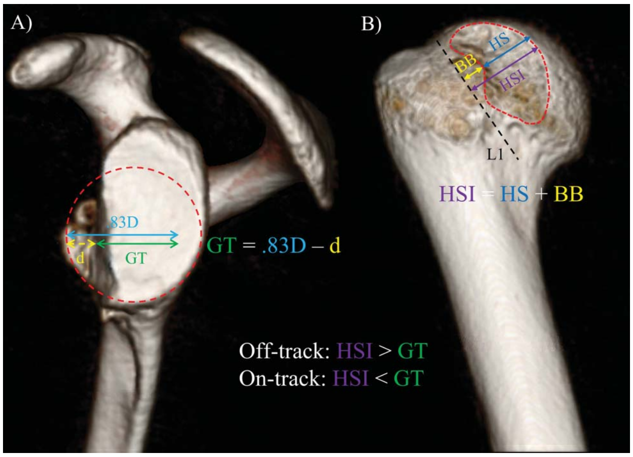
Overall, few studies have assessed the use of MRI for evaluating HSLs. Early research by Kirkley et al[29] demonstrated only moderate agreement (kappa value 0.44) between preoperative MRI and arthroscopy findings in terms of identifying and quantifying humeral head defects. However, 3D MRI appears to offer enhanced detection of HSLs, allowing for the quantification of humeral head defects comparable with that of

Figure 10



Axial (**A**) and coronal (**B**) CT scans of a right shoulder demonstrating the method by Cho et al[33] to calculate the depth (D) and width (W) of a Hill-Sachs lesion.

Figure 11



Calculating the glenoid track (GT) and Hill-Sachs interval for determining whether a Hill-Sachs (HS) lesion is "on-track" (HSI < GT) or "off-track" (HSI > GT), described by Di Giacomo et al. **A**, A circle is superimposed over a sagittal view of a three-dimensional CT view of the glenoid, using the inferior border of the glenoid as a reference. The diameter of the best-fit circle (D) and the width of the glenoid defect (d) are measured and entered into the equation provided to calculate the GT. **B**, The HSI is measured using a three-dimensional CT reconstruction of the humerus. To calculate the HSI, the width of the HS is simply added to the width of the intact bone bridge (BB) between the medial margin of the rotator cuff attachment (L1) and the lateral edge of the HS. HSI = Hill-Sachs interval. Image courtesy of Dr. Eric Makhni.

3D CT.[30] As discussed previously, although MRI has the added benefits of allowing for the evaluation of soft-tissue structures and eliminating radiation, 3D MRI is expensive and not yet routinely used in clinical practice.

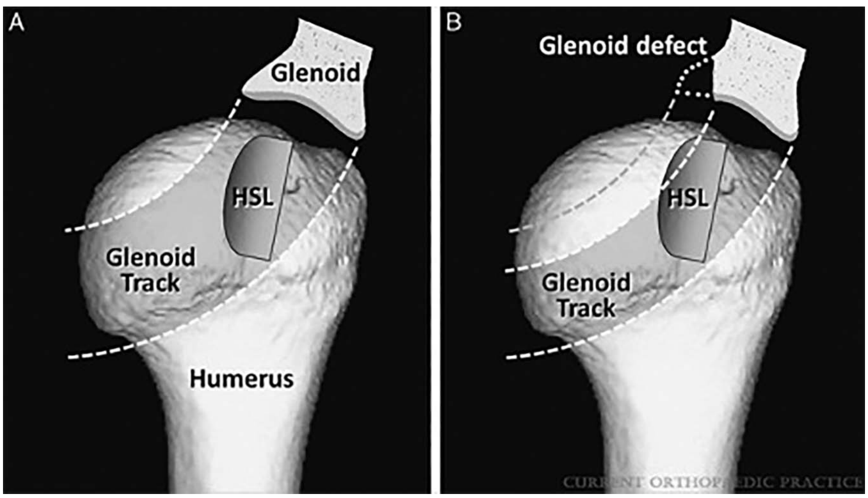
Quantification of Humeral Head Bone Loss

Although a HSL may have little clinical significance in isolation, recurrent instability can arise through engagement of a HSL with the rim of the glenoid as described by Burkhart and De Beer.[4] HSLs involving less than 25% of the humeral head were thought to pose little risk of recurrence.[31] It is now well understood that both size and location influence the risk of engagement, with larger and medial HSLs more likely to engage the glenoid.[32] Moreover, HSLs are more likely to engage in patients with bipolar bone loss (i.e., bony defects involving both the humeral head and the glenoid). Cho et al described a method of calculating the size of the HSL by using a virtual circle including the articular surface of the humeral head and measuring the depth and width of the defect in multiple planes to determine percent bone loss (Figure 10). The authors observed that in addition to greater size, horizontal orientation of a HSL relative to the humeral shaft also increased the risk of engagement.[33]

Bipolar Bone Loss

To better assess the risk of a HSL engaging with the glenoid during normal shoulder range of motion, Yamamoto et al[34] developed the glenoid track (GT)

Figure 12



Demonstration of the interplay between the glenoid track (GT) and a Hill-Sachs lesion (HSL). **A**, With an intact GT without bone loss, the HSL stays within the GT, and there is no engagement of the humeral defect with the glenoid rim. **B**, With a bony defect, the glenoid track narrows and permits the HSL to engage with the glenoid rim and leads to instability. Reference: Shoulder instability: treating bone loss. Itoi, Eiji; Yamamoto, Nobuyuki. Current Orthopaedic Practice. 23(6):609-615, November/December 2012. doi: 10.1097/BCO.0b013e318265e0a1 concept. Initially described in 2007, the GT is the region of the posterior humerus in direct contact with the glenoid as the arm is abducted and externally rotated. If a HSL extends beyond the medial border of the GT, the HSL may engage the anterior rim of the glenoid resulting in recurrent dislocation. Conversely, if the HSL remains within the GT, engagement is unlikely. The width of the GT at 90° of arm abduction was initially measured to be 84% of the intact glenoid width based on cadaveric specimens,[34] but this value was later revised to 83% using 3D MRI of living subjects.[35] As such, bipolar bone loss leads to reduced glenoid track width and an increased risk of engagement.

Using the concept of the GT as a starting point, Di Giacomo et al[36] devised the "on-track" versus "off-track" model as a method of identifying HSLs at an increased risk of engagement. By definition, an "off-track" HSL is likely to engage the glenoid, whereas an "on-track" HSL is unlikely to engage. The overall process of determining whether a HSL is "on-track" or "off-track" can be broken down into three steps (Figure 11). The first step is to calculate the GT. For a patient with bone loss, a circle is superimposed on an en face view of a 3D CT reconstruction of the injured glenoid to estimate the diameter of the intact glenoid (D). The GT is then calculated by subtracting the width of the glenoid defect (d) from 83% of the intact glenoid diameter ($GT = 0.83D - d$). In the second step, a posterior view of a 3D CT reconstruction of the humeral head is used to measure the width of the HSL and the width of the bone bridge between the rotator cuff insertion and the lateral aspect of the HSL. These two values are added together to obtain the Hill-Sachs interval (HSI). The third step is to compare the GT and the HSI. If the HSI is greater than the GT ($HSI > GT$), the medial margin of the HSL extends beyond the GT, the HSL is likely to engage the glenoid, and the HSL is "off-track." Conversely, if the HSI is less than the GT ($HSI < GT$), the medial margin of the HSL remains within the GT, the HSL is unlikely to engage the glenoid, and the HSL is "on-track" (Figure 12).

Implications of Bone Loss for Surgical Management

In general, surgical management of anterior shoulder instability involves repairing injured soft-tissue structures and/or addressing glenohumeral bone loss. First-time dislocations with minimal bone loss or "on-track" lesions can typically be treated with a soft-tissue stabilization procedure (e.g., Bankart repair), which may be performed through an open or arthroscopic approach.[37] Patients with significant bone loss or "off-track" lesions have high rates of recurrence after Bankart repair alone and often require reconstitution of the glenohumeral bony architecture.[4] In this manner, accurate quantification of glenohumeral bone loss based on preoperative imaging is key in determining the appropriate surgical treatment of anterior shoulder instability. The amount of glenoid bone loss that necessitates reconstruction, a concept referred to as critical bone loss, remains a topic of considerable debate with recent estimates as low as 13.5%.[38] Although glenohumeral bone loss is most often addressed through reconstruction of the glenoid surface, patients with particularly large HSLs may require reconstitution of the humeral head by filling the defect with either soft-tissue structures (e.g., Remplissage procedure) or bone graft to prevent engagement.[31]

Summary

The evaluation and management of anterior shoulder instability frequently presents unique challenges for the treating orthopaedic surgeon, particularly in patients with glenohumeral bone loss. In such patients, the degree of glenohumeral bone loss often has implications for both the risk of recurrence and in determining the optimal surgical technique to reduce the risk of postoperative recurrence. As such, the importance of accurate quantification and localization of bone loss on preoperative imaging cannot be overstated. Although radiographs allow for a crude approximation, 3D CT represents the benchmark for assessing glenohumeral bone loss. More recently, 3D MRI has shown accuracy and reproducibility similar to that of 3D CT while also allowing for improved visualization of soft-tissue structures, but limited access and high costs have precluded its widespread adoption.

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