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Operative Techniques in

Sports Medicine

Assessment of Bone Loss in the Shoulder

Matthew T. Provencher, MD, CAPT, MC, USNR,[*,†] Liam A. Peebles, BA,[*] Travis J. Dekker, MD,[†] Zachary S. Aman, BA,[*] and Mitchell I. Kennedy, BS[*]

The accurate identification and quantification of both glenoid bone loss and the presence of a Hill-Sachs lesion is essential in the setting of anterior shoulder instability as it directly dictates patient outcomes. The ability to diagnose and address these potential osseous defects of the glenohumeral joint based on patient history, physical exam, and the findings of various imaging modalities in a clinical setting is fundamental to the overall success of a surgeon's treatment algorithm. Multiple methods exist to quantify bone loss based on diagnostic imaging or arthroscopy, and the surgeon should be mindful of the respective pearls and pitfalls of each imaging modality and their ability to accurately diagnose shoulder bone loss. Pertinent findings in a patient's history such as age, level of activity, enlistment status, and events of recurrent anterior glenohumeral instability can help one not only predict the presence of bone loss, but the location and size of the defect as well. Furthermore, symptoms and signs of chronic instability along with accurate quantification of glenoid bone loss are essential in the algorithm of selecting the correct surgical procedure to provide optimal stabilization and maximize clinical outcomes.
Oper Tech Sports Med 27:2-11 © 2019 Published by Elsevier Inc.

KEYWORDS Glenoid bone loss, Hill-Sachs lesion, recurrent glenohumeral instability

Introduction

Due to an osseous architecture that allows for a large arc of motion as well as rotation, the glenohumeral joint is inherently predisposed to an elevated risk of instability. The incidence of glenohumeral instability events has been estimated to be 0.08/1000 person-years in the general US population, and is significantly greater in active, contact/collision sport, and military populations.[1-5] Recent literature suggests that military personnel in particular are at a 20 times greater risk of experiencing shoulder instability compared to the general US population in the form of either subluxation or dislocation.[3,6] Primary and recurrent instability of the glenohumeral joint is commonly associated with soft tissue damage to the glenoid labrum attachment, which is known as a Bankart tear. Falling onto an outstretched arm with the shoulder abducted and externally rotated is the most common mechanism of injury causing anterior dislocation, in which damage occurs to the anterior band of the inferior glenohumeral ligament along with avulsion of the anteroinferior labrum.[7] This damage to the inferior glenohumeral ligament and anteroinferior labrum defines a Bankart lesion and has been reported in as high as 90% of traumatic anterior shoulder dislocations.[8] In the setting of chronic recurrent glenohumeral instability, the ligamentous stabilizers of the joint experience elongation and attenuation, and the literature has reported that anywhere from 50% to 82% of recurrent patients present with a Bankart lesion.[9-11]

However, osseous defects of the glenoid and humeral head have been found to be heavily implicated in the recurrence of glenohumeral instability as well, thus it is imperative to accurately diagnose and assess these bony pathologies prior to treatment decision making.[12-14] In cases of recurrent glenohumeral instability, numerous studies have cited occurrence rates of bony glenoid injury ranging from 36% to 93.7%, as higher rates of bone loss are associated with a greater number of instability events.[15-18] Furthermore, it has been reported that patients with as little as 13.5% glenoid bone loss (GBL) experience worse functional outcomes following primary surgical stabilization procedures.[14,19] Similar incidence rates of posterolateral humeral head compression fractures, known as

*Steadman Philippon Research Institute, Vail, CO.
†The Steadman Clinic, Vail, CO.
Address reprint requests to Matthew T. Provencher, MD, CAPT, MC, USNR, The Steadman Clinic, 181 West Meadow Drive, Suite 400, Vail, CO 81657. E-mail: mprovencher@thesteadmanclinic.com

https://doi.org/10.1053/j.otsm.2019.01.002
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Hill-Sachs lesion (HSLs), have been reported in approximately 40%-90% of all anterior shoulder instability events and up to 100% in patients with recurrent instability.[20-23] Therefore, the osseous integrity of the glenohumeral architecture specifically has been reported to be one of the most influential factors in the outcomes of surgical repair.[24,25]

Possessing a comprehensive understanding of glenohumeral anatomy and the associated osseous structures is paramount to providing an accurate assessment of bone loss in the shoulder as well as the overall success of surgical stabilization procedures. The glenoid articular surface and labrum are approximately 9 mm in depth in the superoinferior direction and 5 mm deep in the anteroposterior (AP) direction.[26] Following primary traumatic dislocation, articular constraints that act to stabilize the shoulder in the AP direction may sustain damage, which in turn reduce glenoid socket depth and its associated restraining capabilities. Upon traumatic dislocation with avulsion of the anteroinferior labrum, fracture of the glenoid rim may occur, resulting in a bony Bankart lesion. Bony defects of the anterior glenoid produce an arc disparity between the glenoid and humeral head, which allow for the humeral head to subluxate anteriorly with less force and have a detrimental effect on the glenoid's ability to resist axial forces.[24,27] Therefore, it is intuitive that with a greater number of recurrent dislocations or subluxations, the patient will most likely develop greater amount of GBL and increased glenohumeral instability.

Glenohumeral instability can be further exacerbated by the presence of a concomitant HSL, which is classified as bipolar bone loss when osseous lesions of the anterior glenoid and posterolateral humeral head are present.[28,29] HSLs typically occur during an anterior glenohumeral subluxation or dislocation, commonly when the shoulder is forced into abduction and external rotation.[30] When the humeral head experiences a traumatic anterior force, the associated capsulolabral attachments are stretched and often torn, which allow for it to translate anteriorly even further and results in a compression fracture of the posterosuperolateral aspect of the humeral head as it impacts the anterior glenoid. Similar to osseous lesions of the anterior glenoid, HSLs tend to worsen in severity upon recurrent dislocations, as the glenohumeral constraints become further attenuated and allow for repetitive anterior translation of the humeral head.[30] This continuous anterior translation results in recurring damage to the posterosuperolateral aspect of the humeral head, as its relatively softer cancellous bone subsequently impacts against the harder cortical bone of the anterior glenoid.[31] HSLs can further confound GBL when they engage with the anterior aspect of the glenoid rim upon anteroinferior dislocation or subluxation. Engagement of a HSL has been described by Burkhart and De Beer[27] as when the osseous defect of the humeral head is aligned parallel to the glenoid rim and engages with it while the shoulder is in abduction and external rotation. However, when the HSL is not in a parallel orientation with the glenoid rim and thus does not engage when in abduction and external rotation, it is considered to be "non-engaging" and will not promote additional GBL as is seen in the case of "engaging" HSLs.[31]

Patient History and Physical Exam

Recurrent glenohumeral instability commonly results from a Bankart tear of the glenoid labrum attachment. However, in cases of recurrent subluxation or dislocation, patients will frequently present with injury to the osseous architecture of the glenoid and humeral head as well. The ability to accurately assess these potential osseous defects of the glenohumeral joint based on patient history and physical exam findings in a clinical setting is fundamental to the overall success of a surgeon's treatment algorithm. Intricate findings in the patient's history and the physical examination can indicate the presence of GBL, and a careful preoperative evaluation to quantify and manage osseous deficiency of the anterior glenoid can greatly aid the overall treatment process. Following the initial traumatic dislocation or subluxation of the shoulder, the presence of a glenoid rim fracture or attritional bone loss may compromise the static capsulolabral restraints of the joint, making recurrent instability more likely in the future. In order to accurately predict and diagnose the presence of such osseous deficiencies of the glenoid prior to imaging, it is important to understand the patterns of glenohumeral instability as well as clinical factors such as age, gender, level activity, and events of recurrent instability. These findings from a patient's history and physical exam not only guide surgical decision making but can provide clues that help predict the risk of future recurrence and attritional bone loss as well.

The diagnosis of GBL should be suspected in patients that present after sustaining high-energy injuries in which the arm was axially loaded and abducted $\geq 70°$ with extension $\geq 30°$.[24,32] These patients tend to be younger athletes that are highly active, as this population is at the greatest risk of recurrent instability; furthermore, their risk of recurrent instability increases directly with patient activity level.[4,5] In patients with suspected GBL, it is commonly noted that they will present with a prolonged history of instability, experience a progressive ease in subluxation or dislocation of the glenohumeral joint and report a mechanical "clunk" upon manipulation of the defective shoulder. Prior treatments, whether operative or nonoperative, and their respective outcomes should be reviewed along with previous surgical reports and imaging studies to establish the initial injury pattern and adequacy of proposed treatment for the patient's unique pathology. These historical factors then provide a basis to guide a surgeon's physical exam of both the patient's injured as well as contralateral shoulder.

It is imperative that both shoulders are inspected in order to identify physical deformity, prior surgical scarring, scapular dyskinesia, and/or potential atrophy of the rotator cuff.[24,27] This comparison of the injured and contralateral shoulders can also aid in quantifying the direction and magnitude of glenohumeral laxity. To assess both the direction and magnitude of instability, physical manipulations of the shoulder such as the Jobe relocation test,[33] Gagey hyperabduction sign,[34] apprehension sign,[35] and sulcus sign[36] may be useful to employ when doing so (Fig. 1). The primary

Figure 1 The sulcus sign physical exam is used to assess for glenohumeral instability or excessive joint laxity. With the arm in a straight, neutral position and relaxed to the side of the patient, the elbow is grasped and traction is applied in an inferior direction. With excessive inferior translation, a depression occurs just below the acromion between the superior aspects of the glenoid and humeral head. (Color version of figure is available online.)

physical examination should always include a careful neurovascular evaluation of the entire upper extremity, testing of active and passive shoulder motion, assessment of rotator cuff strength, and provocative labral signs. Patients with notable bone loss of the anterior glenoid will typically demonstrate a positive apprehension test in 90° of shoulder abduction and 90° of external rotation, as well as significant anterior or inferior translation of the humeral head over the glenoid rim. Physical findings of this nature may indicate the presence of GBL and should be further investigated with advanced imaging modalities.

To devise an optimal treatment algorithm, close evaluation of osseous injury to the humeral head is required as bipolar bone loss is a common phenomenon, especially in cases of recurrent instability. The history of a patient can lend useful information during the initial assessment of a potential HSL and associated glenohumeral instability. Special attention should be paid to patient-reported symptoms including deep shoulder pain, recurrent instability that is unprovoked or with provocative positioning, mechanical abnormalities (eg, clicking, catching, and crepitus), as these are frequently associated with the presence of a HSL. During physical examination of the shoulder, the load and shift test can be informative to the surgeon, as it assesses the stability of the glenoid rim and humeral head by shifting the shoulder anteriorly. If there is apparent grinding of the glenohumeral joint, it may be indicative of HSL or a glenoid defect that causes abnormal contact on the articular surface.[37] During shoulder apprehension tests, if a patient demonstrates apprehension at lesser degrees of abduction, namely in mid-range, this too may signify the presence of a HSL or bipolar bone loss.[38] Finally, the overall appearance, range of motion, strength, and sensation of the injured shoulder should be compared with those of the contralateral shoulder to evaluate the subjective degree of humeral head deficiency.[30]

Imaging Modalities to Assess Bone Loss

Plain Radiographs

Because routine plain radiographs are often part of the first steps of patient diagnostic workup, the use of this modality to assess for bony lesions of the shoulder may be favorable to clinicians as it offers an efficient, low-cost, and low radiation diagnostic alternative to other imaging modalities.[39] While several studies have advocated for plain radiographs for these reasons, diagnostic sensitivity, specificity, and accuracy can be greatly influenced by patient positioning.[40]

Glenoid Bone Loss

In studies reporting the accuracy and reliability of specific patient positions for plain radiographic imaging, the axillary view, West Point View, true AP radiographs, and the Bernageau view have been recommended. Of these methods, the Bernageau view has been reported to be the most accurate and reliable when referenced to 3D CT imaging,[39-41] although it is difficult to evaluate inferior bony lesions with this method.[40] The axillary view and true AP radiographs have been reported to have low accuracy and reliability when quantifying bone loss.[40,42] However, true AP shoulder radiographs can still be useful in determining if there is a loss of contour, or disruption of the sclerotic line, along the anteroinferior glenoid (Fig. 2). The West Point view has shown efficacy in identifying bone loss, but may not be accurate in

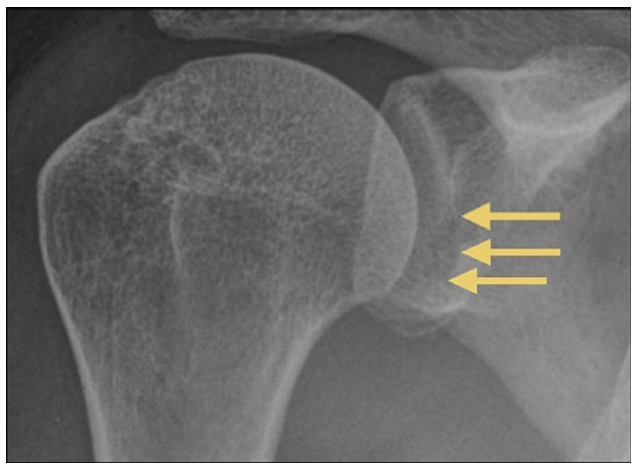


Figure 2 True anteroposterior radiograph of a right shoulder demonstrating loss of the sclerotic glenoid line (arrows) due to an anterior glenoid rim deficiency. (Color version of figure is available online.)

clinical settings.[40]

Overall, plain radiographs have been reported to be inferior to modalities such as 3D CT imaging when quantifying GBL, which may affect clinical decision making. Therefore, it is recommended that plain radiographs should not be used as the sole modality for managing GBL. However, plain radiographs can be useful as an initial screening tool prior to undergoing other imaging protocols to quantify GBL and to proceed with surgical decision making.

Hill-Sachs Lesion

Although radiographs are not the primary means for identification of HSL, routine radiographs of the AP, axillary, and modified axillary view (West Point view) can be helpful when evaluating humeral head defects (Fig. 3). Rowe et al.[25] utilized the axillary view and reported mild to severe HSLs to range from 2 to 4 cm in length and 0.3 to >1 cm in depth. Though, the West Point view is the more commonly used view, by prone positioning of the patient with the beam angled 25° from the midline and directed through the axilla.[43] This view is specifically sensitive to HSLs, because the internal rotation of the humeral head brings any posterolateral defect into direct view.[30,43] The West Point view has even been correlated with CT in evaluating estimated GBL.[40]

Quantification Methods for CT and MRI

Several methodologies for quantifying the degree of GBL exist in the literature. Simply, these techniques have been derived from either surface area or diameter-based measurement methods. The common concept of measuring GBL stems from the notion that the inferior glenoid in the en face view resembles a true circle, and that the degree of bone loss can be calculated utilizing the geometrical properties of a circle or comparing the ratio of measurements taken on a healthy, contralateral shoulder.[15,44] Although there is a lack of consensus and heterogeneity in reporting in the literature, this section serves to describe these measurement techniques and their clinical implications.

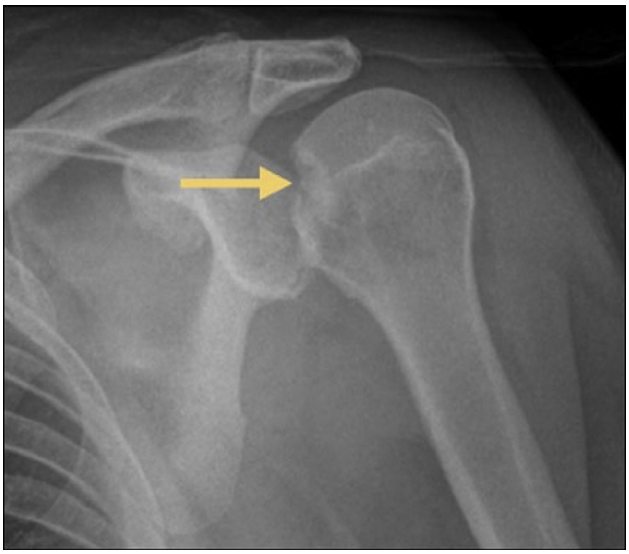


Figure 3 Anteroposterior radiograph of the left shoulder positioned in external rotation. A Hill-Sachs lesion is visualized (arrow). (Color version of figure is available online.)

Surface Area Techniques

The percentage of GBL using surface area techniques are performed by measuring the area of the true circle not occupied by the glenoid surface and dividing this area by the area of the best-fit circle (Fig. 4).[45] Sugaya et al.[44] first described the "circle method" to determine percentage of bone loss area which is calculated by dividing the area that is not filled by the glenoid by the surface area of the best-fit circle. This method was further developed by Baudi et al.[46] known as the PICO method by calculating the area of the glenoid defect by the area of the healthy contralateral glenoid surface area as determined by 2 identical best fit circles.

The PICO method has been reported to be highly accurate and reliable when assessing bone loss,[46,47] and further demonstrated to be more clinically favorable than linear-based measurements[45,48] when performed on 3D CT images. However, this method typically requires bilateral shoulder imaging and most commonly limited to 3D and 2D CT imaging only, although some studies have reported similar results using the ipsilateral glenoid and MRI.[49] It should be acknowledged that surface area calculations require more advanced software and are more complex than linear measurements, however, it has been suggested that quantifying GBL with these methods are more accurate and reliable, leading to more informed decision making.

Diameter (Linear)-Based Techniques

Linear measurements have been reported to be advantageous because they do not need advanced imaging software and

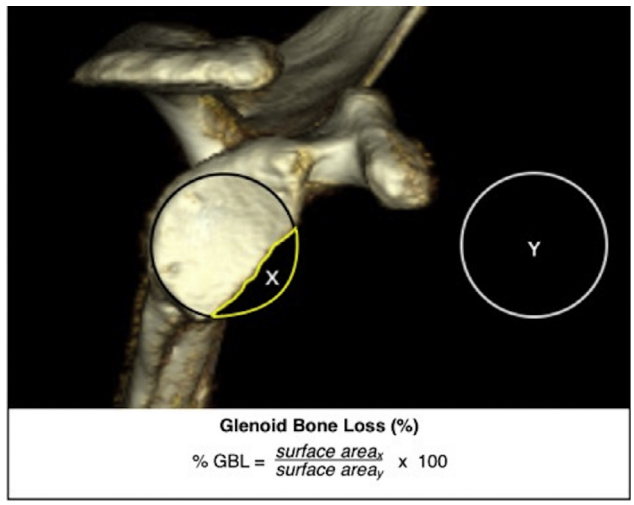


Figure 4 Percentage of glenoid bone loss can be determined through the use of the surface area technique. This is performed by measuring the area of the true circle not occupied by the glenoid surface (X) and dividing this area by the area of the best-fit circle (Y). Preoperative determination of percentage of glenoid bone loss is crucial to guide surgical decision making for procedures that aim to augment osseous defects of the glenoid. (Color version of figure is available online.)

can be quickly applied in the clinical setting.[45] In addition, these methods can be used intraoperatively using arthroscopic measurements, which are described later in this chapter. Several variations of linear based models have been described in the literature. For instance, quantification of bone loss can be determined using the contralateral shoulder or using the best-fit circle technique. The use of the contralateral shoulder may be advantageous because it has been reported that there are no significant differences between healthy and intact contralateral glenoid area, although this assumes that the contralateral shoulder is indeed healthy.[49] In comparison, the best-fit circle width loss techniques are performed on only the injured shoulder and defect size is determined by calculating the width of the glenoid surface and dividing the width by the diameter of the true circle.[45]

Emerging studies have reported that quantification using bilateral CT scans, such as the Glenoid Index, provides the most accurate assessment of GBL. This method consists of comparing the ratio of the measured widths of the injured glenoid to the healthy glenoid.[50] Altan et al.[51] reported in a clinical study that there were no statistically significant differences between Glenoid Index calculations and surface area based measurement technique in patients with >6% GBL. The authors noted that, although insignificant, as the percentage of the bone loss increased, the differences in measurements increased as well.[51]

The location of the bony defect has been reported to play a large role in the accuracy of bone loss quantification for linear measurements. This is because linear measurements can only represent defects in the AP plane. In other words, defects that are located in the anteroinferior portion of the glenoid can be significantly underestimated. This was exemplified by a study performed by Provencher et al.[32], who reported that diameter-based measurements are the most inaccurate when the defect is located anteroinferiorly at a 45° angle with respect to the long axis of the glenoid.

Recent studies using 3D CT imaging have called into question the use of diameter-based measurements. This is because these measurements have been reported to significantly overestimate GBL.[45] For the best-fit circle technique, it has been argued that its inaccuracy is due to an incorrect geometric formula that more closely applies to calculating the area of a square, rather than a circle.[52] In a study by Bhatia et al.,[52] these inaccuracies were most notably found in bony defects that range between 15%-25%. Therefore, these studies have suggested that unnecessary bony augmentation may be performed due to the overestimation of bone loss which exceed the critical threshold of 20%-21% for recurrent instability.[40,52,53]

Magnetic Resonance Imaging

Glenoid Bone Loss

The main advantages of using MRI to detect and quantify GBL include the ability to evaluate both soft tissue and bony pathology concurrently and the avoidance of radiation exposure.[54] However, innate factors limiting the accuracy of MRI have been reported to be scapular tilt and difficult visualization of the glenoid rim in the presence of soft tissue.[55] These factors may lead to inaccurate measurements because of the difficulty of obtaining a true en face slice of the glenoid, as well as difficulty in determining the edge of the glenoid rim, which is crucial when quantifying bone loss via width-length methods.

Although inconsistency in the literature exists regarding whether or not MRI can be used as a substitute to CT, previous studies have reported that MRI does not have significantly different measurements when comparing the 2 modalities.[49,55] Gyftopolous et al.[55] reported that MRI measurements are equally as accurate as 3D CT with small margins of error using the circle method. Similarly, Huijsmans et al.[49] reported nonsignificant differences in accuracy using the best-fit circle method.

While other studies have reported strong accuracy and correlations with 3D CT measurements,[56,57] MRI has been reported to be less sensitive and less reliable than the use of 3D CT.[58] Overall, 2-dimensional measurements such as the width-length ratio may be less reliable than surface area measurements because of the disadvantages described above.[59] Therefore, when using MRI, surface area measurements, such as the PICO method or other best fit-circle techniques, are suggested to be more clinically useful when assessing GBL.[49,54]

2D CT and 3D CT Imaging

Glenoid Bone Loss

CT imaging has been the most extensively studied modality for assessing GBL.[32,59] Although CT scans are more costly and require high levels of radiation exposure in comparison to other modalities,[42,44,50,60] few studies have supported its replacement. In several studies directly comparing different imaging modalities, 3D and 2D CT has been reported to be the most accurate and reliable above MRI, plain radiographs, and arthroscopic methods, with 3D CT imaging recommended as the current gold standard.[42,48,61] In addition, 3D CT has been reported to have 90%-100% specificity in identifying bone loss.[44,62]

When comparing 3D and 2D CT imaging, 3D CT has been reported to be more accurate and reliable.[48] It has been suggested that 3D CT provides the ability to obtain a true en face view more accurate representation of the glenoid surface, which may provide more accurate calculations using surface area measurement methods.[58] In contrast, 2D CT imaging is affected by scapular tilt, which alters the true en face view of the glenoid and impact the accuracy of bone loss quantification.[58] Therefore, the en face view for measurement in a clinical setting should be carefully determined to provide the most accurate assessment.

While 2D CT imaging is limited by scapular tilt, 3D CT imaging requires expensive computer software which may not be available to all healthcare systems.[45] Furthermore, 3D CT is more time consuming due to the conversion of 2D CT images to 3D images.[45] When taking into consideration the differences between measurement techniques, 2D CT has been reported to be more accurate than MRI when using surface area measurements, and is suggested to be preferred over the use of MRI in a clinical setting.[42,55]

Hill-Sachs Lesion

HSLs are essentially engaging bipolar lesions, due to the stipulation that engagement causes the creation of the lesion itself, although occasionally, HSLs may be present with little to no GBL.[63,64] Therefore, determining the severity of the HSL adjacent to the degree and location of GBL is essential because certain concomitance will help guide treatment decisions.[65,66]

Assessment of the glenoid by 3D CT has become more favorable relative to 2D CT and plain radiographs, due to superior accuracy and reproducibility.[42,48,61] The current literature advocates for greater focus on the location of the HSLs relative to the glenoid track (GT) in defining the component of on-track or off-track, in order to determine if the lesion is deemed a "true engaging Hill-Sachs lesion."[67,68] Various assessment protocols for determining glenoid lesions by CT have been detailed in the literature, with early techniques focusing on measures of defect length[69] or width-to-length ratio,[15,70] and progressing into defect size by the glenoid index relative to the contralateral uninjured glenoid relative to the glenoid index.[50,70]

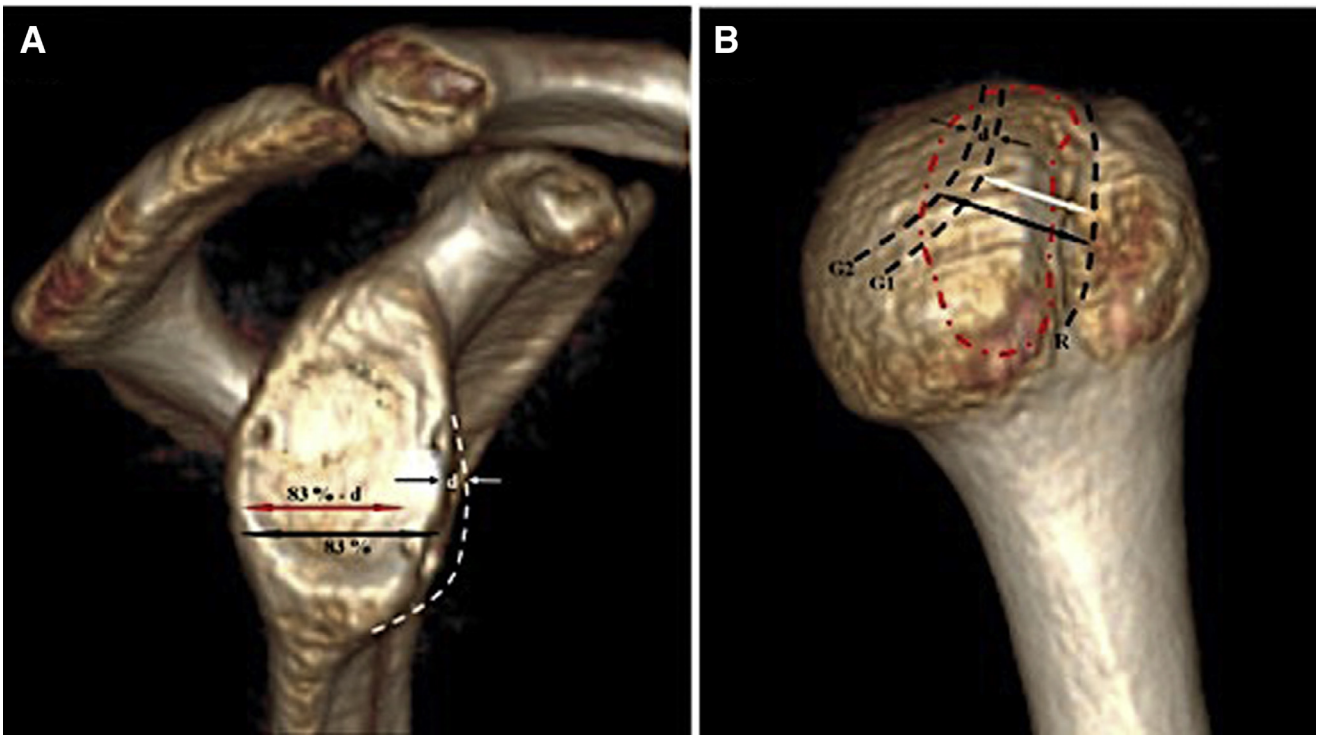
The glenoid tract must first be identified, by approximating 83% of the greatest horizontal width of the glenoid (Fig. 5).[71] The size of the glenoid defect may then be estimated by using the contralateral intact glenoid as a frame of reference and subtracting the greatest horizontal width of the injured glenoid,[65] as the variability between uninjured contralateral glenoid areas has been shown to be 1.8%.[72] Assessment of the HSL follows by utilizing the posterior view of the humeral head. From the medial margin of the rotator cuff attachments, a line, equivalent to the patient specific GT width, is superimposed onto the humerus, representing the Hill-Sachs interval (HSI); the presence of a glenoid defect requires subtraction of the defect length from the 83% measured distance of the intact contralateral shoulder, in order to approximate the altered glenoid tract and subsequent HSI. An on-track HSL is therefore classified when positioned within the HSI, and an off-track HSL is classified when overlapping with the medial margin of the glenoid tract.[65]

Di Giacomo et al.[65] then developed a treatment algorithm, based on the premise that variable glenoid lesion severity and HSL position relative to the glenoid tract requires differential treatment, as instability is reliant on the glenoid-humeral head relationship when the shoulder is in an "at-risk position."[66] A modified treatment algorithm based on the nature of the HSL defect was adapted from Giacomo et al. and is shown in Table 1.[65]

Arthroscopic Evaluation

Glenoid Bone Loss

Burkhart et al.[73] was the first to describe the anatomic bare area of the glenoid and its use as the anatomic center point of the glenoid face. This facilitated easy measurement of bone loss arthroscopically as one could infer in the patient with



Figures 5 (A, B) The 3D CT reconstructions of a glenoid with a bony defect (A) humeral head with medium-sized Hill-Sachs lesion (B). Using contralateral glenoid as a reference (100%), 83% width is determined, the distance from the medial margin of the footprint of the rotator cuff to the medial margin of the glenoid track. Defect width (d) is subtracted from this 83% length to obtain glenoid track width for this case (red double-headed arrow). Dotted line (R) represents the medial margin of the rotator cuff attachment. Line G1 indicates location of medial margin of glenoid track. With no glenoid bony defect, the medial margin of the glenoid track would have been dotted line G2. (Color version of figure is available online.)

Table 1 A Modified Treatment Algorithm Based on the Nature of the Hill-Sachs Lesion and Glenoid Defect Size can be Used to Guide Surgical Treatment Decision Making

Tract Relation	Glenoid Defect Size	Suggested Treatment
On-track	<25%	Arthroscopic Bankart repair
	≥25%	Latarjet procedure
Off-track	<25%	Arthroscopic Bankart repair with remplissage procedure
	≥25%	Latarjet procedure with humeral bone graft or remplissage procedure (if engaging lesion persists after the Latarjet procedure)

anterior instability that the bone from the posterior margin of the glenoid to the bare area was still intact. As a result, the circle formed by the inferior articular margin below the mid-glenoid notch with center point at the bare area allowed for direct comparison of posterior bone integrity to that of anterior bone loss using a probe (Fig. 6). This technique has been validated against 3D CT measurements demonstrating consistent and accurate results when measuring arthroscopically compared to that of the diameter and surface area techniques of 3D CT reconstructions of the glenoid face.[74-76]

Interestingly, qualifying the bare spot of the glenoid as the anatomic center of the glenoid face has been more controversial and can affect the reproducibility of reporting bone loss arthroscopically.[77] The bare spot can be inconsistently identified and has been reported as not being present in patients at a rate ranging between 5%-48%.[77-79] Furthermore, Tokish et al.[78] noted that the anatomic bare area can be eccentrically located, causing confusion to the surgeon leading to apparent bone loss or bone gain. As a result, they recommend not using the glenoid bare area as the sole marker for bone loss measurement.[78] Due to the inconsistency of the glenoid bare area, Detterline et al.[80] described the secant cord theory (SCT) to more accurately identify anterior GBL with a much smaller standard of deviation of measurement error (Figs. 7 and 8).

The authors describe using a standard posterior portal and using the probe as the overall measurement device. The probe is first placed on an area of intact and normal glenoid anterior rim. The total length from the portal site is determined to the intact anterior glenoid and normal posterior glenoid rim are recorded. Next, the probe tip is placed in the central aspect of the bone loss region. Two additional measurements are recorded at this time from the posterior portal the total length to the area of bone loss as well as the length to the normal posterior rim along the same chord. Using the algebraic equation described in the figures, it is possible to calculate the expected chord length measurement versus the actual chord length and derive a more accurate ratio of GBL.

In summary, the bare area of the glenoid can be an inconsistent marker but does provide for quick and rough estimates of GBL. With the use of preoperative planning (3D CT or MRI), the use of the anatomic bare area can simply be a confirmation of already predetermined findings. If the surgeon is debating between treatment methods (bone block augmentation or soft tissue procedures), and a more accurate arthroscopic evaluation of GBL is required, the secant chord theory is a more reliable and accurate modality of measuring GBL.

Hill-Sachs Lesion

Arthroscopy gives the surgeon the benefit of being able to stress the shoulder in a dynamic fashion to evaluate whether

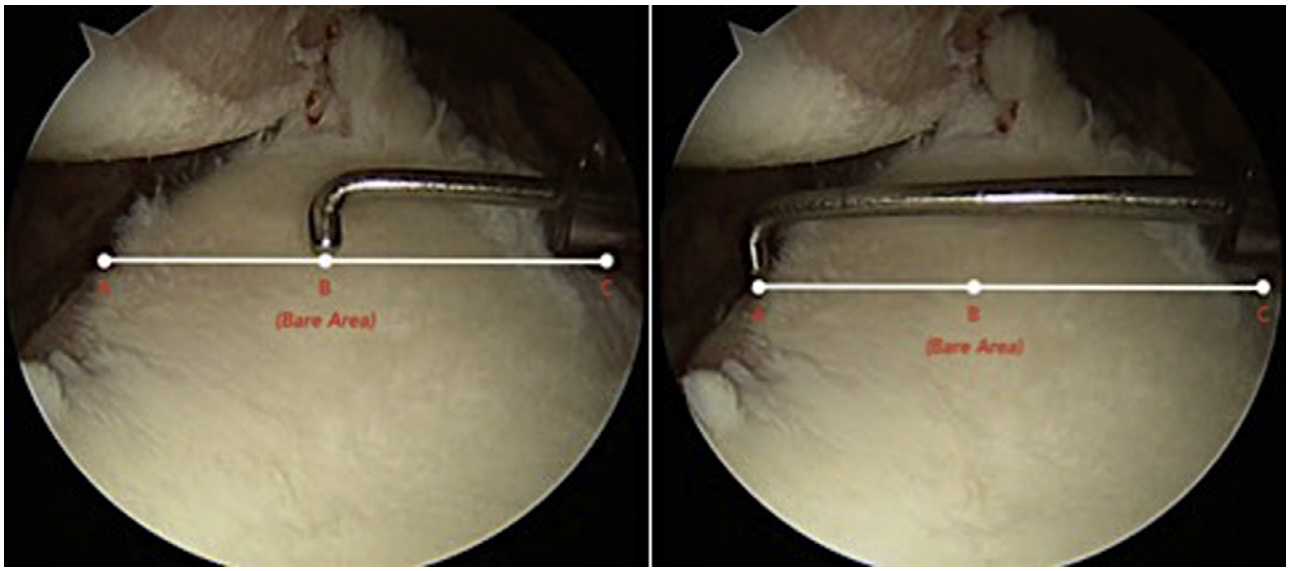


Figure 6 Arthroscopic determination of percent glenoid bone loss based on glenoid bare area. Percent Bone Loss = [(BC) − (AB)]/(2 × BC)] × 100%. (Color version of figure is available online.)

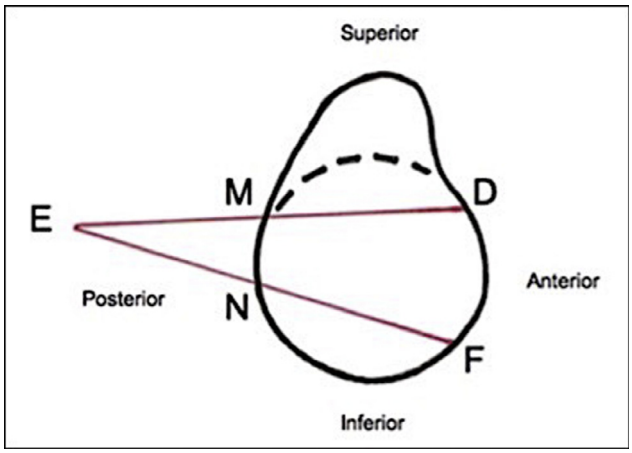


Figure 7 Secant chord theory (SCT) method of calculating bone loss. According to the geometric theorem, FN = (DE × ME/NE) − NE.[80] (Color version of figure is available online.)

the HSL engages the anterior and inferior portion of the glenoid. Regardless of size, evaluating for an engaging HSL is essential as it portends to recurrence and poor outcomes in the setting of arthroscopic repair.[27] To perform an adequate exam, the arm is put in the at-risk position (90° of forward flexion, 90° of abduction, and progressive external rotation) dynamically evaluating the interface between the HSL and the anterior and inferior aspect of the glenoid. If the HSL engages, by definition, the bipolar bone loss is considered off-track and prone to worse outcomes with arthroscopic repair.[65]

The validity of the dynamic exam and whether it is performed prior to or after the arthroscopic repair has been debated.[64,65] As a result, Di Giacomo et al.[65] discussed using the arthroscopic findings of both the GBL and HSL prior to repair to consider if a shoulder is "on-track" or "off-track." Even in the setting of "non-critical bone loss" (<20%), a shoulder can be accurately evaluated for being in "off-track"

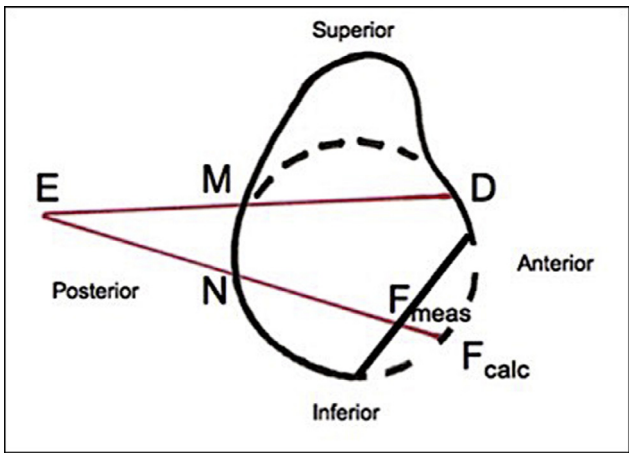


Figure 8 With anterior bone loss present, the measured chord FN ($F_{meas}N$) will be less than the calculated value of FN ($F_{calc}N$) since the inferior portion of the glenoid is no longer circular. Percent bone loss is equal to ($FN_{calc} - FN_{meas}$)/ FN_{calc}.[80] (Color version of figure is available online.)

status which would portend to worse outcomes. First, the GBL is measured using the bare spot as the center of the circle as previously discussed to determine the proposed versus actual diameter of the circle encompassing the inferior 2/3 of the glenoid. The GT is then determined by the following formula: 0.83D-d= GT. The "D" is the diameter of the circle and the "d" is the estimated bone loss based on direct visualization arthroscopically. Next, Di Giacomo et al. evaluated the distance for the HSI, or the total distance from the rotator cuff insertion to the medial aspect of the HSL. The HSI is the sum of the bone bridge between the rotator cuff and the HS lesion and the total width of the HSL itself. With these 2 data points, the track can be determined by simply comparing the HSI to the GT. If the HSI is greater than the GT, the shoulder is considered off-track and the medial rim of the HSL extends beyond that of the glenoid rim. This method has been validated clinically demonstrating improvement in clinical outcomes when evaluating for the track concept compared to the use of anterior GBL alone.[81]

Conclusion

The accurate identification and quantification of both GBL and the presence of a Hill-Sachs lesion is essential in the setting of anterior shoulder instability as it directly affects patient outcomes. In the first time dislocator with suspected osseous defects or those patients with a history of multiple subluxation events, advanced imaging should be obtained to fully evaluate for the compromise of both soft tissue and bony defects. Multiple methods exist to quantify bone loss and the surgeon should be aware of both the benefits and shortcomings of each imaging modality when it comes to the accuracy of identifying GBL and accurately quantifying the size of Hill-Sachs lesions. A predetermined plan from advanced imaging should dictate the surgical procedure and then be confirmed during diagnostic arthroscopy to ensure that the patient receives the optimal surgical procedure that would minimize the risk of further shoulder instability events.

References

1. Porcellini G, Campi F, Pegreffi F, et al: Predisposing factors for recurrent shoulder dislocation after arthroscopic treatment. J Bone Joint Surg Am 91:2537-2542, 2009. https://doi.org/10.2106/JBJS.H.01126
2. Hovelius L, Augustini BG, Fredin H, et al: Primary anterior dislocation of the shoulder in young patients. A ten-year prospective study. J Bone Joint Surg Am 78:1677-1684, 1996
3. Owens BD, Duffey ML, Nelson BJ, et al: The incidence and characteristics of shoulder instability at the United States Military Academy. Am J Sports Med 35:1168-1173, 2007. https://doi.org/10.1177/0363546506295179
4. Pagnani MJ, Dome DC: Surgical treatment of traumatic anterior shoulder instability in American football players. J Bone Joint Surg Am 84-A:711-715, 2002
5. Buckup J, Welsch F, Gramlich Y, et al: Back to sports after arthroscopic revision bankart repair. Orthop J Sports Med 6:2325967118755452. https://doi.org/10.1177/2325967118755452, 2018
6. Owens BD, Dawson L, Burks R, et al: Incidence of shoulder dislocation in the United States military: Demographic considerations from a high-risk population. J Bone Joint Surg Am 91:791-796, 2009. https://doi.org/10.2106/JBJS.H.00514

7. Bankart AS: Recurrent or habitual dislocation of the shoulder-joint. Br Med J 2:1132-1133, 1923
8. Owens BD, Nelson BJ, Duffey ML, et al: Pathoanatomy of first-time, traumatic, anterior glenohumeral subluxation events. J Bone Joint Surg Am 92:1605-1611, 2010. https://doi.org/10.2106/JBJS.I.00851
9. Warren RF: Subluxation of the shoulder in athletes. Clin Sports Med 2:339-354, 1983
10. Mizuno K, Hirohata K: Diagnosis of recurrent traumatic anterior subluxation of the shoulder. Clin Orthop Relat Res: 160-167, 1983
11. Burkhead WZ Jr., Rockwood CA Jr.: Treatment of instability of the shoulder with an exercise program. J Bone Joint Surg Am 74:890-896, 1992
12. Boileau P, Villalba M, Hery JY, et al: Risk factors for recurrence of shoulder instability after arthroscopic Bankart repair. J Bone Joint Surg Am 88:1755-1763, 2006. https://doi.org/10.2106/JBJS.E.00817
13. Nakagawa S, Ozaki R, Take Y, et al: Relationship between glenoid defects and Hill-Sachs lesions in shoulders with traumatic anterior instability. Am J Sports Med 43:2763-2773, 2015. https://doi.org/10.1177/0363546515597668
14. Dickens JF, Owens BD, Cameron KL, et al: The effect of subcritical bone loss and exposure on recurrent instability after arthroscopic bankart repair in intercollegiate American football. Am J Sports Med 45:1769-1775, 2017. https://doi.org/10.1177/0363546517704184
15. Griffith JF, Antonio GE, Tong CW, et al: Anterior shoulder dislocation: Quantification of glenoid bone loss with CT. AJR Am J Roentgenol 180:1423-1430, 2003. https://doi.org/10.2214/ajr.180.5.1801423
16. Guity MR, Akhlaghpour S, Yousefian R: Determination of prevalence of glenoid bony lesions after recurrent anterior shoulder dislocation using the 3-D CT scan. Med J Islam Repub Iran 28:20, 2014
17. Carrazzone OL, Tamaoki MJ, Ambra LF, et al: Prevalence of lesions associated with traumatic recurrent shoulder dislocation. Rev Bras Ortop 46:281-287, 2011. https://doi.org/10.1016/S2255-4971(15)30196-8
18. Edwards TB, Boulahia A, Walch G: Radiographic analysis of bone defects in chronic anterior shoulder instability. Arthroscopy 19:732-739, 2003
19. Shaha JS, Cook JB, Song DJ, et al: Redefining "critical" bone loss in shoulder instability: functional outcomes worsen with "subcritical" bone loss. Am J Sports Med 43:1719-1725, 2015. https://doi.org/10.1177/0363546515578250
20. Calandra JJ, Baker CL, Uribe J: The incidence of Hill-Sachs lesions in initial anterior shoulder dislocations. Arthroscopy 5:254-257, 1989
21. Rowe CR, Patel D, Southmayd WW: The Bankart procedure: A long-term end-result study. J Bone Joint Surg Am 60:1-16, 1978
22. Taylor DC, Arciero RA: Pathologic changes associated with shoulder dislocations. Arthroscopic and physical examination findings in first-time, traumatic anterior dislocations. Am J Sports Med 25:306-311, 1997. https://doi.org/10.1177/036354659702500306
23. Saupe N, White LM, Bleakney R, et al: Acute traumatic posterior shoulder dislocation: MR findings. Radiology 248:185-193, 2008. https://doi.org/10.1148/radiol.2481071003
24. Piasecki DP, Verma NN, Romeo AA, et al: Glenoid bone deficiency in recurrent anterior shoulder instability: Diagnosis and management. J Am Acad Orthop Surg 17:482-493, 2009
25. Rowe CR, Zarins B, Ciullo JV: Recurrent anterior dislocation of the shoulder after surgical repair. Apparent causes of failure and treatment. J Bone Joint Surg Am 66:159-168, 1984
26. Howell SM, Galinat BJ: The glenoid-labral socket. A constrained articular surface. Clin Orthop Relat Res: 122-125, 1989
27. Burkhart SS, De Beer JF: Traumatic glenohumeral bone defects and their relationship to failure of arthroscopic Bankart repairs: Significance of the inverted-pear glenoid and the humeral engaging Hill-Sachs lesion. Arthroscopy 16:677-694, 2000
28. Chen AL, Hunt SA, Hawkins RJ, et al: Management of bone loss associated with recurrent anterior glenohumeral instability. Am J Sports Med 33:912-925, 2005. https://doi.org/10.1177/0363546505277074
29. Arciero RA, Parrino A, Bernhardson AS, et al: The effect of a combined glenoid and Hill-Sachs defect on glenohumeral stability: A biomechanical cadaveric study using 3-dimensional modeling of 142 patients. Am J Sports Med 43:1422-1429, 2015. https://doi.org/10.1177/0363546515574677
30. Provencher MT, Frank RM, Leclere LE, et al: The Hill-Sachs lesion: Diagnosis, classification, and management. J Am Acad Orthop Surg 20:242-252, 2012. https://doi.org/10.5435/JAAOS-20-04-242
31. Armitage MS, Faber KJ, Drosdowech DS, et al: Humeral head bone defects: Remplissage, allograft, and arthroplasty. Orthop Clin North Am 41:417-425, 2010. https://doi.org/10.1016/j.ocl.2010.03.004
32. Provencher MT, Bhatia S, Ghodadra NS, et al: Recurrent shoulder instability: Current concepts for evaluation and management of glenoid bone loss. J Bone Joint Surg Am 92 Suppl 2:133-151, 2010. https://doi.org/10.2106/JBJS.J.00906
33. Jobe FW, Kvitne RS, Giangarra CE: Shoulder pain in the overhand or throwing athlete. The relationship of anterior instability and rotator cuff impingement. Orthop Rev 18:963-975, 1989
34. Gagey OJ, Gagey N: The hyperabduction test. J Bone Joint Surg Br 83:69-74, 2001
35. Magee D: Orthopaedic Physical Examination. (ed 2). Philidelphia: WB Saunders, 1992
36. Neer CS 2nd, Foster CR: Inferior capsular shift for involuntary inferior and multidirectional instability of the shoulder. A preliminary report. J Bone Joint Surg Am 62:897-908, 1980
37. Fox JA, Sanchez A, Zajac TJ, et al: Understanding the Hill-Sachs Lesion in its role in patients with recurrent anterior shoulder instability. Curr Rev Musculoskelet Med 10:469-479, 2017. https://doi.org/10.1007/s12178-017-9437-0
38. Scalise JJ, Miniaci A, Iannotti JP: Resurfacing arthroplasty of the humerus: indications, surgical technique, and clinical results. Tech Shoulder Elbow Surg 8:152-160, 2007. https://doi.org/10.1097/bte.0b013e31806196e6
39. Pansard E, Klouche S, Billot N, et al: Reliability and validity assessment of a glenoid bone loss measurement using the Bernageau profile view in chronic anterior shoulder instability. J Shoulder Elbow Surg 22:1193-1198, 2013. https://doi.org/10.1016/j.jse.2012.12.032
40. Itoi E, Lee SB, Amrami KK, et al: Quantitative assessment of classic anteroinferior bony Bankart lesions by radiography and computed tomography. Am J Sports Med 31:112-118, 2003. https://doi.org/10.1177/03635465030310010301
41. Murachovsky J, Bueno RS, Nascimento LG, et al: Calculating anterior glenoid bone loss using the Bernageau profile view. Skeletal Radiol 41:1231-1237, 2012. https://doi.org/10.1007/s00256-012-1439-9
42. Bishop JY, Jones GL, Rerko MA, et al: 3-D CT is the most reliable imaging modality when quantifying glenoid bone loss. Clin Orthop Relat Res 471:1251-1256, 2013. https://doi.org/10.1007/s11999-012-2607-x
43. Bollier MJ, Arciero R: Management of glenoid and humeral bone loss. Sports Med Arthrosc Rev 18:140-148, 2010. https://doi.org/10.1097/JSA.0b013e3181e88ef9
44. Sugaya H, Moriishi J, Dohi M, et al: Glenoid rim morphology in recurrent anterior glenohumeral instability. J Bone Joint Surg Am 85-A:878-884, 2003
45. Bakshi NK, Cibulas GA, Sekiya JK, et al: A clinical comparison of linear- and surface area-based methods of measuring glenoid bone loss. Am J Sports Med 46:2472-2477, 2018. https://doi.org/10.1177/0363546518783724
46. Baudi P, Righi P, Bolognesi D, et al: How to identify and calculate glenoid bone deficit. La Chirurgia Degli Organi Movimento 90:145-152, 2005
47. Magarelli N, Milano G, Baudi P, et al: Comparison between 2D and 3D computed tomography evaluation of glenoid bone defect in unilateral anterior gleno-humeral instability. La Radiologia Medica 117:102-111, 2012. https://doi.org/10.1007/s11547-011-0712-7
48. Bois AJ, Fening SD, Polster J, et al: Quantifying glenoid bone loss in anterior shoulder instability: Reliability and accuracy of 2-dimensional and 3-dimensional computed tomography measurement techniques. Am J Sports Med 40:2569-2577, 2012. https://doi.org/10.1177/0363546512458247
49. Huijsmans PE, Haen PS, Kidd M, et al: Quantification of a glenoid defect with three-dimensional computed tomography and magnetic resonance

imaging: A cadaveric study. J Shoulder Elbow Surg 16:803-809, 2007. https://doi.org/10.1016/j.jse.2007.02.115
50. Chuang TY, Adams CR, Burkhart SS: Use of preoperative three-dimensional computed tomography to quantify glenoid bone loss in shoulder instability. Arthroscopy 24:376-382, 2008. https://doi.org/10.1016/j.arthro.2007.10.008
51. Altan E, Ozbaydar MU, Tonbul M, et al: Comparison of two different measurement methods to determine glenoid bone defects: area or width? J Shoulder Elbow Surg 23:1215-1222, 2014. https://doi.org/10.1016/j.jse.2013.11.029
52. Bhatia S, Saigal A, Frank RM, et al: Glenoid diameter is an inaccurate method for percent glenoid bone loss quantification: Analysis and techniques for improved accuracy. Arthroscopy 31:608-614, 2015. https://doi.org/10.1016/j.arthro.2015.02.020 . e601
53. Yamamoto N, Itoi E, Abe H, et al: Effect of an anterior glenoid defect on anterior shoulder stability: A cadaveric study. Am J Sports Med 37:949-954, 2009. https://doi.org/10.1177/0363546508330139
54. e Souza PM, Brandao BL, Brown E, et al: Recurrent anterior glenohumeral instability: The quantification of glenoid bone loss using magnetic resonance imaging. Skeletal Radiol 43:1085-1092, 2014. https://doi.org/10.1007/s00256-014-1894-6
55. Gyftopoulos S, Hasan S, Bencardino J, et al: Diagnostic accuracy of MRI in the measurement of glenoid bone loss. AJR Am J Roentgenol 199:873-878, 2012. https://doi.org/10.2214/AJR.11.7639
56. Tian CY, Shang Y, Zheng ZZ: Glenoid bone lesions: comparison between 3D VIBE images in MR arthrography and nonarthrographic MSCT. JMRI 36:231-236, 2012. https://doi.org/10.1002/jmri.23622
57. Lee RK, Griffith JF, Tong MM, et al: Glenoid bone loss: Assessment with MR imaging. Radiology 267:496-502, 2013. https://doi.org/10.1148/radiol.12121681
58. Moroder P, Plachel F, Huettner A, et al: The effect of scapula tilt and best-fit circle placement when measuring glenoid bone loss in shoulder instability patients. Arthroscopy 34:398-404, 2018. https://doi.org/10.1016/j.arthro.2017.08.234
59. Saliken DJ, Bornes TD, Bouliane MJ, et al: Imaging methods for quantifying glenoid and Hill-Sachs bone loss in traumatic instability of the shoulder: A scoping review. BMC Musculoskelet Disord 16:164, 2015. https://doi.org/10.1186/s12891-015-0607-1
60. Kwon YW, Powell KA, Yum JK, et al: Use of three-dimensional computed tomography for the analysis of the glenoid anatomy. J Shoulder Elbow Surg 14:85-90, 2005. https://doi.org/10.1016/j.jse.2004.04.011
61. Rerko MA, Pan X, Donaldson C, et al: Comparison of various imaging techniques to quantify glenoid bone loss in shoulder instability. J Shoulder Elbow Surg 22:528-534, 2013. https://doi.org/10.1016/j.jse.2012.05.034
62. Moroder P, Resch H, Schnaitmann S, et al: The importance of CT for the pre-operative surgical planning in recurrent anterior shoulder instability. Arch Orthop Trauma Surg 133:219-226, 2013. https://doi.org/10.1007/s00402-012-1656-7
63. Warner JJPGC, Itoi E, Lafosse L: Shoulder instability: An international perspective on treatment. ICL 107. In: Presented at the 2013 Annual Meeting of the American Academy of Orthopaedic Surgeons, Chicago, IL; 2013
64. Provencher MTAJ, Boileau P, Ryu RKN, et al: Challenging problems in shoulder instability: How to get it right the first time and what to do if you don't. ICL 282. In: Presented at the 2013 Annual Meeting of the American Academy of Orthopaedic Surgeons, Chicago, IL; 2013
65. Di Giacomo G, Itoi E, Burkhart SS: Evolving concept of bipolar bone loss and the Hill-Sachs lesion: From "engaging/non-engaging" lesion to "on-track/off-track" lesion. Arthroscopy 30:90-98, 2014. https://doi.org/10.1016/j.arthro.2013.10.004
66. Yamamoto N, Itoi E, Abe H, et al: Contact between the glenoid and the humeral head in abduction, external rotation, and horizontal extension: A new concept of glenoid track. J Shoulder Elbow Surg 16:649-656, 2007. https://doi.org/10.1016/j.jse.2006.12.012
67. Kurokawa D, Yamamoto N, Nagamoto H, et al: The prevalence of a large Hill-Sachs lesion that needs to be treated. J Shoulder Elbow Surg 22:1285-1289, 2013. https://doi.org/10.1016/j.jse.2012.12.033
68. Kelkar R, Wang VM, Flatow EL, et al: Glenohumeral mechanics: A study of articular geometry, contact, and kinematics. J Shoulder Elbow Surg 10:73-84, 2001. https://doi.org/10.1067/mse.2001.111959
69. Gerber C, Nyffeler RW: Classification of glenohumeral joint instability. Clin Orthop Relat Res: 65-76, 2002
70. Itoi E, Lee SB, Berglund LJ, et al: The effect of a glenoid defect on anteroinferior stability of the shoulder after Bankart repair: A cadaveric study. J Bone Joint Surg Am 82:35-46, 2000
71. Omori Y, Yamamoto N, Koishi H, et al: Measurement of the glenoid track in vivo as investigated by 3-dimensional motion analysis using open MRI. Am J Sports Med 42:1290-1295, 2014. https://doi.org/10.1177/0363546514527406
72. Jeske HC, Oberthaler M, Klingensmith M, et al: Normal glenoid rim anatomy and the reliability of shoulder instability measurements based on intrasite correlation. SRA 31:623-625, 2009. https://doi.org/10.1007/s00276-009-0492-0
73. Burkhart SS, Debeer JF, Tehrany AM, et al: Quantifying glenoid bone loss arthroscopically in shoulder instability. Arthroscopy 18:488-491, 2002. https://doi.org/10.1053/jars.2002.32212
74. Hamamoto JT, Leroux T, Chahla J, et al: Assessment and evaluation of glenoid bone loss. Arthrosc Tech 5:e947-e951, 2016. https://doi.org/10.1016/j.eats.2016.04.027
75. Griffith JF, Yung PS, Antonio GE, et al: CT compared with arthroscopy in quantifying glenoid bone loss. AJR 189:1490-1493, 2007. https://doi.org/10.2214/AJR.07.2473
76. Shin SJ, Jun BJ, Koh YW, et al: Estimation of anterior glenoid bone loss area using the ratio of bone defect length to the distance from posterior glenoid rim to the centre of the glenoid. Knee Surg Sports Traumatol Arthrosc 26:48-55, 2018. https://doi.org/10.1007/s00167-016-4312-x
77. Miyatake K, Takeda Y, Fujii K, et al: Validity of arthroscopic measurement of glenoid bone loss using the bare spot. Open Access J Sports Med 5:37-42, 2014. https://doi.org/10.2147/OAJSM.S58748
78. Barcia AM, Rowles DJ, Bottoni CR, et al: Glenoid bare area: Arthroscopic characterization and its implications on measurement of bone loss. Arthroscopy 29:1671-1675, 2013. https://doi.org/10.1016/j.arthro.2013.06.019
79. Saintmard B, Lecouvet F, Rubini A, et al: Is the bare spot a valid landmark for glenoid evaluation in arthroscopic Bankart surgery. Acta orthopaedica Belgica 75:736-742, 2009
80. Detterline AJ, Provencher MT, Ghodadra N, et al: A new arthroscopic technique to determine anterior-inferior glenoid bone loss: Validation of the secant chord theory in a cadaveric model. Arthroscopy 25:1249-1256, 2009. https://doi.org/10.1016/j.arthro.2009.05.019
81. Shaha JS, Cook JB, Rowles DJ, et al: Clinical validation of the glenoid track concept in anterior glenohumeral instability. J Bone Joint Surg Am 98:1918-1923, 2016. https://doi.org/10.2106/JBJS.15.01099