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SYSTEMATIC REVIEW

CT estimation of glenoid bone loss in anterior glenohumeral instability

A SYSTEMATIC REVIEW OF EXISTING TECHNIQUES

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Aims
Recurrent dislocation is both a cause and consequence of glenoid bone loss, and the extent of the bony defect is an indicator guiding operative intervention. Literature suggests that loss greater than 25% requires glenoid reconstruction. Measuring bone loss is controversial; studies use different methods to determine this, with no clear evidence of reproducibility. A systematic review was performed to identify existing CT-based methods of quantifying glenoid bone loss and establish their reliability and reproducibility

Methods
A Preferred Reporting Items for Systematic reviews and Meta-Analyses-compliant systematic review of conventional and grey literature was performed.

Results
A total of 25 studies were initially eligible. Following screening, nine papers were included for review. Main themes identified compared 2D and 3D imaging, as well as linear- compared with area-based techniques. Heterogenous data were acquired, and therefore no meta-analysis was performed.

Conclusion
No ideal CT-based method is demonstrated in the current literature, however evidence suggests that surface area methods are more reproducible and lead to fewer over-estimations of bone loss, provided the views used are standardized. A prospective imaging trial is required to provide a more definitive answer to this research question.

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Keywords: Shoulder, Radiology, Shoulder dislocation, Tomography, X-Ray computed

Introduction
Anterior glenohumeral joint dislocation is common, with an incidence of around 12/100,000.[1] Recurrence is related to several factors including glenoid bone loss, and surgical intervention is often required.[2,3]

Since DeBeer and Burkhart[4,5] identified poorer outcomes in a cohort of patients with > 25% bone loss, attention has been focused on the glenoid. More recently, Sheean et al[6] described the concept of the glenoid track, which has drawn attention to the resultant combination of glenoid and humeral defects.

Surgical management options include soft-tissue repair and bony reconstruction, and complex decision-making is involved in deciding the appropriate course of management. Patient factors such as age and obesity, pathological factors (for example, presence of Hill Sachs lesion), and associated soft-tissue damage play an important role. Preoperative imaging helps guide appropriate surgical intervention. Depending on the author, current literature suggests that if the bony defect is greater than around 16% to 20%, a bone graft procedure or Latarjet technique should be considered.[7] If it is less than 16%, then a soft-tissue procedure may be employed successfully.[8] Precise calculation of the extent of bone loss is therefore crucial in this aspect of decision-making. In the majority of people, the glenoid diameter measures 24 to 26 mm, ranging from 23 to

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30 mm.[9] In a 30 mm glenoid, 16% bone loss equates to 4.8 mm, while 10% bone loss equates to 3 mm, a difference of 1.8 mm. Given the relatively small glenoid size and even smaller area of bone loss, discrepancies in measurement can provide relatively large differences in calculated bone loss.

Verweij et al[10] undertook a systematic review of all of the imaging methods for glenoid bone loss. This reviewed evidence for quantification of bone loss using radiograph, 2D and 3D CT, MRI, and arthroscopy, and concluded that there was no single gold standard modality, due to heterogeneity of data seen. Using MRI to measure bone loss has been described, but requires 3D scanners, which are not in common usage.[11]

Arthroscopic assessment has been described as the "gold standard" by some authors, however this is invasive and requires intraoperative rather than preoperative decision-making. CT is considered to be a highly sensitive and specific technique of detecting and quantifying glenoid bone loss, and the most accurate radiological modality for visualization of the cortical glenoid rim. It is readily and rapidly available in most hospitals compared with MRI. Numerous measurement methods are commonly used, including the "circle of best fit", the "Pico" and the "Sugaya method", as well as several involving mathematical computations using both 2D and 3D CT.[12-15]

Each measurement technique has advantages and disadvantages and limited validation in the literature. Additionally, the figures used to justify surgery are based on evidence using several heterogenous techniques, making comparisons exceedingly difficult.The aim of this systematic review is to analyze the current literature to identify techniques used to estimate glenoid bone loss on CT imaging and their evidence base.

Methods

Eligibility criteria. All papers involving patients older than 16 were eligible. All studies investigating CT estimation of glenoid bone loss, whether 2D or 3D, were included. Cadaveric and biomechanical studies were also included, provided they answered the study question. Studies evaluating MRI as a standalone technique, and using arthroscopic measurement, were excluded. MRI is more difficult to obtain and is less amenable to 3D reconstruction. Arthroscopy requires a general anaesthetic, which the authors are keen to avoid in the evaluation of a diagnostic tool for preoperative planning.

Information sources. Search dates included January 2009 to December 2019. Conventional literature was searched using OVID Medline, PubMed, CINAHL and Embase. The grey literature was searched using Opengrey, EThOS, Proquest, and Open DOAR. There were no similar reviews on the Cochrane database.

Search. All databases were searched with identical search terms: 1) "CT measurement AND glenoid bone loss AND recurrent instability"; 2) "CT measurement techniques AND glenoid bone loss AND accuracy"; 3) "CT measurement AND glenoid bone loss"; and 4) "CT analysis AND glenoid bone loss AND recurrent instability". Multiple search threads were used to increase the number of included studies, because at each search stage there were few eligible papers. The references for each article were scrutinized for further studies to include.

Study selection. Initial screening by title was performed to exclude paediatric papers (i.e. under 18 years of age) and those which focused on MRI or arthroscopy. The remaining abstracts were scrutinized, and further exclusions made, based on incorrect imaging modality or irrelevance to the research question. Full-text articles of the remaining studies were assessed, and final exclusions made. Articles were assessed by two independent reviewers (GLG, DT) and any differences in article inclusion were discussed and resolved by consensus.

Data collection process. Methods of glenoid bone loss measurement used were ascertained for each study. There were limited studies directly comparing individual CT measurement techniques, and therefore a broad qualitative overview was documented, including a description and limitations of each technique, and degree of intra- and interobserver agreement where this was included in the study. Information captured included numbers of shoulders included, patient demographic details to ensure reasonable generalization, and measurement technique used. The main outcomes obtained were over- or underestimation of bone loss. This heterogenous group of studies was associated with a degree of reporting bias. All are retrospective, and we acknowledge that there will be selection bias.

Results

Study selection. Using search criteria, 40 studies were eligible, leaving 25 after duplicates removed. Following initial screening, five studies were excluded as they involved paediatric patients, incorrect pathology or imaging modality, or were irrelevant to the research question. Of the remaining 20 abstracts, five were excluded based on incorrect pathology or unrecorded measurement technique. A total of 15 full-text articles were reviewed and eight excluded, as they did not relate to the review question. Reference lists for each of the seven remaining included articles were screened and a further two papers included, leaving studies for review.[16-24]

Study characteristics and results of individual studies. Nine included studies were individually evaluated and findings summarized in Table I.

Throughout this review, if validation has been performed it is discussed and referenced. If no mention is made of validation, it has not been performed.

Table I. Summary of included papers.

Paper	Level of evidence	Purpose	Number of shoulders, demographics	Measurements	Outcomes
2D vs 3D CT					
Bois et al[16]	3	Evaluate accuracy and reliability of 2D/ 3D CT measurements of GBL Mechanical/ lab-based model	4 sawbone models (2 anteroinferior defects, 2 anterior defects) 6 assessors – 6 datasets	2D – glenoid index 3D – En face view- glenoid index (linear)/ Pico (SA) Best fit circle Longitudinal axis from supra-infraglenoid tubercles through centre of circle Index – uses widest part of circle and perpendicular line Pico – as above	2D CT measurements not valid and should not be used 3D Linear methods only reliable if assessor manipulates reference point and volume and only useful for defects parallel to long axis Pico more reliable Linear measurements overestimate GBL
Lacheta et al[17]	3	Comparing 2D and 3D quantification methods of GBL	n = 52 Mean age 32 (21 to 51) 6 raters – blinded to dataset	No view specified Best fit circle contoured to posteroinferior glenoid – maximal diameter measured Linear measurement – measure distance from anterior rim to centre and compared with anterior rim to defect - ratio Assess intraobserver differences in 1) Circle of best fit dimensions and 2) bone loss width % bone loss	3D CT - better intraobserver agreement for all 3 parameters than 2D Ratio method inconsistent even in 3D Main source of error is inconsistent measurement/ placement of best fit circle
Kubicka et al[18]	3	Establishing reliability of measurements performed on 2D and 3D CT for glenoid bone loss	n = 100 (39 F, 61 M) Mean age 43.4 yrs (20 to 85)	5 measurements 2 observers Compared 2D and 3D intraobserver	3D CT more reliable, less intraobserver error
Surface area vs linear					
Bakshi et al[19]	3	Comparison of linear vs surface area measurements of GBL on CT Power study performed	n = 30 (25 M/ 5 F) Mean age 24.9 yrs (15 to 58)	En face view, bilateral CT, digital subtraction Linear = AP distance from centre of best fit circle (centre to anterior edge, centre posterior edge) SA = Pico – best fit circle from uninjured side superimposed on injured side Area of defect subtracted to obtain percentage	Linear method overestimates glenoid bone loss by > 5% $p < 0.0001$
Parada et al[20]	3	Measuring accuracy and reliability of circle-line method of measuring GBL compared with glenoid index method	13 surgeons	3D CT - en face view CLM: Best fit circle drawn Line drawn from centre to edge and compared with centre to defect, expressed as % Glenoid index method – vertical line from supra-infraglenoid tubercle, then perpendicular line at widest part Ratio uninjured:injured	CLM more reliable than glenoid index linear method
CT vs MRI					
Friedman et al[21]	2	Comparing CT and MRI measurements when assessing GBL – intraobserver error	n = 22 (20 M/ 2 F) Mean age 28 yrs (15 to 60) 4 surgeons blinded to patient ID and clinical history.	“Best view to show defect” on both methods Linear measurement – Vertical line supra-infraglenoid tubercles Perpendicular line measured across widest part	Measurement of height has greater intraobserver reliability than width CT measurements more reliable and accurate than MRI
Clinical correlation and imaging variability					
Shijith et al[22]	4	Correlate clinical findings in recurrent shoulder dislocation with CT findings	n = 44 All male Mean age 29.5 yrs	Bilateral shoulder CT scans and clinical examination (apprehension) Oblique coronal slices Best fit circle, linear measurement with glenoid index technique (injured width/width ×100)	On-track lesions increased risk of dislocation compared with off-track No mention of limitations with measurement

Continued

Table I. Continued

Paper	Level of evidence	Purpose	Number of shoulders, demographics	Measurements	Outcomes
McNeil et al[23]	3	Evaluate attritional bone loss of bony Bankart fragment Clinical correlation	n = 139 Mean age 29.2 yrs (19 to 49)	3D CT – en face view Surface area digital subtraction technique to obtain % bone loss (Pico) For attrition of bony fragment – bony fragment measured and compared to area of bone loss, expressed as %	Bony Bankart fragment attrition is important predictor of recurrence of dislocation (rather than overall % GBL)
Moroder et al[24]	3	Analyze effect of lack of standardization of view on reliability of measurement of GBL	n = 10 (9 M, 1 F) Mean age 34 yrs (16 to 61) 3 surgeons reviewed images	3D models rendered from CT data – en face view Further views at stepwise horizontal 5° rotations 72 images obtained Surgeons shown and asked to pick best en face view Compared conventional technique to spoon technique (using best fit circle placed on rim forming highest points of glenoid as opposed to contour to posteroinferior edge)	Intraobserver agreement on best en face view only 30% Good reliability for each measurement of glenoid (best fit circle area/ glenoid defect diameter) Tilt of view resulted in different measurements of above parameter but this was negated by use of spoon technique (moving best fit circle)

AP, anteroposterior; CLM, circle line method; GBL, glenoid bone loss; SA, surface area.

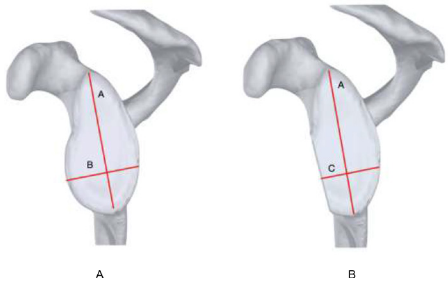

Fig. 1

Illustration of landmark linear measurement. The "Griffiths Index". Anterior shoulder dislocation: Quantification of glenoid bone loss with CT.[13] A: Measurements performed on the normal shoulder, B: measurements performed on the injured shoulder.

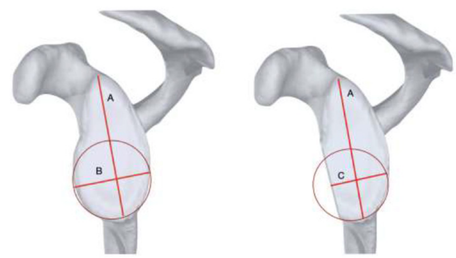

Fig. 2

Illustration of the "Glenoid index". From Chuang et al.[12]

Three main themes presented in the studies were deemed important in quantifying glenoid bone loss in recurrent instability: 2D versus 3D imaging, use of linear- or area-based measurements, and comparison with MRI.

2D vs 3D imaging. CT has been widely regarded as the modality of choice in evaluating bony pathology, including glenoid bone loss. The first theme establishes whether 3D CT is equal to, better, or worse than 2D imaging. Three studies evaluating this conclusively suggest that measurements are more reliable on 3D CT.[16–18] Bois et al[16] even state that 2D imaging is "invalid" and should not be used to evaluate bone loss. This is contradicted by Magarelli et al[25] who concluded, when using Pico assessment, that 2D and 3D scans are interchangeable after comparing agreement between 2D multiplanar reconstruction and 3D volume rendering techniques using Bland-Altman method, with percentage agreement being 97% ($p < 0.0001$). The view found to be most reproducible is the "en face" view on 3D reconstruction.[15-17,23,24] Moroder et al[24] assessed the reliability of this view and suggested that although individual measurements of glenoid morphology (i.e. area of circle of best fit, anteroposterior (AP) diameter, and defect diameter) were reliable between surgeons, there was only a 30% interobserver agreement on the view selected and therefore what constituted an en face view. Furthermore, they identified that differences in the degree of horizontal tilt of the glenoid significantly changed the measurements taken. Hence, if not all chosen views are equal between surgeons, then comparisons between studies is impossible. Therefore, 3D CT with a standardized en face view is the suggested imaging modality which is most likely to provide reproducible measurements.

Linear methods. The second theme highlighted was the comparison between surface area and linear methods. The simplest technique, based on 2D scans, was described by Griffith et al[13] and has become known as the "Griffith Index". This involves drawing a vertical line (A) from the supraglenoid tubercle to the infraglenoid tubercle on the uninjured side, then drawing a line at the widest point of the glenoid perpendicular to this reference line (B). The process is repeated with the injured glenoid (Figure 1). The normal ratio (B/A) is 0.7 and an injured glenoid ratio (C/A) is less than this. Validation against an arthroscopic "gold standard" was undertaken. Two important points should be noted from Griffiths paper. Firstly, several methods were analyzed and the authors

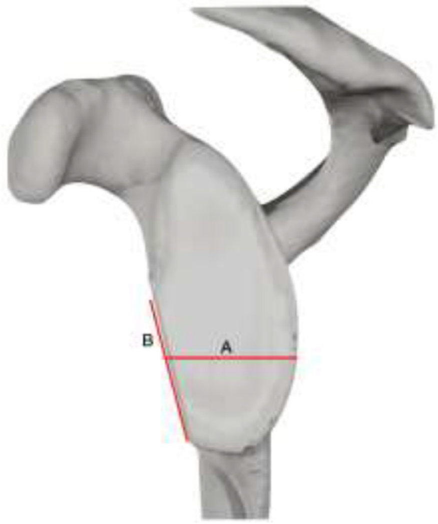

Fig. 3
Illustration of the "Gerber index".[3]

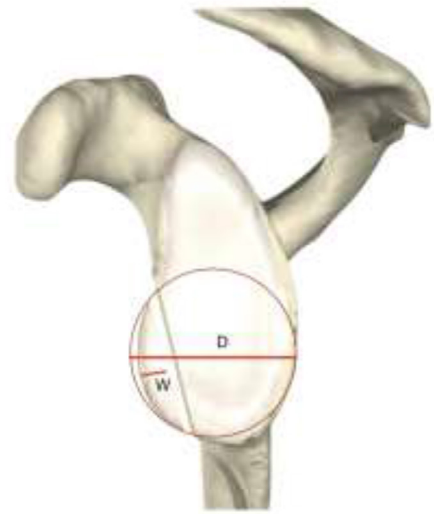

Fig. 4
Alternative linear method, as described by Sugaya.[27]

felt that a simple comparison of measurements B and A was the most reliable method of determining bone loss; secondly, the technique which has now become eponymous was good but less accurate, as the formatting and orientation of CT slices used in this technique are more likely to underestimate the degree of bone loss.

Chuang et al[12] modified this technique in 2008, adding a circle of best fit to the uninjured side as the reference for the injured diameter. The term "Glenoid Index" was given for this relationship (Figure 2). A glenoid index on 3D CT of 0.75 or more was hypothesized to predict need for soft-tissue surgery (arthroscopic Bankart repair), and less than 0.75 predicted open Latarjet. At the time of surgery, this was demonstrated to be accurate in 96% of cases; however the total number of patients included was small at 25.

Gerber and Nyffeler[3] measured the maximum diameter of the glenoid (A), and the length of the defect (B). Calculating B/A gives the Gerber Index; a ratio rather than a direct measurement (Figure 3), which has been shown to be simple and reproducible.[26]

An alternative linear method, measuring the bone fragment on 3D CT, was described by Sugaya in 2005.[27] The circle of best fit is created, and diameter (D) determined. The maximum AP width of the bone fragment is measured (W). The percentage bone loss is then calculated as (W/D) ×100 (Figure 4).

Barchilon et al[28] analyzed two techniques, comparing one of them on a 2D and 3D reconstruction. A digital circle of best fit was applied to the lower glenoid. The radius of the glenoid (R) was calculated by measuring from the margin of the circle to the centre. The distance from the centre to the anterior margin of the glenoid (d) was measured (Figure 5).

They used the formula

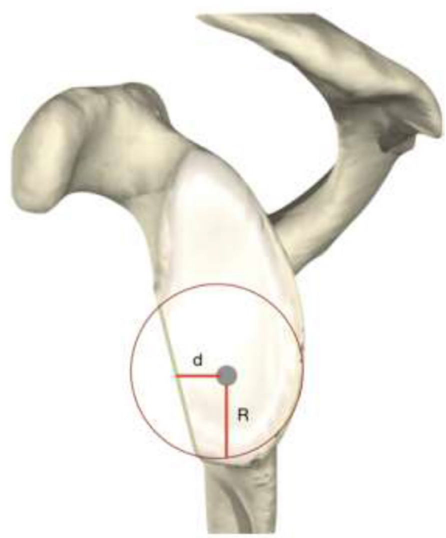

Fig. 5
Barchilon's method of digitally calculating circle of best fit.[28]

$$\text{Percent Bone Loss} = \frac{1}{\pi}\left(\cos^{-1}\left(\frac{d}{R}\right) - \left(\frac{d}{R}\sqrt{1-\left(\frac{d}{R}\right)^{2}}\right)\right)$$

They compared these two techniques to a computerized function, and concluded all three were equivalent after obtaining comparable measurements for the area of bone loss, including comparable standard deviations.

Parada et al[20] devised a linear method described as the "circle line method" (CLM) in order to quantify bone loss using a best fit circle and then measuring the diameter (D) of the circle to calculate the glenoid area (a). The superoinferior length of the defect is identified and drawn onto the best fit circle as a chord (C).

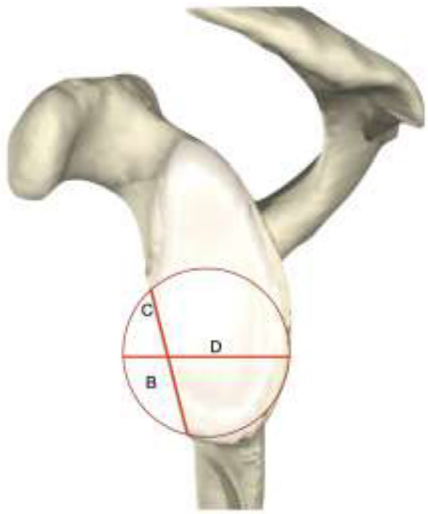

Fig. 6

Parada's centre line method.[20]

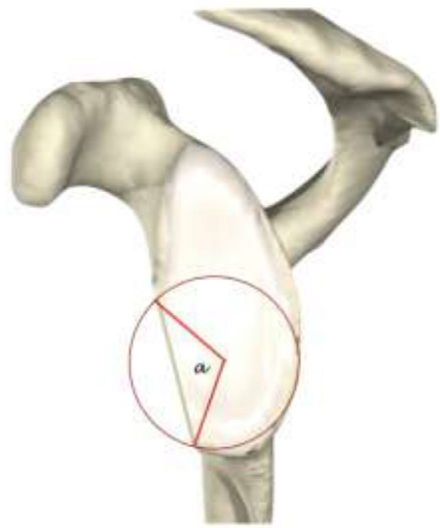

Fig. 7

Dumont's method of calculating best fit circle.[29]

The equation for a chord is: chord length = 2 r sin (c/2). This is used to calculate the central angle c. and in turn used to calculate the bone loss area (B) where B= (r2/2)×((pi/180) c -sin c). The percentage glenoid bone loss is then calculated as (B/A) ×100 (Figure 6).

In comparison to the traditional glenoid index method, they found this more reproducible, as it was deemed simpler to place a best fit circle rather than accurately reproduce identical vertical lines from the supraglenoid tubercle. Statistical analysis using an analysis of variance (ANOVA) and Tukey post hoc testing confirmed there was a significant difference between the CLM and standard line measurements ($p < 0.001$), with CLM being more reproducible.

Dumont et al[29] described another technique on 3D CT images which required additional measurements based on the circle of best fit, and measuring the angle subtended by two lines drawn from the superior and inferior margins of the defect, using the calculation: % Area bone loss=((a -sina)/2Pi)× 100 (Figure 7). The authors suggest this method is more reliable as it does not rely on standard views.

Overall, a multitude of linear- and surface area-based techniques are used and have been shown to be reproducible in largely small numbers of papers with low evidence level. All these techniques are influenced by the ability to obtain a standardized view on which to measure and are heterogenous in their outcomes. No ideal method is therefore presented.

Area methods. Of these methods, the most commonly used is the "Pico" method described by Baudi et al[30] based on 2D CT. A circle of best fit is placed on the posteroinferior border of the glenoid and its area (A) established. The area of the bone fragment is measured (B) and digitally subtracted, giving a percentage surface area

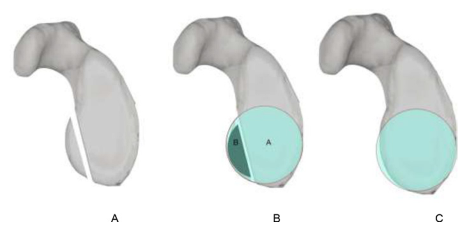

Fig. 8

Pico method. From Baudi et al[30] A: Illustration of 2D CT with anterior glenoid bone fragment, B: best fit circle incorporating the bone fragment. C: best fit circle on the contralateral glenoid.

(Figure 8). In cases where the bone fragment could not be identified, the authors used the uninjured side to derive the best fit circle using bilateral CT and used this as the area A. The area of the circle not covering bone was assumed to be the equivalent to area B and was used to derive the percentage bone loss.[16] Magarelli et al[31] confirmed that there was high intra- and interobserver reliability with this technique, however it should only be used in unilateral instability.

Bakshi et al[19] showed that linear methods significantly overestimated bone loss compared with surface area methods ($p < 0.0001$), but in small numbers of patients ($n = 28$). Bois et al[16] demonstrated the Pico surface area method, using intraclass correlation, was more accurate and reliable than linear methods, and that linear methods overestimate loss. With use of 3D CT, the Pico method had the least percentage error (at 4.93%). Furthermore, they suggested linear methods are only useful for defects which are parallel to the long axis, underestimate those that are perpendicular to it, and are only reliable if the reference points can be manipulated.

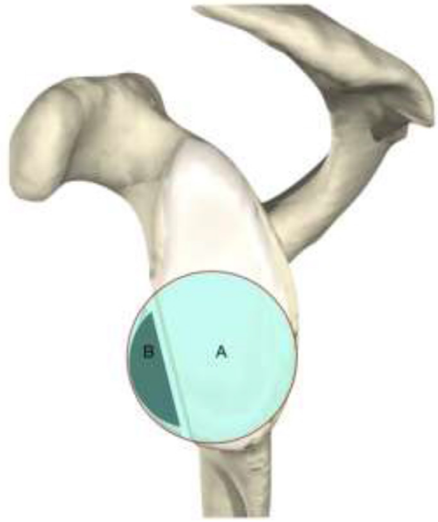

Fig. 9

Sugaya adaptation of Pico method, from Sugaya et al.[15]

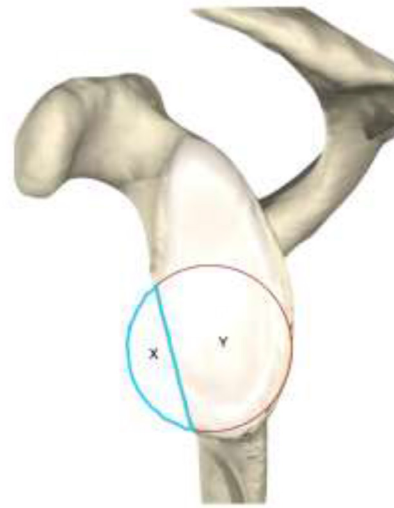

Fig. 10

Calculation of area of attrition of Bankart fragment. McNeil et al[23]

3D surface rendering enables more accurate measurements of the glenoid face, and all more recently published techniques use this image manipulation.

Sugaya et al[15] described a very similar technique to that of Baudi, but based on 3D CT, measuring the area of the bone fragment (B) and the area of the best fit circle (A), then using the ratio B/A to calculate the deficit. They only used the injured side to develop the circle of best fit, demonstrated in Figure 9. Huijsmans et al[32] performed validation of this technique, concluding that the intra- and interobserver reliability were good. The criticism of this study is the small sample size and that it is underpowered.

Rather than quantifying bone loss as a percentage of the normal glenoid, McNeil et al[23] suggested that attrition of the bony Bankart fragment is important in predicting future dislocation. Using a 3D CT en face view to digitally trace the defect, percentage overall glenoid bone loss was calculated using the formula % bone loss = (area X/ area Y) × 100 (Figure 10). They correlated with clinical examination and found that bony Bankart attrition is an important predictor of recurrent instability.

These studies also demonstrate a number of techniques which are reproducible in small samples, but require standardized imaging views. Again, no ideal technique exists.

The third theme is comparison with MRI, which is important given its associated reduced ionizing radiation dose. This is outside the scope of this review, but overall it appears that measurements are less reliable on MRI than CT as delineating landmarks is more subjective, as shown by Friedman et al.[21]

Discussion

Anterior shoulder dislocation is a common injury, with a high rate of recurrence in young patients and high-level athletes. Glenoid bone integrity is critical for shoulder stability, and it is recognized that the risk of further dislocations is associated with the degree of bone loss.[12-15,17] Many surgeons base the choice of operative intervention, be it soft-tissue versus bony stabilization, on the extent and location of glenoid bone loss, although more recently importance has been placed on the presence of Hill-Sachs lesions and whether these are "on track" or "off track". Sheean et al[6] suggested a surgical decision algorithm based upon the extent of bone loss on CT (up to 25% or > 25%) and the presence of absence of a Hill-Sachs on-track lesion. This highlights that, although not the sole factor in decision-making, the amount of bone loss is a useful measurement to guide management, and hence the need for an accurate means of obtaining this.

MRI has no ionizing radiation risk, but is poorer at delineating bony landmarks and has less interobserver reliability when conducting morphological measurements.[17,32] It is also more time-consuming and costly. Comparison of 3D Zero echo time MRI with 3D CT measurement of glenoid widths has been studied by De Mello et al.[33] This MRI technique has been shown to have excellent intra- and interobserver agreement with regard to measurement, and has demonstrated similar resolution to CT with equal post-imaging processing times to reconstruct images.[33] Although promising, this technique is not readily available in all centres.

Arthroscopy is useful for assessing the soft-tissues and allows visualization of the glenoid, but is difficult to use for accurate quantification of the extent of bone loss, is not useful as a preoperative planning tool, and requires a general anaesthetic. CT reliably delineates bony morphology and can be relatively easily reconstructed into three dimensions; however, it does confer an ionizing radiation dose.[12-14]

3D CT is currently the most widely used modality, with the en face view most commonly employed for measurement using both linear and surface area methods. There is evidence, however, that this view is not standardized and can be affected by scapular tilt and variant patient anatomy.[24]

Several CT methods have been established to quantify bone loss, broadly divided into linear and surface area methods. Each technique depends on many factors to improve accuracy, including accurate description and identification of landmarks, obtaining a reproducible glenoid view, and the chosen method of calculation.[12,15-24,28-30]

Both approaches have been shown to be reproducible, however evidence suggests linear methods may overestimate bone loss,[16,19] which may affect surgical decision-making and lead to more complex surgical intervention.

Several studies advocated methods using the uninjured shoulder as a comparison.[34,35] This assumes perfect symmetry and morphologically identical glenoids, to obtain accurately calculated bone loss. Shi et al[36] concluded there was excellent side-side consistency however Parada et al[20] advised caution after identifying 8% of glenoids having a side-side difference of > 3 mm. It also assumes that CT slices chosen are the same with identical placement of best fit circle. Placement of this circle on the glenoid surface and its size between observers has been identified as a cause for error.[20,21]

In conclusion, accurate and reliable methods of quantifying glenoid bone loss are key in aiding surgical decision-making in managing recurrent shoulder dislocations. Multiple techniques have been described, with no ideal measurement or imaging modality yet identified. 3D CT, using surface area measurement, is the most reliable and accessible method at present. Identifying standard views and a comparative study of techniques is required to further improve measurement.

Take home message

- The degree of glenoid bone loss in recurrent anterior glenohumeral joint dislocation affects the ongoing management and therefore accurate measurement of this is important.
- Multiple imaging modalities and techniques are described, with no ideal method identified.
- Identifying standard views within each modality will help establish more accurate techniques.

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