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CT methods for measuring glenoid bone loss are inaccurate, and not reproducible or interchangeable

D. Tennent,
T. Antonios,
M. Arnander,
V. Ejindu,
N. Papadakos,
A. Rastogi,
Y. Pearse

From St. George's Hospital NHS Trust, London, UK

Aims

Glenoid bone loss is a significant problem in the management of shoulder instability. The threshold at which the bone loss is considered "critical" requiring bony reconstruction has steadily dropped and is now approximately 15%. This necessitates accurate measurement in order that the correct operation is performed. CT scanning is the most commonly used modality and there are a number of techniques described to measure the bone loss however few have been validated. The aim of this study was to assess the accuracy of the most commonly used techniques for measuring glenoid bone loss on CT.

Methods

Anatomically accurate models with known glenoid diameter and degree of bone loss were used to determine the mathematical and statistical accuracy of six of the most commonly described techniques (relative diameter, linear ipsilateral circle of best fit (COBF), linear contralateral COBF, Pico, Sugaya, and circle line methods). The models were prepared at 13.8%, 17.6%, and 22.9% bone loss. Sequential CT scans were taken and randomized. Blinded reviewers made repeated measurements using the different techniques with a threshold for theoretical bone grafting set at 15%.

Results

At 13.8%, only the Pico technique measured under the threshold. At 17.6% and 22.9% bone loss all techniques measured above the threshold. The Pico technique was 97.1% accurate, but had a high false-negative rate and poor sensitivity underestimating the need for grafting. The Sugaya technique had 100% specificity but 25% of the measurements were incorrectly above the threshold. A contralateral COBF underestimates the area by 16% and the diameter by 5 to 7%.

Conclusion

No one method stands out as being truly accurate and clinicians need to be aware of the limitations of their chosen technique. They are not interchangeable, and caution must be used when reading the literature as comparisons are not reliable.

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Introduction

The surgical management of anterior glenohumeral instability is still evolving, with failure rates of up to 30% with soft-tissue stablization.[1] Although the reasons for failure are multifactorial, glenoid bone loss is a critical factor. Bigliani et al[2] identified significantly worse outcomes after soft-tissue repair in patients who had more than 25% glenoid bone loss. Burkhart and De Beer[3] recommended that these patients with this degree of bone loss should be managed with glenoid augmentation, and good results have been obtained with this approach.[4]

Several studies have reported high recurrence rates following soft-tissue stablization surgery at the threshold value of 25% and as a result, the threshold value has decreased from 20% to 15%.[5,6] Shaha et al[7] recommended a threshold of 13.5%, and Cavalier

Correspondence should be sent to Duncan Tennent; email: duncan@tennent.net

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et al[8] recommended 10% in patients under 23 years. Many methods for assessing glenoid bone loss have been described, and most use CT with or without 3D reconstruction.[9,10] The glenoid has an mean diameter of 26 mm (23 to 30).[11] At the upper end of the range, a critical bone loss value of 15% equates to 4.5 mm bone loss, and 10% equates to 3 mm, a difference of only 1.5 mm. Measurement techniques must therefore be able to discriminate between these very small differences.

Many of the published methods for assessing glenoid bone loss have never been validated.[9] Even though some have been shown to be reliable, none have compared accuracy against a benchmark control. At smaller threshold values, such as 15% recommended by Gowd et al,[6] measurement errors will have a relatively greater impact on accuracy, and it cannot be assumed that the accuracy of a technique determined using higher threshold values will be the same as the accuracy of a technique using lower threshold values.

Most techniques require the derivation and application of a circle of best fit (COBF). To date, very little work has been undertaken to confirm whether the COBF derived from an intact, contralateral glenoid is the same as the COBF derived from the glenoid that has bone loss and the existing data gives no clear answers.[12] Furthermore, Parada et al[13] advised caution as there could be significant side-side differences in glenoid size.

This investigation had three aims:

1. To assess the accuracy of the most commonly quoted techniques used to measure glenoid bone loss;
2. To assess the reproducibility of each of these techniques;
3. To determine whether the circle of best fit (COBF) is better derived from an intact or a deficient glenoid.

Hypothesis 1: All techniques would be accurate and reproducible at levels of bone loss both above and below a 15% threshold.

Hypothesis 2: The COBF generated on an intact glenoid would be the same as one generated on a glenoid with bone loss.

Methods

Creating test 3D models. We used three identical anatomically accurate scapula models (3B Scientific, UK). One intact model was scanned in a GE Revolution CT scanner with acquisition of 0.625 mm axial slices reformatted to produce a 3D model. This served as a reference of an uninjured glenoid (glenoid 0). The glenoid surface was oriented perpendicular to the horizontal.[14] The CT model could be rotated around a single axis (y axis).

We defined the diameter of the intact glenoid by obtaining the widest measurement perpendicular to the long axis of the glenoid using a digital calliper (Adoric, USA). The model was then cut as perpendicular to the long axis as possible with a handsaw to create 13% anterior bone loss. The width of the glenoid diameter was re-measured (Figure 1). We defined true bone loss as the difference between the original diameter and the diameter of the cut glenoid, expressed as a percentage. A CT scan was then obtained and formatted as previously to create Glenoid 1.

The model was then further cut at 18% and 23%, and scanned to create glenoid 2 and glenoid 3. The remaining two intact physical models were treated in the same way. These percentage defects were chosen because they fall on either side of the most widely accepted thresholds of "critical" bone loss (15% and 20%).

In all, ten 3D CT images were generated: one native uncut glenoid (glenoid 0), and three at each of the three levels of bone loss (three each of glenoids 1, 2, and 3). The images were anonymized, relabelled, and randomized in the PACS system (IntelliSpace PACS; Philips, the Netherlands).

Glenoid measurement techniques. Measurement techniques broadly fall into three categories: linear, area, and mathematical.

Linear techniques. Linear techniques measure the width of the residual glenoid and express this as a percentage of the diameter of the native glenoid. The diameter of the native glenoid can be determined in three ways: first, from the contralateral side (Figure 2); second, using a COBF, obtained from the ipsilateral glenoid (Figure 3); and third, using a COBF obtained from the contralateral intact glenoid (Figure 4).

Area techniques. Area techniques measure the area of the glenoid defect and express this as a percentage of the area of the native glenoid. The area of the native glenoid is determined from a COBF which can be obtained either from the contralateral, intact glenoid (Pico technique) or from the ipsilateral glenoid (Sugaya technique) (Figure 5).

Mathematical techniques. Several mathematical methods of measuring bone loss have been described. In this study, we elected to use the circle line method, as described by Parada et al[15] (Figure 6).

Test measurements. Four fellowship-trained orthopaedic shoulder surgeons (DT, AT, MA, YP) and threefellowship trained musculoskeletal radiologists (AR, NP, VE) performed the five measurements (Figure 7) on the nine randomly ordered images (using glenoids 1, 2, and 3) using an ipsilateral COBF on two separate occasions. Measurement of diameter was made perpendicular to the cut edge of the glenoid. From these measurements, it was possible to obtain percentage defect values using the techniques described above. All participants were unaware of the size of the defect in the physical model.

Later, participants obtained a COBF fit from glenoid 0. This was applied to each of the nine test scans and the diameter of the residual glenoid (d) was measured

Fig. 1

Calliper measurement of the diameter of the model.

(Figure 3). For the area measurements, each of these images was converted into a JPEG file. The area of glenoid bone loss was measured using the freehand measurement tool in ImageJ software.[16]

Each test was repeated at an interval of a minimum of two weeks. All bone loss measurements were then calculated by one author (DT). The circle line method was calculated using the formula for the area of the segment of a circle based on chord length and diameter. Chord length (C) = 2 r sin(c/2) where r = radius and c = central angle, with the area of the segment (B) calculated as $B = r^2/2((\pi/180)C - \sin C)$.

Data analysis. We determined accuracy in two ways. First, we examined the relationship of the calculated value to

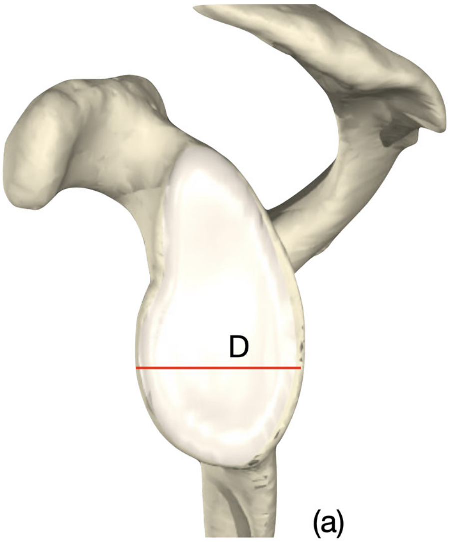

Fig. 2

Relative diameter technique. The diameter of the injured glenoid (d) is expressed as a percentage of the diameter of the contralateral glenoid (D).

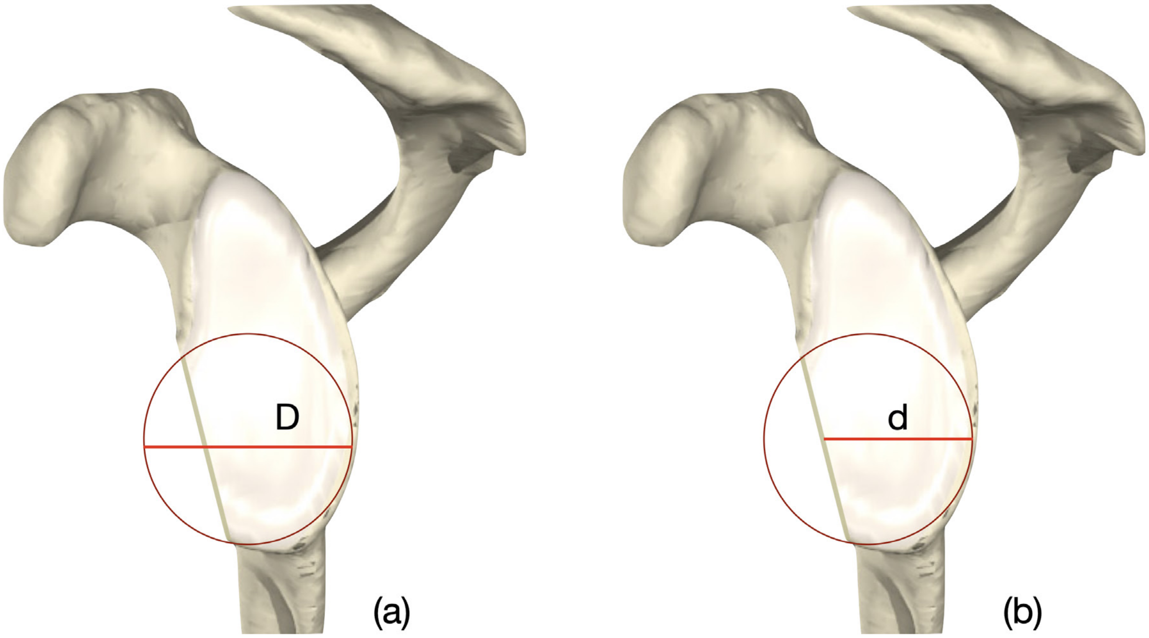

Fig. 3

Linear ipsilateral COBF The diameter of the injured glenoid (d) is expressed as a percentage of the diameter of the circle of best fit (D).

the measured value (mathematical accuracy) for each technique. Second, we examined the statistical accuracy of each technique to predict the need for bone grafting based on the predefined thresholds. Mean percentage bone loss for each technique was calculated. This value was compared with the true value obtained using the digital callipers (Table I and Figure 8).

Using a threshold bone loss of 15%, glenoid 1 (13.8%) would be expected to produce values below threshold, and glenoid 2 (17.6%) would be expected to produce

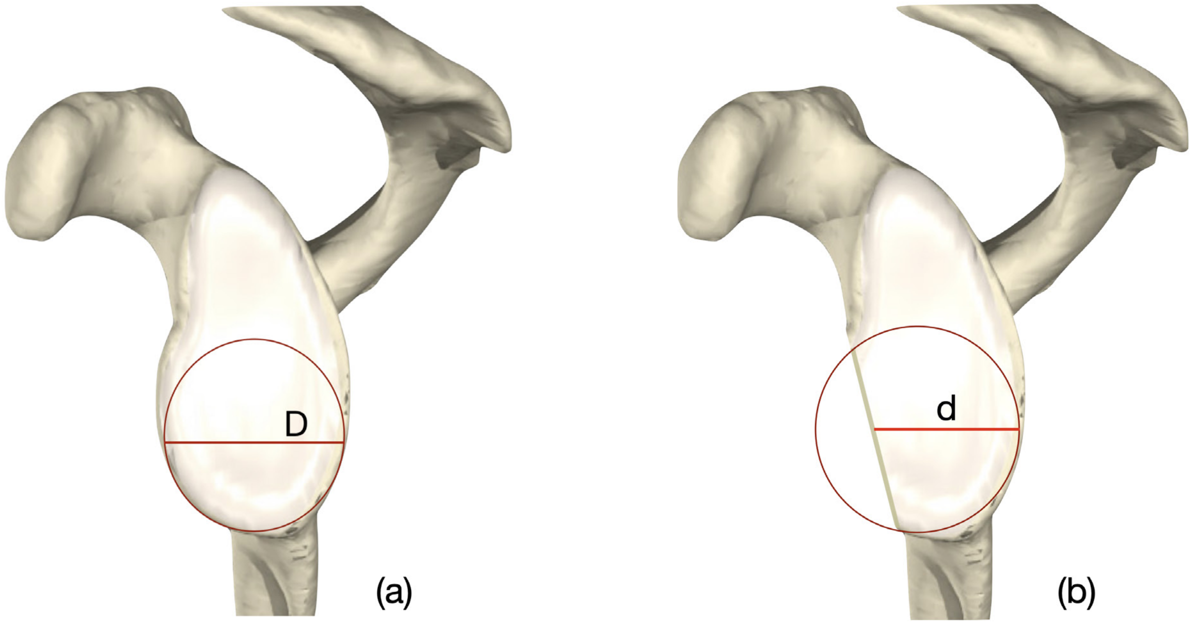

Fig. 4

Linear contralateral circle of best fit (COBF). The diameter of the remaining glenoid (d) is expressed as a percentage of the diameter of the COBF (D) obtained from the contralateral glenoid.

values above threshold. A true positive was therefore defined as a glenoid 2 measurement above 15%. A false positive was defined as a glenoid 1 measurement above 15%. A true negative was defined as a glenoid 1 measurement below 15%. A false negative was defined as a glenoid 2 measurement below 15%. In this way, sensitivity, specificity, positive, and negative predictive values and accuracy of each technique could be calculated for a 15% threshold.

The reproducibility of each technique was determined by calculating the interclass correlation coefficient (Excel; Microsoft, USA). < 0 demonstrated poor correlation, 0 to 0.2 was slight, 0.21 to 0.4 fair, moderate was 0.41 to 0.6, 0.61 to 0.8 was substantial, and almost perfect is a correlation of > 0.8.[17,18]

Circle of best fit analysis. A post hoc power analysis identified that a sample size of 12 measurements would be needed to achieve significance at 0.05%. We analyzed the results using a single-tailed ANOVA test (Excel; Microsoft).

Results

The size of the glenoid diameter defect measured by the digital callipers was 13.8% for glenoid 1, 17.6% for glenoid 2, and 22.9% for glenoid 3.

Mathematical accuracy. The mean values determined using each technique are given in Table I, and represented graphically as box and whisker plots in Figure 8. There was no single technique that had a mean value closest to the true value at all levels of bone loss. The mean values of contralateral referenced techniques were no closer to the true value than ipsilateral techniques. Area techniques (Sugaya and Pico) were closer to the true value at all levels of bone loss than linear techniques and had narrower ranges, with the exception of the Pico technique at 13.8% bone loss.

At 13.8% bone loss, the value obtained using the Sugaya technique (14.4%) was closest to the true value. The mean values obtained using the linear, ipsilateral COBF, and contralateral COBF techniques were all above the threshold value of 15%. Although the mean values obtained using the Pico and circle line techniques were below the threshold value of 15%, they were furthest away from the true value (by 4.5% and 3.3%) than the other techniques and they were therefore arguably least accurate.

At 17.6% bone loss, the Pico technique (17.0%) was closest to the true value. The mean values obtained using all three linear techniques and the Sugaya technique were less accurate and much larger than the true value. The value obtained using the circle line method was 2.1% below the true value, but just above the threshold value for bone grafting.

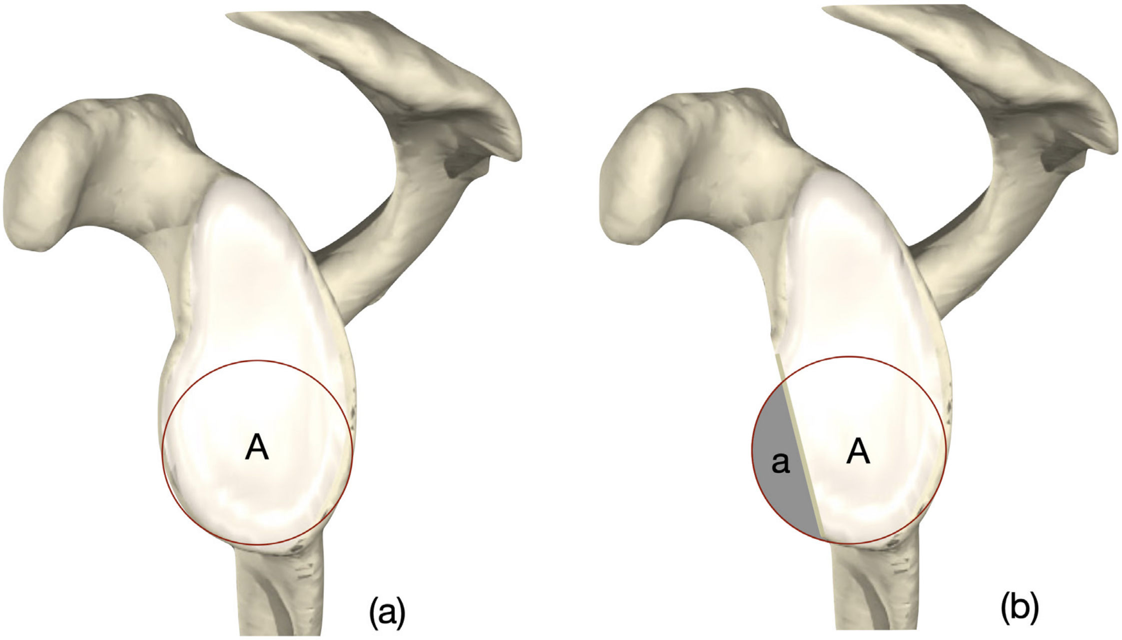

Fig. 5

Pico technique (area contralateral circle of best fit (COBF). A COBF from the contralateral glenoid is applied to the injured side. The area of the defect is expressed as a percentage of the total area. The Sugaya technique (REF) is the same but derives a COBF from the ipsilateral glenoid.

At 22.9%, bone loss all techniques were above the 15% threshold. The linear relative diameter technique was the most accurate with a mean value of 22.2%.

Statistical accuracy. The sensitivity, specificity, positive predictive value, negative predictive value, and accuracy were calculated for the techniques based on their ability to correctly indicate the need for bone grafting above a threshold bone loss of 15% (Table II).

No single method had both high sensitivity and specificity. Methods that had high sensitivity lacked specificity and those that had high specificity lacked sensitivity. The Pico technique was most accurate (statistically and mathematically) with 97.1% accuracy, and was good at correctly predicting the need for bone grafting. When it was positive, there was 100% chance that bone defect was over 15%. However, it had a high number of false-negatives and, as such, had poor sensitivity and negative predictive value; it failed to identify a number of cases which would have reached the threshold.

The next most accurate was the Sugaya technique. It had 100% sensitivity and identified all cases that required bone graft, but had poor specificity and positive predictive value, such that over 25% measurements were incorrectly deemed to be above threshold bone loss.

The linear techniques had poor overall accuracy. They had 100% sensitivity, but had poor specificity and positive predictive value.

Reproducibility and interobserver agreement. The interclass correlation coefficients (ICCs) are given in Table III. The most reproducible techniques were the relative diameter technique at 13.8%, and the Pico technique at 17.6% and 22.9%. The most reproducible technique overall was the Pico technique with excellent ICCs at all levels of bone loss. The relative diameter technique had an excellent ICC at 13.8% bone loss and a good ICC at 17.6% bone loss, but poor reproducibility at 22.9%. Overall, contralateral techniques were no more reproducible than ipsilateral techniques.

Circle of best fit analysis. The COBF is fundamental to several techniques. The diameter of the COBF for the intact glenoid was smaller than the true diameter of the glenoid which suggests that there is a tendency to underestimate the margin of the glenoid on CT; however, the diameters obtained from the non-intact glenoids were closer to the true diameter (Table IV). There was no statistically significant difference between the diameters of the COBFs derived from the deficient glenoids (Table V). The diameter of the COBF of the intact glenoid was 5 to 7% smaller than the diameters of the COBFs derived from the deficient glenoids. This was statistically significant.

Discussion

In 2000, Burkhart and DeBeer[3] popularized the concept of “critical bone loss”. They described the “inverted pear”

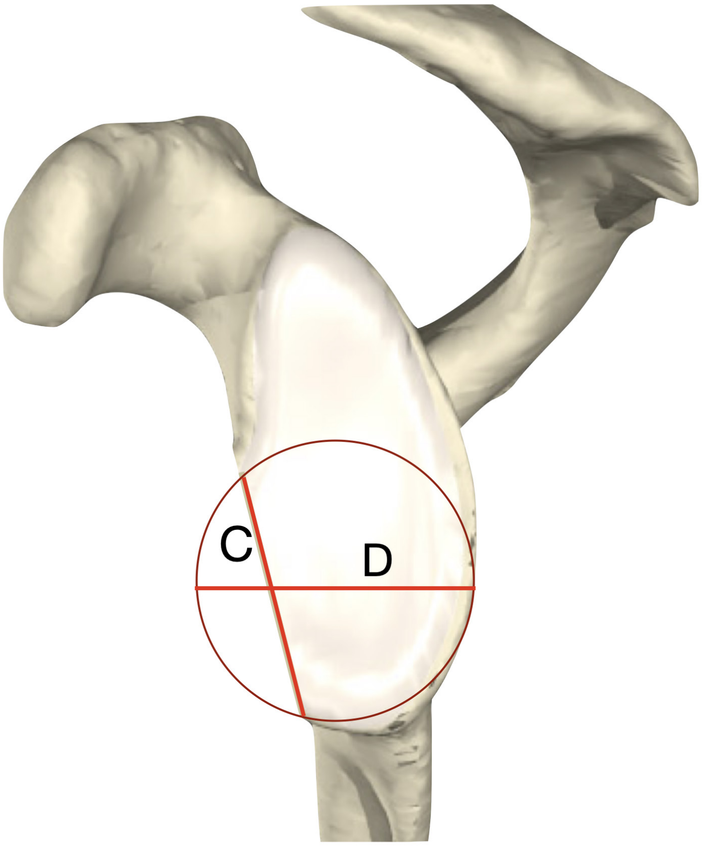

Fig. 6

Circle line method (Parada technique) an ipsilateral circle of best fit (COBF) is generated. The length of the anterior glenoid is measured between the two points at which it intersects the COBF (C).

glenoid representing 25% bone loss as a threshold for reconstruction. This value has steadily dropped since then; Di Giacomo et al[19] highlighted the importance of the Hill-Sachs lesion in the context of bifocal bone defects and introduced the concept of the "glenoid track". Key to both concepts is having an accurate, reproducible assessment of the bone loss.

Multiple techniques have been described to evaluate bone loss, but there is no consensus on which technique is best. Evaluation studies have included the reproducibility of a single technique,[20] comparison of different techniques,[21,22] and comparison with an established technique.[23,24] Several of these have errors in their description of the techniques and methodological flaws, and none compare measurements against a benchmark control. Verweij et al[10] reviewed the validation studies performed for 17 different radiological methods. Only three involved 3D CT and these were limited in their scope.[15,23,25] Some studies used arthroscopic assessment of the distance to the glenoid bare spot as a reference measurement; however, this was inconsistent.[12,13] A recent systematic review by Green et al[9] concluded that there was little evidence to support any individual technique, and recommended that further work needed to be done. Additionally, Weil et al[26] observed that the reporting of measurement technique in the literature is at best inconsistent and advised that authors should, at a bare minimum, include the technique if not a description of the method used.

As far as we are aware, this is the first study to compare the accuracy of the common techniques for calculating bone loss using a physical control and therefore against an accurate reference.

We chose a physical linear measurement as our control as this ties in with the concept of the glenoid track. One might therefore expect the linear techniques to outperform the area and mathematical techniques in our study; however, this was not the case either in comparison with the control (mathematical accuracy) or when the statistical accuracy of the techniques was calculated with reference to the ability of the technique to determine the need for bone reconstruction or not. With respect to mathematical accuracy, the Sugaya technique was the most

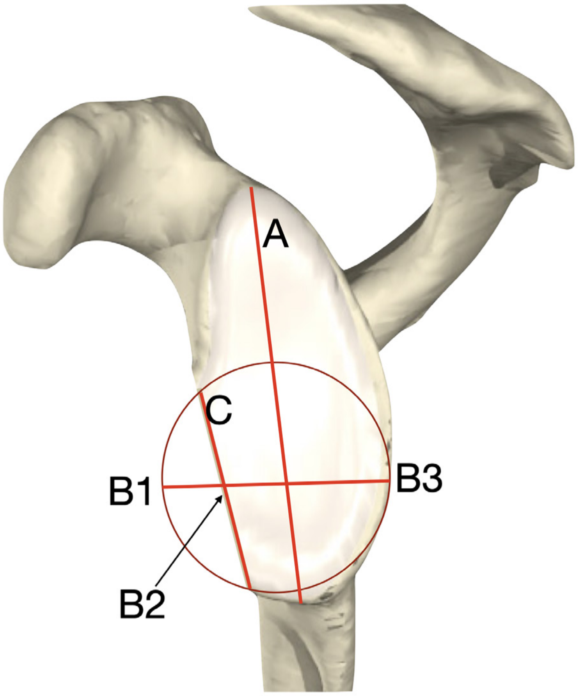

Fig. 7

A, B2-B3, B1-B3 and C were measured using ipsilateral circle of best fit (COBF) on two separate occasions.

Table I. Percentage bone loss.

Variable	Glenoid 1	Glenoid 2	Glenoid 3
Actual bone loss, %	13.8	17.6	22.9
Mean technique, % (range; SD)			
Relative diameter	16.5 (11.6 to 23.1; 2.6)	21.1 (16.1 to 24.7; 2.6)	22.2 (19.9 to 36.5; 3.6)
Linear ipsilateral COBF	16.7 (12.5 to 22.0; 2.3)	21.6 (18.6 to 28.0; 2.0)	27.6 (21 to 36.7; 3.4)
Linear contralateral COBF	15.4 (7.1 to 21.8; 3.3)	22.4 (16.1 to 27.8; 3.3)	29.2 (21.5 to 38.2; 4.9)
Pico (contralateral COBF)	9.3 (7.9 to 11.3; 0.8)	17.0 (13.9 to 20.1; 2.2)	20.9 (16.7 to 24.5; 2.2)
Sugaya (ipsilateral COBF)	14.4 (10.3 to 19.8; 2.6)	19.5 (16.6 to 23.6; 2.5)	20.0 (21.6 to 30.7; 2.6)
Parada technique (circle line method)	10.7 (7.7 to 20.7; 2.6)	15.3 (10.8 to 20.2; 2.2)	21.8 (14.8 to 32.51; 3.86)

COBF, circle of best fit; SD, standard deviation.

accurate when there was a 13.8% defect, the Pico technique was the most accurate when the defect was 17.6%, and the relative diameter technique was most accurate when the defect was 22.9%.

Central to each calculation is the derivation of a COBF, either from the intact or from the deficient glenoid. It would be expected that a COBF derived from an intact glenoid would be more accurate than one from a deficient glenoid as the latter has fewer reference points. We identified that the contralateral COBF underestimates the area of the circle by up to 16% and the diameter by 5 to 7%. Additionally, techniques that rely on an ipsilateral COBF (ipsilateral linear and Sugaya) were no more accurate that the techniques that rely on a contralateral COBF (contralateral linear and Pico). This may be because the measurements are effectively ratios and therefore errors cancel themselves out.

The circle line method was the third most mathematically accurate technique. The mean value at all levels of bone loss was consistently less than the control, but had a wide standard deviation and it is complicated to use, impractical, and cannot be recommended.

Limitations. This study was completed using a single PACS system, and it is possible that there are inherent inaccuracies within the system itself, and the results may not be transferable to other PACS systems.

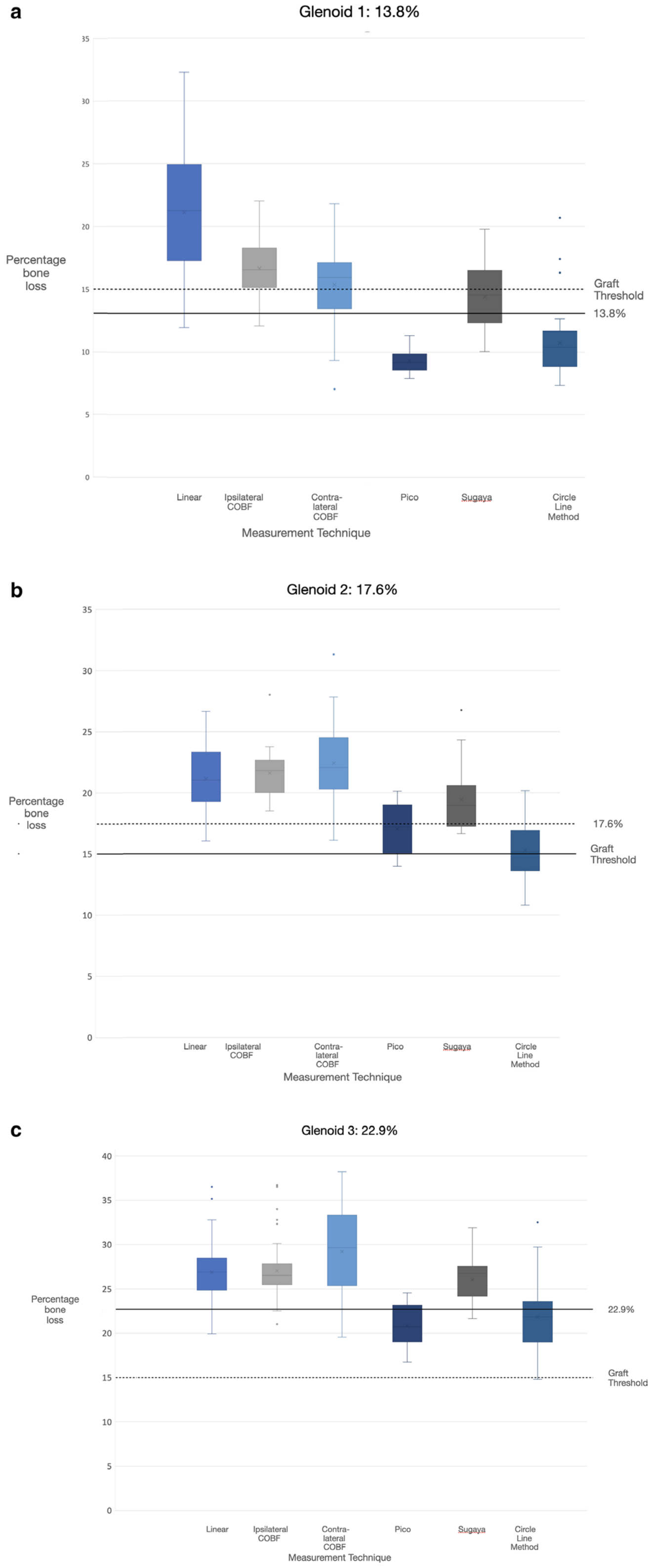

Fig. 8

Box and whisker plot of values of percentage bone loss obtained using each technique at 13.8% bone loss. The solid line represents the true value of percentage bone loss and the dotted line represents the bone graft threshold of 15% bone loss. b) Box and whisker plot of values of percentage bone loss obtained using each technique at 17.6% bone loss. The solid line represents the true value of percentage bone loss and the dotted line represents the bone graft threshold of 15% bone loss. c) Box and whisker plot of values of percentage bone loss obtained using each technique at 22.9% bone loss. The solid line represents the true value of percentage bone loss and the dotted line represents the bone graft threshold of 15% bone loss.

Table II. Sensitivity, specificity, accuracy, positive and negative predictive values for each technique based on 15% threshold.

Technique	Sensitivity	Specificity	Accuracy	Positive predictive value	Negative predictive value
Relative diameter	100	21.2	44.7	35	100
Ipsilateral COBF	100	9.5	54.8	52.5	100
Contralateral COBF	100	33.3	66.7	60	100
Pico	74.4	100	97.1	100	79.2
Sugaya	100	61.9	81	72.4	100
Parada	56	95.2	80.6	87.5	78.1

COBF, circle of best fit.

Table III. Interclass correlation for each measurement technique.

Technique	Glenoid 1	Glenoid 2	Glenoid 3
Mean relative diameter (ICC)	16.54 (0.88)	22.12 (0.64)	22.19 (0.02)
Mean linear Ipsilateral COBF (ICC)	16.67 (-0.08)	21.61 (0.25)	27.06 (0.17)
Mean linear contralateral COBF (ICC)	15.35 (0.345)	22.42 (0.28)	29.22 (0.49)
Mean Pico (contralateral COBF) (ICC)	9.28 (0.77)	17.03 (0.96)	20.86 (0.89)
Mean Sugaya (Ipsilateral COBF) (ICC)	14.3 (0.61)	19.45 (0.53)	26.03 (0.356)
Mean Parada technique (ICC)	10.71 (-0.03)	15.30 (0.15)	21.8 (0.03)

COBF, circle of best fit; ICC, interclass correlation.

Table IV. Comparison of diameters of circle of best fit.

Variable	Control measurements	Glenoid 0	Glenoid 1	Glenoid 2	Glenoid 3
Median COBF diameter, mm (range)	28.9	26.7 (26.2 to 27.5)	28.2 (27.1 to 38.9)	28.1 (25.8 to 30.3)	28.7 (26.9 to 32.7)
Diameter compared to true diameter, %		92	98	97	99
Mean COBF area, cm^2 (range)	6.6	5.6 (5.4 to 5.9)	6.3 (5.6 to 7.3)	6.2 (5.6 to 6.9)	6.6 (5.8 to 8.4)
Area compared to true area, %		84	95	94	100

COBF, circle of best fit.

Table V. Analysis of variance analysis of the circle of best fit glenoid diameters.

Glenoid	0	1	2
1	$p = 1.448 \times 10^{-5}$		
2	$p = 4.265 \times 10^{-5}$ S	$p = 0.120$ NS	
3	$p = 1.603 \times 10^{-6}$ S	$p = 0.505$ NS	$p = 4.315$ NS

NS, not significant; S, significance.

We have also made the assumption in this study that 15% is the level at which subcritical becomes critical bone loss. This number is open to debate and may change over the next few years as more evidence emerges. This paper is important, regardless of the cut-off, because it highlights the inherent inaccuracies of the current measurement techniques.

Additionally, we have made an assumption regarding both the plane of the bone loss and the relationship of this to any linear measurement. Although this may have implications in clinical practice, we felt that we had to provide a simplified scenario for this analysis. Hence, an approximately vertical bone cut (with reference to the long axis of the glenoid) and a linear measurement which was perpendicular to this.

In conclusion, there is no single technique which stands out as being the most accurate and reliable and caution should be applied when using any of them. No technique has high sensitivity, specificity, and accuracy. We observed that at a 15% threshold the area techniques (Pico, Sugaya, and Parada) were more accurate than the linear techniques.

A surgeon who wishes to have as few failed soft-tissue procedures as possible should choose a technique with the highest sensitivity and the smallest number of false-negatives, accepting that they may be performing bone restoring operations on more patients than they need to but with fewer soft-tissue repair failures (linear or Sugaya methods). A surgeon concerned about the higher complication rate associated with bone restoring procedures and wishing to perform them only on those who need it should select a technique that has high specificity and a low false-positive rate accepting that they may have a higher failure rate in their soft-tissue repair cohort (Pico). Of particular note was the observation that the technique, which had a mean value closest to the true value was not necessarily the most accurate at determining the need for bone grafting when threshold bone loss was 15%.

This study also highlights that measurement techniques are not interchangeable and that, until there is an accepted gold standard, recommended bone loss thresholds presented in the literature should be considered with caution.

Take home message

- CT measurement techniques for glenoid bone loss are not interchageable.
- Linear measurement techniques will tend to overestimate bone loss.
- Area measurement techniques will tend to understimate bone loss.

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Author information:

- D. Tennent, FRCS(Orth), Consultant Orthopaedic Surgeon
- M. Arnander, FRCS(Orth), Consultant Orthopaedic Surgeon
- V. Ejindu, FRCR, Consultant Radiologist
- N. Papadakos, FRCR, Consultant Radiologist
- A. Rastogi, FRCR, Consultant Radiologist
- Y. Pearse, FRCS(Orth), Consultant Orthopaedic Surgeon
  St. George's Hospital and Medical School, London, UK.
- T. Antonios, FRCS(Orth), Consultant Orthopaedic Surgeon, Trauma & Orthopaedics, St Peter's Hospital, Surrey, UK.

Author contributions:

- D. Tennent: Conceptualization, Visualization, Formal analysis, Writing – original draft, Writing – review & editing.
- T. Antonios: Conceptualization, Visualization, Formal analysis, Writing – original draft, Writing – review & editing.
- M. Arnander: Conceptualization, Visualization, Formal analysis, Writing – original draft, Writing – review & editing.
- V. Ejindu: Visualization, Writing – original draft, Writing – review & editing.
- N. Papadakos: Visualization, Formal analysis.
- A. Rastogi: Visualization, Writing – original draft, Writing – review & editing.
- Y. Pearse: Conceptualization, Visualization, Formal analysis, Writing – original draft, Writing – review & editing.

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