



Glenoid Bone Loss Determination: Validity and Reliability of the Constellation Technique Versus the Sagittal Best Fit Circle Technique

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Abstract

Objective To propose a new method for glenoid bone loss measurement, the constellation technique (CST); determine its reliability and accuracy; and compare the validity of CST with that of the conventional technique (CVT) and standard measurements for ratio calculation.

Materials and Methods Sixty shoulders with intact glenoids and no glenohumeral instability and arthritis underwent CT scans. Simulated osteotomies were conducted on the 3D models of glenoids at two cutting locations, expressed as clock face times (2:30–4:20; 1:30–5:00). Two experienced surgeons compared three methods for glenoid bone loss measurement; CVT (best-fit circle), CST ('5S' steps), and standard measurement. Eight undergraduates remeasured five randomly chosen shoulders with moderate to severe bone loss. Intraclass correlation coefficients (ICCs) were calculated for raters.

Results With a defect range between 2:30 and 4:20, all 60 glenoids demonstrated minimal bone loss (< 15%); while between 1:30 and 5:00, 42 shoulders were with moderate bone loss (15–20%), and 18 shoulders with severe bone loss ($\geq 20\%$). For experienced raters, no significant differences were noted between protocols for all categories of bone loss ($p \geq 0.051$), with good inter- and intraobserver reliability indicated by ICC. For novice raters, post hoc Tukey analysis found that CST was more accurate in one patient with a standard mean bone loss of $23.2\% \pm 1.9\%$ compared with CVT.

Conclusion The CST turned the key step of glenoid defect evaluation from deciding an *en face* view to determining the glenoid inferior rim. The protocol is simple, accurate, and reproducible, especially for novice raters.

Keywords Glenoid bone loss · Constellation technique · Sagittal best-fit circle · Novice raters · Shoulder dislocation

Introduction

Glenoid bone defects are found in 20% of primary anterior shoulder dislocations and nearly 90% of recurrent cases [1]. Bony deficiency has been recognized as one of predominant risk factors of surgical failure after soft-tissue stabilization, requiring bony augmentations such as the Latarjet procedure

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[2, 3]. Therefore, proper preoperative evaluation of glenoid osseous injuries is a critical step for patients with shoulder instability to tailor the optimal surgical procedures.

Various measurements have been introduced to measure the glenoid bone loss based on an *en face* sagittal oblique view [4–6] using computed tomography (CT) or magnetic resonance images, considering the inferior aspect of the intact glenoid shaped as a circle [7–11]. However, consensus regarding the gold standard for measurements in the clinical practice is lacking [5, 12, 13], as scapula position and best-fit circle placement could potentially alter the measurement results [14]. Although Zhang et al. [15] provided a quantitative definition and a practical method for *en face* view generation with a maximal glenoid projection area, such method would be too complicated to practice routinely with no specific software.

Due to the minimal side-to-side difference, a contralateral side matching method has also been proposed to measure the defect size; however, additional exposure to radiation might not be acceptable for all patients, who required CT scans of both shoulders. Besides, patients with bilateral shoulder instability are not suitable for such method. Arthroscopic defect size calculation with a ruler was also proposed to determine the glenoid bone loss [16]; yet, the method has recently been questioned about the validity owing to its significant overestimation compared with CT [17].

Therefore, the study aimed: (1) to propose a new method for glenoid bone loss measurement, the constellation technique (CST), turning the focus from the *en face* view to the glenoid inferior rim; (2) to determine its reliability and validity; and (3) to compare the validity of CST with that of the conventional method (CVT) and standard measurements for ratio calculation. We hypothesized that the CST would be a more reliable and accurate method than the CVT for glenoid bone loss measurement.

Materials and Methods

Study Population

This was a retrospective case–control study. Patients with intact glenoid with no bone loss confirmed by CT and MRI scans were retrospectively screened in the hospital registry. They were prepared to undergo acromioplasty or rotator cuff repair in Shanghai Sixth People’s Hospital from January 2019 to March 2020. Exclusion criteria were as follows: (1) glenohumeral instability; (2) glenohumeral arthritis greater than Samilson-Prieto grade 1 [18]; (3) a history of shoulder surgery or traumatic injury; (4) skeletal immaturity; (5) neuromuscular disorders; (6) congenital or acquired glenoid deformity; and (7) pregnancy. A series of 60 shoulders of 60 participants were included in the study (22 men

and 38 women; 40 right side and 20 left side; mean age of 47.2 ± 9.5 years; and mean body mass index of 24.3 ± 3.0 kg/m²). The study was carried out in accordance with the World Medical Association Declaration of Helsinki, and received approval from the institutional ethics committee (approval number 2020-KY-043(K)). Informed consent was waived because of the retrospective nature of the study.

Imaging Process and Defect Simulation

Each participant was examined using a multidetector CT scanner (Lightspeed VCT 64, GE, Milwaukee, WI, USA), with a 120-kV tube voltage, 350-mA tube current, 0.625-mm reconstructive slice and interval thickness, and 1.0-s rotation time. The images were then imported into 3D-modeling software (Mimics Research 20.0; Materialise, Leuven, Belgium) to reconstruct the surface mesh models of the scapula and glenoid with the humeral head digitally subtracted.

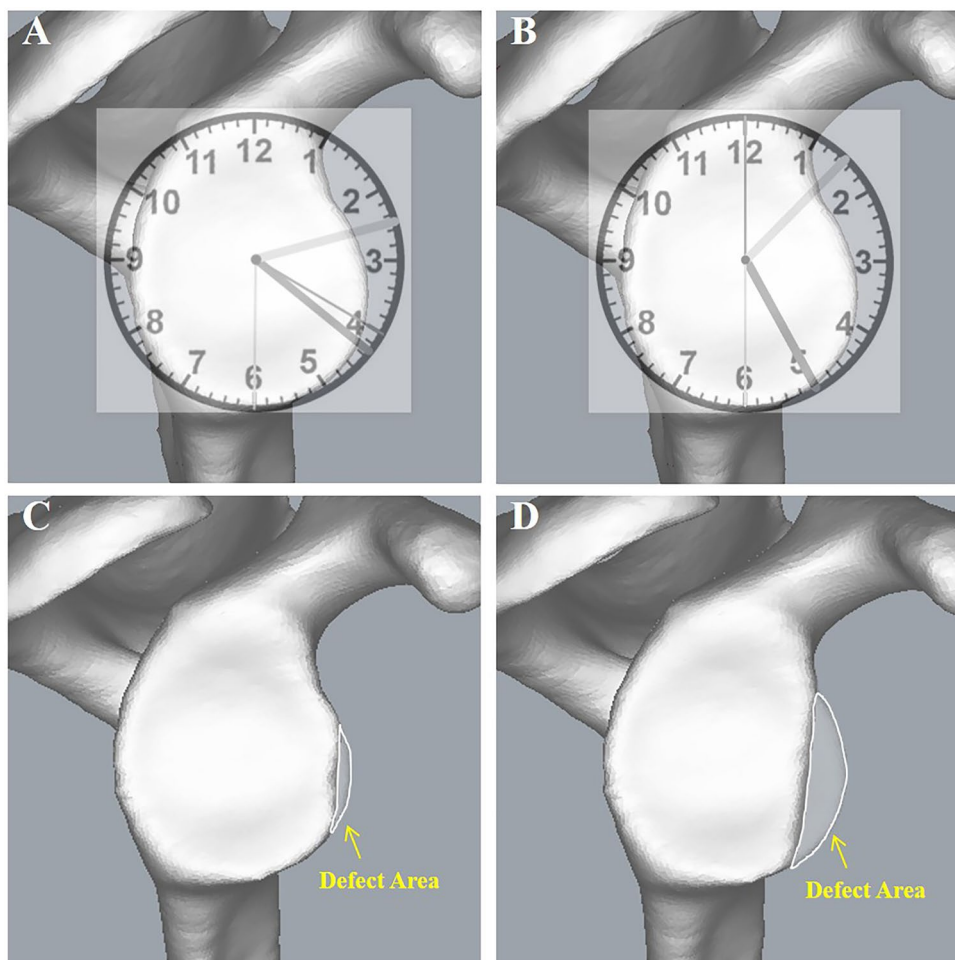
Osteotomies were conducted on 3D models of glenoids with two different cutting locations, expressed as times on the clock face, for anterior glenoid bone defect patterns simulation [19, 20]. The first defect range was determined between the 2:30 and 4:20 clockface position, which was most frequently observed in patients with recurrent anterior shoulder dislocation [19] (Fig. 1A). The second defect was created at the 1:30–5:00 clockface position, a relatively larger defect range with a deficiency frequency of close to 50% [19] (Fig. 1B). The glenoid defect border was then outlined using a transparent mode software, and was automatically calculated as the standard defect surface area in our study (Fig. 1C, D).

Measurements of Glenoid Bone Loss

Conventional Technique (CVT)

The reconstructed models were imported into Rhinoceros 3-dimensional modeling software (Robert McNeel & Assoc, Seattle, WA, USA), oriented to render a typical *en face* view, evaluated and selected by two experienced shoulder orthopedic surgeons, with the largest glenoid articular surface extensions in both vertical and horizontal planes [14]. A best-fit circle was then placed on the remainder rim of the glenoid [5, 14, 20]. Bone loss was indicated by a straight line that connects only two points on the circle (chord) (Fig. 2). The relative glenoid bone loss area (B) was calculated based on the chord length (l) and radius of the circle (r), where $B = r^2 \arcsin(l/2r) - 1/2 \sqrt{(r^2 - l^2/4)}$. Finally, the bone loss ratio was determined by $(B/A) \times 100$, where A = area of the best-fit circle [20, 21].

Fig. 1 Three-dimensional computed tomography scans of an enlarged right scapula expressed as times on the clock face, 2:30–4:20 (A), and 1:30–5:00 (B). The corresponding defect area was out-lined in a transparent mode and calculated as 35.33 mm² (C) and 75.72 mm² (D)



'Constellation' Technique (CST)

CST was based on the glenoid rim regardless of *en face* view. The glenoid bone loss and matched circle were determined in the Rhinoceros software following the '5S' steps (Fig. 3): (1) Seek the remainder rim by rotating the 3D CT image of the reconstructed glenoid; (2) Sketch a line on the glenoid rim from 9 o'clock (half the glenoid superior-inferior diameter) to the inferior defect aspect; (to confirm the sketch that outlines the rim, the glenoid would be rotated and the line segmented) (3) Section the line at 1 mm intervals to render dots in a constellation ('stella' on the glenoid) in the shape of a circle; (4) Select the working or glenoid plane on the basis of the matched circle, then place the plane such that the objects are parallel to the ground; (5) Set the defect area by creating a straight line that indicates bone loss that connects only two points on the circle (chord). Assuming a linear regular pattern of bone loss allowed the use of algebraic geometry to calculate the percentage of glenoid bone loss, which was $(B/A) \times 100$, where B = glenoid bone loss area and A = area of the best-fit circle [20, 21].

Standard Measurement (Control Group)

The standard fitting circle was sketched and simulated from different views, based on the posterior and inferior parts of the intact glenoid rim from the 3 o'clock to 9 o'clock clock-face positions (Fig. 4). After simulated osteotomies were performed on the glenoid, the standard bone loss percentage was defined using the relative ratio of the area between the outlined defect surface and the standard circle (Fig. 1). Considering the intact rim outlining, this protocol was considered the most accurate way to generate the best-fit circle.

Statistical Analysis

The normality of the continuous data was evaluated using the Shapiro–Wilk test. Comparisons of different methods for evaluating bone loss (CVT vs. CST versus standard measurement) were performed by analysis of variance (ANOVA). Intraclass correlation coefficient (ICC) analysis was performed to evaluate continuous variables. To determine the intraobserver reliability, 20 shoulders with intact and two defect patterns were randomly chosen for the

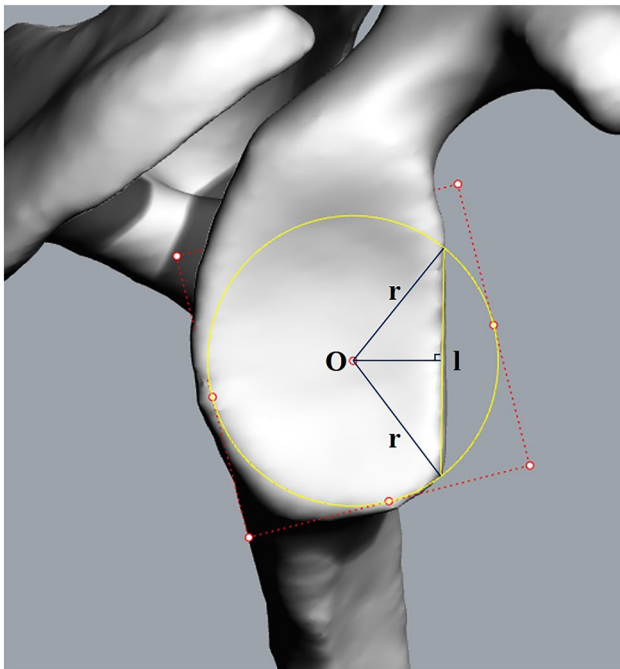


Fig. 2 Three-dimensional computed tomography scan of the right scapula (1:30–5:00 defect pattern) from an *en face* view with a best-fit circle (marked yellow) that was laid based on the intact inferior and posterior glenoid rim distances. The chord length (l) and radius of the circle (r) were 21.67 mm and 13.09 mm, respectively. The bone loss percentage was calculated according to algebraic geometry as 16.25%. ‘O’ represented the center of the best-fit circle

primary observer to re-perform the measurements 4 weeks later in a separate sitting position [22]. Regarding interobserver reliability, a second blinded experienced observer performed the measurements on the same 20 shoulders independently. An ICC of 0.75 or greater was defined as good, and 0.50–0.74, moderate [21, 23]. Categories of bone loss severity were subdivided to determine the effect of severity of bone loss on measurement accuracy as follows: minimal bone loss (noncritical, <15%), moderate bone loss (subcritical, 15–20%), and severe bone loss (critical, $\geq 20\%$). Afterward, eight undergraduates (novice raters) unfamiliar with orthopedics were invited to perform the three measurement techniques on five randomly chosen patients with moderate to severe bone loss. All raters were trained prior to conducting the measurements using the same protocol at the same time. They were blinded to the previous measurement results, patient diagnosis, and treatment plan. Comparison was performed by ANOVA, and post hoc Tukey analysis was subsequently conducted. Interobserver reliability was also calculated for these novice raters. To detect the effect size of 0.50 in the bone loss calculation [21], with a level of significance of 5% and a power of 80%, the required sample size was 42 per group. Analyses were conducted using SPSS

(24.0; IBM, Inc., Armonk, NY, USA). All reported P values are two-sided, and the significance level was set at 0.05.

Results

All simulated defect glenoids ($n = 60$) with a defect range between 2:30 and 4:20 on the clockface demonstrated minimal bone loss (<15%), while 42, with a defect range between 1:30 and 5:30, had moderate bone loss (15–20%), and 18 shoulders had severe bone loss ($\geq 20\%$).

All categories of bone loss demonstrated no significant differences ($p \geq 0.051$) between the different measurement methods performed by the primary experienced rater for the mean defect surface area, mean circle area, and mean bone loss percentage (Fig. 5).

Interobserver reliability for the two independent experienced observers who performed the CVT for the 1:30–5:00 clockface defect patterns was moderate (ICC 0.731; 95% CI 0.472–0.874). Interobserver reliability for the CST, standard measurement, and standard defect surface area calculations was good (ICC ≥ 0.767 ; Table 1). Intraobserver reliability for all measurements was good (ICC ≥ 0.760 ; Table 2).

For the novice raters, post hoc analysis found the CVT for bone loss to be significantly different from the standard measurements in three of five of the study participants. The CST was more accurate in one patient with a standard mean bone loss of $23.2 \pm 1.9\%$ compared with the CVT (Table 3). Interobserver reliability for the CST method was good (ICC 0.751; 95% CI 0.489–0.933), and moderate (ICC 0.585; 95% CI 0.275–0.873) for the CVT method (Table 4).

Discussion

The most important findings of the study were that the newly proposed CST method (‘5S’ steps), with a good inter- and intraobserver reliability, was comparable to the CVT and the standard measurement in glenoid bone loss determination among experienced orthopedic surgeons; and for novice raters, the CST was a potentially more accurate and reliable method than the CVT. The comparisons among different techniques for glenoid bone loss determination were summarized in the Table 5.

Interest of the CST

The key step for CST has turned from deciding an *en face* view to determining the glenoid inferior rim. The glenoid plane based on the circle, generated by multiple dots (‘stella’) on the inferior rim, was selected as our ‘*en face* view’ to make the measurements. Plessers et al. [10] defined the glenoid plane through 16 points along the glenoid rim,

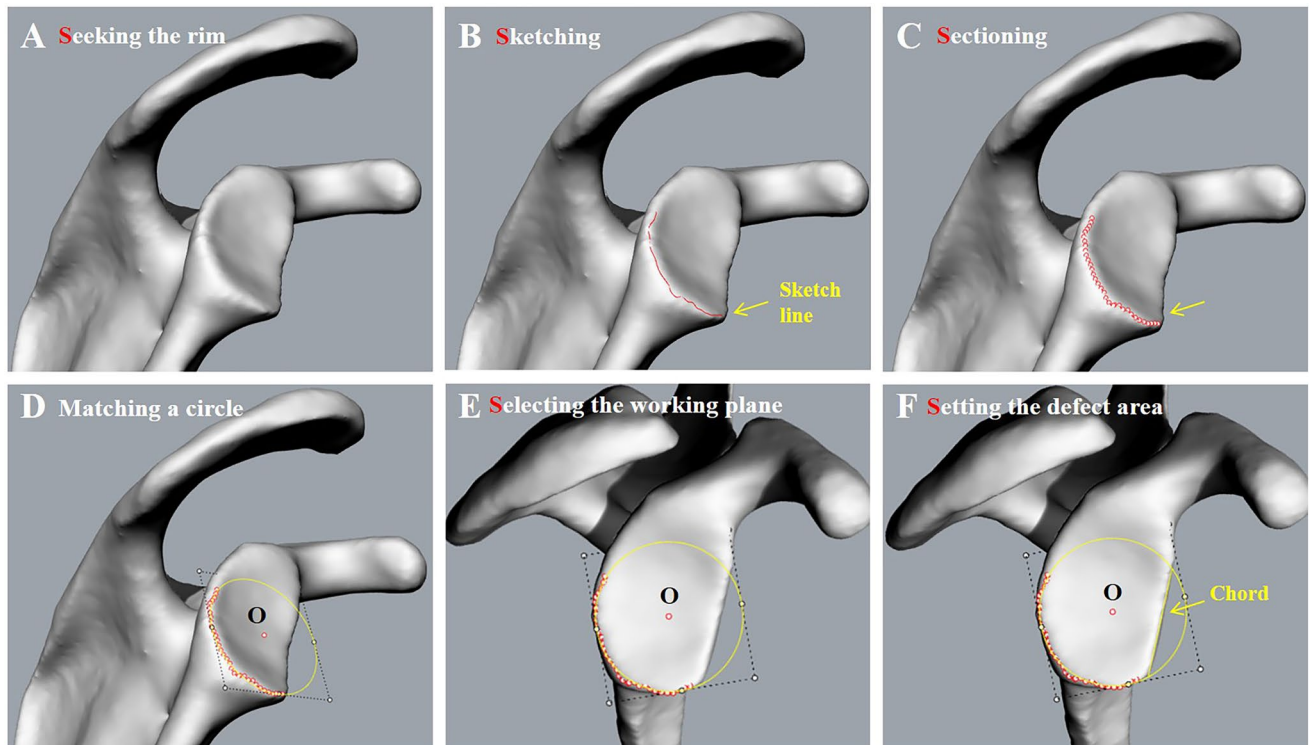


Fig. 3 ‘5S’ steps (A–F) for the constellation technique, the bone loss percentage was measured in a right three-dimensional computed tomography image of a reconstructed scapula (1:30–5:00 defect pattern). The red dots on the glenoid rim were generated from the sketch

and for circle matching. The chord length and radius of the circle are 22.01 mm and 13.43 mm, respectively. The bone loss percentage was calculated according to algebraic geometry as 15.62%. ‘O’ represented the center of the matching circle

with 10 points on the inferior rim for a best-fit circle, and accurately reconstructed the native glenoid surface. In our study, the remainder glenoid rim was more fully used to estimate a glenoid plane and a circle. Compared with an uncertain best-fit contour, especially for novice raters, the CST could be a more accurate and reproducible protocol.

In the protocol of CST, the matched circle on a deep-concavity irregular-shaped glenoid would not be completely inscribed with the remainder glenoid, and the derived section of the circle would be slightly inclined. However, the estimate based on CST was equivalent to the standard measurement results. And the observed errors of inclination and version have been considered small and acceptable [10], with the glenoid plane as the best-fit plane through the points on the glenoid rim [10, 24].

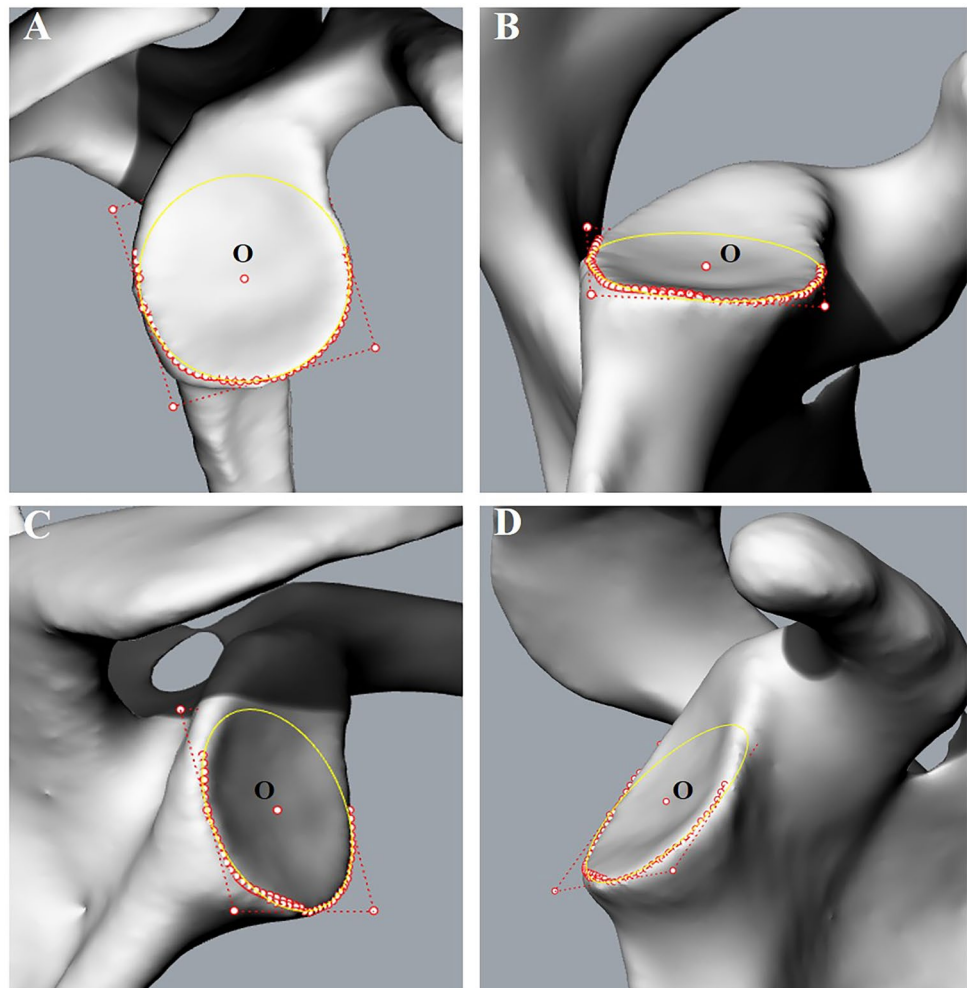
Management of Important Bone Loss

Quantification of glenoid bone defects is crucial for patients with glenohumeral instability in deciding whether to perform a bony procedure, improving postoperative stability [2, 5, 6]. The critical value for the glenoid defect ratio is commonly accepted as 20% [25–27]. However, recently, Shaha et al. [28] retrospectively evaluated clinical

outcomes of an active population, engaged in a high level of activities, after an isolated arthroscopic labral repair. They found a bone defect rate of over 13.5% correlated with a poor clinical outcome. Yet, Shin et al. [29, 30] determined the critical value of bone loss to be 15% biomechanically and 17.3% clinically. As the critical values varied, we performed evaluation across different aspects of bone loss ratio, covering the spectrum of the typical defect percentages found in clinical practice (< 15%, 15–20%, and ≥ 20%).

Glenoid concavity shapes, flat or deep [31, 32] also play a role in maintaining glenohumeral stability. A deep-concavity shaped glenoid with a small defect tends to cause a greater loss of stability than that for a glenoid with a flatter concavity [31]. Besides, the results of this study might also be relevant to populations that might have greatly varied glenoid shapes. Glenoid concavity shape variances should be therefore further considered along with the bone loss estimation in clinical practice in different populations. Further, the maximum width that has been lost of the glenoid would be another underlying focus of the bony surgical procedures to ensure an articular surface area that retains joint stability. With a well-validated measure that estimates glenoid width from glenoid height [33], future

Fig. 4 The standard fitting circle (marked yellow) was based on the posterior and inferior parts of the intact glenoid rim from 3 o'clock to 9 o'clock on the clockface, is sketched and simulated from frontal (A), inferior (B), posterior (C), and anterior (D) views. The red dots on the glenoid rim were generated from the sketch for circle fitting. The radius of the circle was calculated as 12.60 mm. 'O' represented the center of the best-fit circle



clinical and biomechanical studies are required to validate the value of the glenoid width, compared with various bone loss ratio estimation methods on the basis of time.

Clinical Implications

The newly proposed CST method ('5S' steps) provides potentially more accurate and reliable estimates of glenoid bone loss to determine whether to perform a bony procedure (e.g., Latarjet procedure [2, 3]). The assessment using the CST method helps surgeons in preoperative planning and follow-up evaluation for patients with primary or recurrent anterior shoulder dislocation (Fig. 6).

Limits of the Study

The present study had several limitations. First, all measurements were performed on the simulated glenoid defects and depended on the assumption of the 2D surface pertinent to the glenoid and defect area. Glenoids with real bone defects and 3D volume reconstruction and calculation should be

further considered in future studies. Second, although the 3D reconstruction models were smoothed with the same iterations and smooth factor, it was inevitable that there was a margin of error in the representation of the glenoid rim. The effect of smooth factor on the specific measurement values requires further studies. Third, Rhinoceros, a specialized imaging software, was used for dot generation, circle matching, and working plane selection, which might underestimate the generalization of CST method. However, we are working on a universally accepted program that will enable us to perform the '5S' steps with ease for clinical application. Fourth, we assumed a linear regular pattern of glenoid bone loss. Concerns about attritional irregular bone loss have been observed in the treatment of recurrent anterior shoulder instability [34]. Thus, the clinical decision regarding the bony procedure should still be multifaceted. Fifth, the *en face* view or the glenoid plane was determined by the dots on the glenoid rim. Other methods [35, 36] (e.g., Friedman Method [37, 38]) should be further considered in the future studies. Moreover, only eight novice viewers evaluated five shoulders each as most of us joined the lines

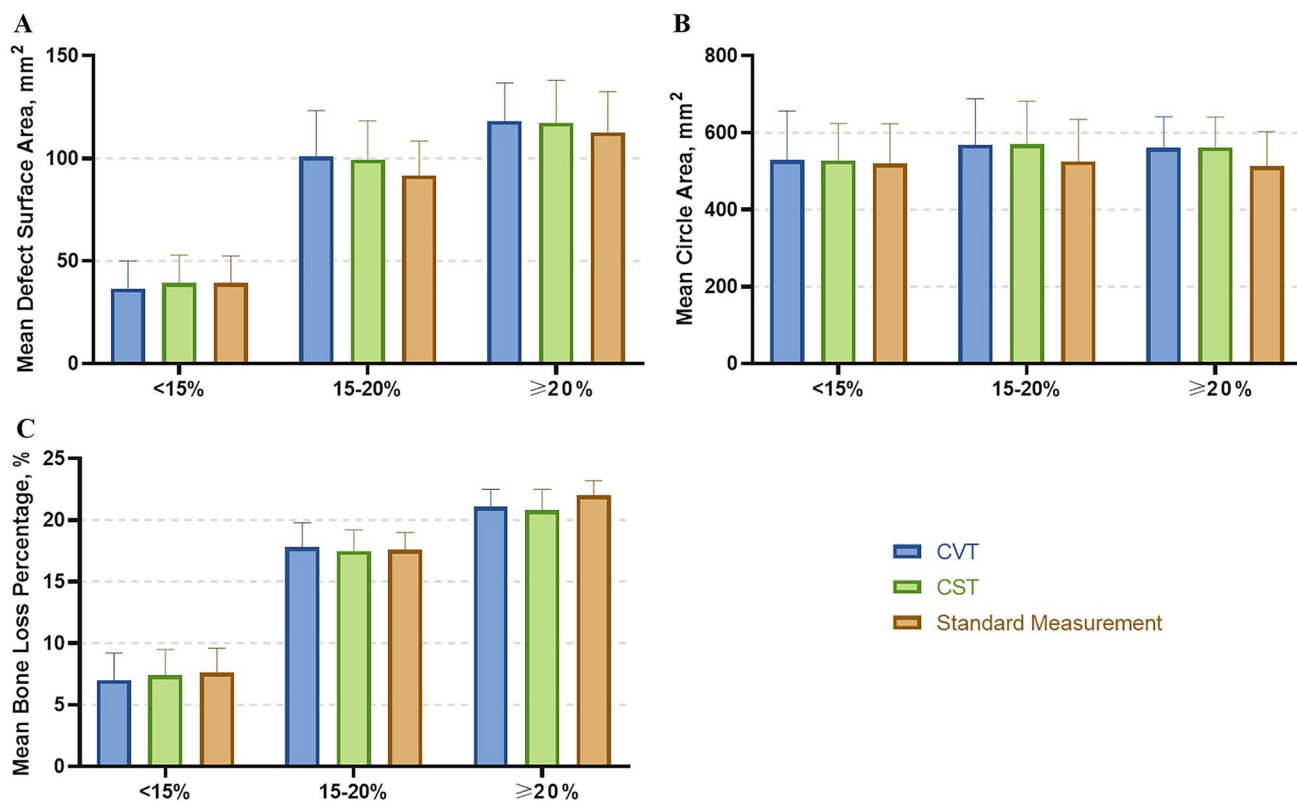


Fig. 5 All bone loss categories show no significant differences ($p \geq 0.051$) between the different methods of measurement in the mean defect surface area, mean circle area and mean bone loss per-

centage. Error bars indicate standard deviation. CST, constellation technique; CVT, conventional technique

Table 1 Interobserver reliability for the experienced raters

Defect pattern (clockface times)	Protocols	ICC	95% CI for ICC
2:30–4:20	CVT	0.751	0.505–0.884
	CST	0.767	0.533–0.892
	Standard measurement	0.864	0.711–0.939
	Standard defect surface area	0.937	0.860–0.972
1:30–5:00	CVT	0.731	0.472–0.874
	CST	0.777	0.551–0.897
	Standard measurement	0.851	0.686–0.933
	Standard defect surface area	0.824	0.636–0.920

CI, confidence interval; CST, constellation technique; CVT, conventional technique; ICC, intraclass correlation coefficient

Table 2 Intraobserver reliability for the experienced raters

Defect pattern (clockface times)	Protocols	ICC	95% CI for ICC
2:30–4:20	CVT	0.809	0.608–0.913
	CST	0.819	0.627–0.918
	Standard measurement	0.846	0.677–0.931
	Standard defect surface area	0.952	0.893–0.979
1:30–5:00	CVT	0.760	0.520–0.888
	CST	0.761	0.523–0.889
	Standard measurement	0.871	0.726–0.942
	Standard defect surface area	0.822	0.632–0.919

CI, confidence interval; CST, constellation technique; CVT, conventional technique; ICC, intraclass correlation coefficient

Table 3 Analysis of variance in novice raters

	Standard measurement for bone loss (%)	Mean bone loss percentage (%)	ANOVA significance	Post hoc analysis: X versus standard measurement
Patient 1	22.6 ± 3.0		0.004	
CVT		18.6 ± 1.8		0.006
CST		18.9 ± 2.0		0.012
Patient 2	23.9 ± 1.6		0.001	
CVT		17.0 ± 2.7		0.001
CST		18.8 ± 4.7		0.015
Patient 3	23.2 ± 1.9		0.001	
CVT		17.8 ± 5.2		0.012
CST		24.9 ± 2.3		0.599
Patient 4	20.8 ± 1.8		0.164	
CVT		19.1 ± 3.6		0.526
CST		17.8 ± 3.4		0.141
Patient 5	18.7 ± 1.0		0.324	
CVT		22.7 ± 6.3		0.304
CST		20.1 ± 6.5		0.865

ANOVA, analysis of variance; CST, constellation technique; CVT, conventional technique

Table 4 Interobserver reliability for mean bone loss percentage measurements in novice raters

Protocols	ICC	95% CI for ICC
CVT	0.585	0.275–0.873
CST	0.751	0.489–0.933
Standard measurement	0.938	0.840–0.985

CI, confidence interval; CST, constellation technique; CVT, conventional technique; ICC, intraclass correlation coefficient

fighting against the COVID-19 outbreak. The findings would be more impactful if more novice reviewers were involved and they viewed the same number of shoulders as the experienced viewers. Finally, in cases of > 25% bone loss, or those extending superiorly over the 1:30 clock position, the matched circle might not provide an accurate assessment, as the excessive defect area would outrange the matched circle. Other linear methods [4, 39–41], or comparison with the contralateral shoulder [42], could be considered an alternative for glenoid bone loss ratio approximation.

In conclusion, the CST was an alternative for glenoid defect evaluation, based on the determination of the inferior

Table 5 Comparisons among different techniques for glenoid bone loss determination

Test	Reliability	Validity	Practicality
CST (current study)	Better than CVT	Comparable to the CVT	Good if with a simple program
CVT	Worse than CST	Comparable to the CST	Good
Contralateral side matching technique	Good [5]	Good [5]	Poor as to the additional exposure to radiation
Arthroscopic technique	Good [5]	Significant overestimation [17]	Good

CST, constellation technique; CVT, conventional technique

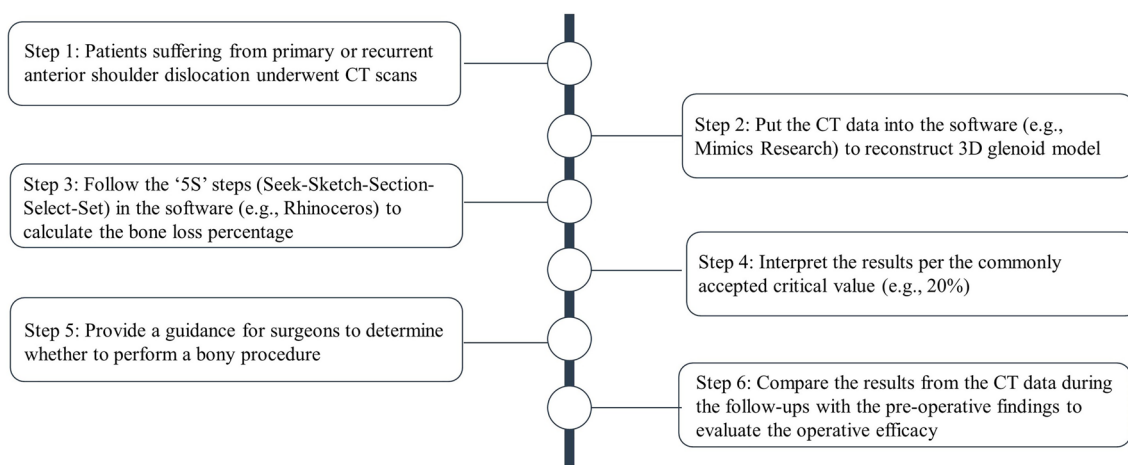


Fig. 6 A flowchart for the process of the evaluation and treatment of patients with anterior shoulder dislocation

rim, and identification of the ‘lost stella’ on the glenoid applying the ‘5S’ steps. The technique is a simple, accurate, and reproducible protocol, especially for novice raters, with the defined glenoid plane for defect area measurement.

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Authors’ Contribution JC, ZF, GX and JZ contributed to conceptualization. JC and ZF contributed to data curation. JC, ZF, JYC, XZ and CX contributed to measurement, formal analysis, and writing. GX, and JZ is responsible for the project administration and supervision.

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Declarations

Conflict of Interest All authors declare that they have no conflict of interest.

Ethics Standard Statement The study was approved by the Ethics Committee of Shanghai Sixth People’s Hospital.

Informed Consent For this type of study informed consent is not required.

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