Original Article

Mathematical modeling of glenoid bone loss demonstrate differences in calculations that May affect surgical decision making

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ABSTRACT

Objective: Two glenoid bone loss calculations are compared across a range of anatomic glenoid sizes.

Methods: 20 cadaveric paired glenoid diameters were measured to create glenoid models with bone loss calculated in 1 mm linear increments up to 50% bone loss comparing the linear measurement percentage (LMP) to the circle line method (CLM) gold standard.

Results: The LMP overestimates glenoid bone loss at every potential 1 mm increment across each glenoid model until bone loss reaches 50%.

Conclusion: The widely-used LMP method overestimates bone loss compared to a gold standard potentially misleading surgeons towards bony reconstruction in shoulder instability during preoperative planning.

1. Introduction

Recurrent anterior shoulder instability can lead to glenoid bone loss which has been demonstrated to be a risk factor for poor results following an arthroscopic soft-tissue repair.^{1–3} From the original description of the “inverted pear” glenoid⁴ to newer reports that demonstrate a “sub-critical value” of glenoid bone loss that can still affect outcomes,² much attention has been placed on an accurate measurement of glenoid bone loss when determining the optimal treatment plan for the patient with recurrent instability. Traditional thresholds of 20%–27% of glenoid bone loss have given way to less acceptable amounts of bone loss with even 13.5% glenoid bone loss now being utilized as a potential decision point for surgeons to turn to a bony reconstructive procedure instead of a soft-tissue repair alone.^{2,5,6} Newer surgical algorithms recognize the importance of bipolar bone loss and have introduced the concept of the glenoid track which defines “on-track” and “off-track” lesions based on complex measurements of not only glenoid bone loss, but humerus bone loss as well.^{6,7}

These reports have led to increased debate on how to best measure glenoid bone loss and which imaging study is best suited for this

measurement. Advanced imaging studies such as magnetic resonance imaging (MRI), computed tomography (CT) and three-dimensional reconstructions of CTs (3DCT) have all been evaluated.^{8–16} Many different measurement techniques exist, although no one technique is recognized as superior to the others. Certain automated measurement systems exist, however, these are not universally available to surgeons in all clinic or hospital settings.^{8,13,17–24} The most commonly reported technique is a linear, ratio-based technique often referred to as the linear measurement percentage (LMP) technique. This has been investigated by other authors who have explained how the geometry of the technique leads to an overestimation of glenoid bone loss.¹⁹ More recently, a simple, reproducible method termed the circle line method (CLM) was proposed that may be more accurate when certain assumptions are correct. These fundamental assumptions include: (1) the glenoid surface is that of a perfect circle, and (2) attritional bone loss causes a linear pattern of bone loss and not an irregular line of bone loss (Fig. 1). The purpose of this study was to compare two glenoid bone loss calculations, the circle line method (CLM) and linear measurement percentage (LMP) technique across a range of anatomic cadaveric glenoid sizes with increasing amounts of bone loss. The hypothesis was that the LMP will overestimate

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glenoid bone loss throughout all percentages of bone loss and additionally throughout all sizes of anatomic glenoids.

2. Methods

2.1. Level of evidence: level III

A total of 20 paired scapulae were harvested from embalmed cadavers of known gender and age. Institutional Review Board approval was not required for the purposes of this cadaveric study. Inclusion criteria were any cadaver with bilateral intact scapulae. Samples were excluded from the study if there was any hardware present in the scapula or if there was evidence of osteoarthritis, previous trauma or glenoid bone loss. The only demographic information available for the cadavers was age and gender. There were 11 female cadavers and 9 male cadavers with an average age of 83.9 years (range 66–96, St Dev: 9.2). Race and ethnicity were not available and could not be determined.

Gross dissection to the glenoid cavities was performed, and labral and capsular tissue was removed around the surface of the glenoid until only the articular surface remained. Two anthropometrical measurements of the glenoid cavity were obtained for each scapula. These parameters included maximal glenoid height (GH), identified as the line between the most cranial aspect of the cavity and the most caudal point and the maximal glenoid cavity diameter, identified as the widest measurement between the most anterior aspect of the cavity and the most posterior point. Measurements were made using a digital caliper (Mitutoyo 500–784 Absolute Digital Caliper, Mitutoyo, Aurora, IL) calibrated to 0.00 mm (Fig. 1). These calipers include a resolution of 0.01 mm, repeatability of 0.00005"/0.01 mm and accuracy rated plus or minus 0.02 mm. The smallest, largest and average diameters measured from the anatomic cadaveric glenoid specimens were used to create three circular glenoid models. For each glenoid model, bone loss was then calculated mathematically in 1 mm linear increments up to 50% bone loss using the LMP method and the CLM.

The LMP method is an often-used calculation and is based on a best-fit circle glenoid. In our model, the glenoid is circular and the diameter is known. The percent bone loss was calculated by the following equation:

Percent bone loss = bone loss/glenoid diameter x 100%, where bone

loss is the amount of bone loss in increments of 1 mm.

The CLM has been previously documented using chord length to calculate the area of a circular segment (area of bone loss) and the percent of bone loss.²⁵ The pertinent calculation includes:

Chord length = $2r \sin(C/2)$.

Area of segment = area of bone loss = $r^2/2 (\pi/180C - \sin C)$, where r is the radius and C is the central angle.

Percent bone loss = area of bone loss/total area of circle x 100%.

Using a circular glenoid model with linear bone loss, the CLM becomes the gold standard, as it is mathematically calculating the actual area of bone lost. To further simplify the analysis, the area equations were algebraically rearranged to derive an equation based on the linear bone loss length. That is.

Area of segment = area of bone loss = $r^2 \cos^{-1}(r-h/r) - (r-h) \sqrt{2rh - h^2}$.

Each method was used to calculate bone loss for all three glenoid models (smallest, largest and average diameters of cadaveric glenoid specimens), from bone loss of 0–50% in linear increments of 1 mm. Microsoft® Excel (Redmond, WA, USA) was utilized to perform these calculations. Percent error overestimation was calculated by subtracting the CLM gold standard value from the LMP measurement of glenoid bone loss. Again, this mathematical model was created using actual glenoid diameters, but mathematically derived amounts of bone loss assumes a linear pattern of bone loss. Therefore, the CLM is not an estimate, but represents a true value of bone loss.

3. Results

The LMP results compared to the CLM results are equal at 0% bone loss and again at 50% bone loss, but the LMP method overestimated bone loss at every other model of actual bone loss on all three glenoid size models (minimum diameter, maximum diameter and average diameter of cadaveric glenoid specimens) (Figs. 2–4).

Most important was examining the differences between the LMP and CLM results at specific values of glenoid bone loss well supported in the literature that could affect the surgeon's decision-making process (Fig. 5). In the minimum cadaveric glenoid diameter model (25 mm), 4 mm of bone loss is calculated with the LMP as 16% (greater than the 13.5% level proposed by Shaha et al.²), while the CLM reveals a true bone loss of only 10%. In the average size cadaveric glenoid diameter model (29 mm), 4 mm of bone loss is calculated with the LMP as 14%, although the CLM reveals a true bone loss of only 8%. Lastly, in the maximum size glenoid cadaveric diameter model (36 mm), 5 mm of bone loss is calculated with the LMP as 14%, although the CLM reveals a true bone loss of only 8%. In all examples of glenoid size from cadaveric specimens, the LMP and CLM are most different at the mid-range of bone loss (~20%), and as bone loss approaches 50%, the values become more similar and are eventually equal at exactly 50% bone loss (Table 1). The mean percent overestimation of bone loss calculated by the LMP technique when compared to the CLM gold standard across the investigated critical values of glenoid bone loss of all three glenoid models was $5.5\% \pm 0.25\%$ (range 5.1%–5.8%).

4. Discussion

The most important finding of the present study is the overestimation of the widely-used LMP technique in measuring bone loss compared to the CLM gold standard at each 1 mm increment of bone loss in minimum, maximum and average size models from anatomic cadaveric glenoid specimens. The two methods calculate equal bone loss at 0% and 50% glenoid bone loss, but the LMP overestimates at every other point in between. Furthermore, the LMP technique overestimates glenoid bone loss at an average of 5% at the significant thresholds of 13.5%, 20% and 25% of glenoid bone loss, which are traditionally used markers to guide clinical decision making. Differences between the two methods were greatest at the 20% threshold for bone loss across all three glenoid size

Fig. 1. Photograph depicting measurement of the diameter of a cadaveric glenoid with digital calipers. Glenoid has been dissected of all soft tissue.

Fig. 2. This graph demonstrates the difference between the LMP and CLM calculations for progressively increasing glenoid bone loss by mm of bone on the x-axis and showing the percentage of bone loss by the respective calculation along the y-axis for a glenoid diameter of 25 mm which represents the small range of glenoid diameters.

Fig. 3. This graph demonstrates the difference between the LMP and CLM calculations for progressively increasing glenoid bone loss by mm of bone on the x-axis and showing the percentage of bone loss by the respective calculation along the y-axis for a glenoid diameter of 29 mm which represents the average glenoid diameter.

models with a percent overestimation range of 5.7–5.8%. However, the percent overestimation is also clinically relevant at the 13.5% and 25% threshold for bone loss across all three glenoid size models with a percent overestimation range of 5.5–5.7% and 5.1–5.5%, respectively. In all three glenoid size models, the LMP could direct surgeons to selecting a bony reconstruction procedure while the CLM would justify an arthroscopic stabilization procedure.

Many different measurement techniques exist as researchers attempt to find a simple, reproducible and accurate method to quantify glenoid bone loss that is also easily performed by clinicians in an office setting to

offer real-time information for surgical decision making. Meeting all these criteria has been a difficult task, and no one method has prevailed as the gold standard for surgeons who are attempting to decide on the best treatment option for their patients with anterior glenohumeral instability and glenoid bone loss. Certainly, there are other factors besides glenoid bone loss that must be evaluated in deciding whether or not a bony glenoid reconstruction is indicated. Patient age, degree of sport participation, participation in contact sports and presence of hyperlaxity have all been shown as prognostic factors in a patient's ability to succeed after a soft-tissue repair.^{8,26} Failure of a previous

Fig. 4. This graph demonstrates the difference between the LMP and CLM calculations for progressively increasing glenoid bone loss by mm of bone on the x-axis and showing the percentage of bone loss by the respective calculation along the y-axis for a glenoid diameter of 36 mm which represents the large range glenoid diameter.

Fig. 5. The image on the left (glenoid 1) demonstrates a glenoid with minimal bone loss. The diameter (Line CD) is 25.2 mm, the chord (Line AE) is 17.1 mm giving a CLM bone loss measurement of 7.9%. The amount of bone loss (Line CB) is 3.5 mm, along with the diameter produces a LMP measurement of bone loss of 13.9%. The image on the right (glenoid 2) demonstrates a glenoid with more substantial bone loss. The diameter (Line CD) is 31.9 mm, the chord (Line AE) is 26.3 mm giving a CLM bone loss measurement of 16.0%. The amount of bone loss (Line CB) is 6.7 mm, along with the diameter produces a LMP measurement of bone loss of 21.0%.

soft-tissue repair may lead the surgeon to opt for a bony reconstruction regardless of the presence of anterior glenoid bone loss.

A more typical scenario, however, involves the surgeon attempting to calculate the glenoid bone loss to use in their decision making to determine if a bony reconstruction procedure is the best surgical option. Many methods have been employed to help make this determination, most utilizing the assumption that a best-fit circle can be placed to the inferior aspect of the glenoid, using the glenoid bare spot as the center of the circle.²⁰ The best-fit circle assumption allows the use of algebraic geometry to solve for the missing area of the circle if the bone loss occurs in a linear fashion. Irregular or geographical bone loss or bony Bankart fractures do not fit this model (Fig. 6) and cannot be easily measured unless automated software or “tracing” the defect is utilized.

Although many forms of imaging have been used to measure bone loss, the 3D CT is widely accepted as the most accurate and reliable modality.^{8,15} The 3D CT allows the surgeon to rotate the glenoid view from anterior to posterior to reveal the presence of any medialized bone

that may appear to be part of the glenoid surface from the *en face* view. This medialized bone can be displaced greatly and is not effective in providing stability to the glenohumeral joint, so it is excluded when glenoid bone loss calculations are completed.

Some surgeons are fortunate enough to have specialized radiographic imaging software that can calculate the area of bone loss and compare it to the area of the best-fit circle.^{13,17,27} Other authors have demonstrated that these images can be downloaded and then uploaded to freely available software to make these calculations, however this can be timely and not always feasible or compliant on hospital computer systems.¹³

Parada et al. introduced the CLM as a technique which is based on simplifying earlier work by many other previous authors who solved the algebraic geometry issue which takes advantage of the use of the arc angle and the chord, or straight line connecting two points on a circle.²⁵ This method again relies on the two critical assumptions that all algebraic geometric bone loss methods utilize: (1) the critical surface area of

Table 1

Differences in glenoid bone loss between LMP and CLM results at specific values.

Important Threshold of Bone Loss that May Affect Decision-Making	Glenoid Size (mm)	Amount of Glenoid Bone Loss (mm)	Bone Loss as Calculated by LMP (%)	Bone Loss as Calculated by CLM (%)	LMP Error Overestimation (%)
~13.5%	Minimum (25 mm)	4	16.0%	10.3%	5.7
	Average (29 mm)	4	13.8%	8.3%	5.5
	Maximum (36 mm)	5	13.9%	8.4%	5.5
~20%	Minimum (25 mm)	5	20.0%	14.2%	5.8
	Average (29 mm)	6	20.7%	14.9%	5.8
	Maximum (36 mm)	7	19.4%	13.7%	5.7
~25%	Minimum (25 mm)	7	28.0%	22.9%	5.1
	Average (29 mm)	8	27.6%	22.4%	5.2
	Maximum (36 mm)	9	25.0%	19.5%	5.5

mm = millimeter; LMP = linear measurement percentage; CLM = circle line method.

Fig. 6. The two 3D CT reconstructions demonstrate bony Bankarts that do not have a linear pattern of bone loss, making it inaccurate to attempt to measure effective bone loss with either the LMP or CLM techniques.

the glenoid is represented by a circle and (2) glenoid bone loss occurs in a measurable, straight line. Although many forms of glenoid bone loss do not meet the second requirement, especially with acute bony Bankart fractures, the typical example of attritional glenoid bone loss does create a linear pattern of bone loss.

Bahtia et al. also sought to compare linear measurement percentage (LMP) with a true geometric calculation using mathematics modeling software.¹⁹ The author's calculation based on width of bone loss and diameter of the glenoid is significantly more complex than a simple ratio used with LMP. Their equation was: Percent bone loss = $(100/2\pi) (2 \times \arccos [1 - 2 (w/D)] - \sin \{2 \times \arccos [1 - 2 (w/D)]\})$, where w = glenoid defect width and D = diameter. This study also showed that LMP overestimates bone loss and pointed out that this equation would only work if the glenoid was shaped as a square and not a circle when calculating bone loss. The results showed an overestimation of bone loss at all percentages up to 50%. The average bone loss overestimation was 3.9% with the maximum overestimation of 5.8% when the width was found to be 20% of the diameter of the glenoid.

Our current study further corroborates the notion that the LMP

technique overestimates glenoid bone loss around 5% specifically at the critical thresholds of bone loss used to guide surgical decision-making processes, which could be used as a corrective factor. Furthermore, our study was able to produce similar findings using cadaveric glenoid specimens at variable anatomic glenoid diameters (25 mm, 29 mm, and 36 mm), which likely better represents the general population of patients seen in clinical practice as opposed to using mathematical modeling alone. Additionally, the mathematics involved in calculating bone loss by the method proposed by Bhatia et al. may be too cumbersome for clinical practice by the authors own admission.¹⁹ Although the sample size of our cadaveric study was relatively small, the small variation between the percent LMP overestimation between minimum, average and maximum anatomic glenoid sizes suggests that a 5% corrective factor may prove clinically useful when utilizing the more convenient, simple and easily conceptualized LMP used to calculate glenoid bone loss.

Ultimately, the issue of overestimating bone loss may be as serious of an issue as underestimating bone loss when it comes to selecting the appropriate procedure for a patient. Underestimating bone loss could lead a provider to selecting an arthroscopic soft-tissue stabilization procedure when a bony reconstruction is indicated, causing a failure of the procedure and necessitating a further procedure for the patient and perhaps even increased damage to the articular cartilage. Equally disastrous would be a miscalculation of glenoid bone loss that leads the surgeon to incorrectly indicate a patient for a bony reconstruction procedure when an arthroscopic soft-tissue stabilization procedure is indicated. The complication profile of a Latarjet is much greater than an arthroscopic Bankart repair^{28,29} and patients should not be subjected to these complications if the procedure is not indicated.

4.1. Limitations

A limitation of this study is the obvious fact that it utilizes a mathematical model and is not a true representation of clinical data. Despite this fact, it was felt that this modeling allowed a real comparison of measurement systems in a known model of bone loss. Also, these cadaveric specimens were of an average age much older than a typical instability patient, however, it would not be thought that the glenoid diameter would change with age. Another limitation is that only glenoid bone loss with a linear pattern of wear could be compared between these measurement systems, as we did not account for a model with a more geographic pattern of bone loss.

5. Conclusion

The CLM is based on algebraic geometry, taking advantage of the use of the arc angle and the chord. Glenoid bone loss calculations can be compared mathematically using two critical assumptions that all algebraic geometric bone loss methods utilize: (1) the critical surface area of the glenoid is represented by a circle, and (2) glenoid bone loss occurs in a measurable, straight line. In conclusion, the widely-used LMP method overestimates bone loss compared to a gold standard at each 1 mm increment, except for 0% and 50% bone loss, when calculated on minimum, maximum and average diameter glenoids. The overestimation of glenoid bone loss has the potential to lead surgeons towards a bony reconstruction procedure with a higher complication profile when an arthroscopic soft-tissue stabilization procedure is actually indicated in patients with shoulder instability.

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Ethical approval

This article does not contain any studies with human participants, and therefore IRB approval was not required.

Author contributions

SAP, ADR and MTP researched literature and conceived the study. SAP, MCJ, MTD, BGG and SAP were involved in protocol development, cadaveric and mathematical data collection and data analysis. MCJ, BGG and ADR wrote the first draft of the manuscript, and MTD carried out all major section revisions with input from all authors. All authors reviewed and edited the manuscript and approved the final version for publication.

Declaration of competing interest

The authors declare that they have no competing interests.

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