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Accuracy of CT-based measurements of glenoid version for total shoulder arthroplasty

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Background/Hypothesis: The arthritic glenoid is typically in retroversion and restoration to neutral version is recommended. While a method for measurement of glenoid version using axial computed tomography (CT) has been reported and has been widely accepted, its accuracy and reproducibility has not been established.
Methods: In 33 patients scheduled for shoulder arthroplasty, glenoid version and maximum wear of the glenoid articular surface were measured with respect to the scapular body axis on 2-dimensional- (2D) CT slices as well as on 3-dimensional- (3D) reconstructed models of the same CT slices.
Results: Clinical CT scans were axially aligned with the patient's torso but were almost never perpendicular to the scapular body. The average absolute error in version measured on the 2D-CT slice passing through the tip of the coracoid was 5.1° (range, 0 - 16°, $P < .001$). On high-resolution 3D-CT reconstructions, the location of maximum wear was most commonly posterior and was missed on the clinical 2D-CT slices in 52% of cases.
Conclusion: Error in measuring version and depth of maximum wear can substantially affect the determination of the degree of correction necessary in arthritic glenoids. Accurately measuring glenoid version and locating the direction of maximum wear requires a full 3D-CT reconstruction and analysis.
Level of Evidence: Level 1; Diagnostic Study.

Keywords: Total shoulder arthroplasty; shoulder arthritis; 3-D reconstruction; scapular axis; glenoid version

In end-stage glenohumeral arthritis, wear is usually greater in the posterior half of the glenoid articular surface effectively increasing glenoid retroversion.[11,12] Aligning the glenoid prosthesis to the face of the retroverted glenoid predisposes to instability of the joint and increases the risk for glenoid implant loosening secondary to abnormal forces across the implant and cement-bone interface.[3,9] Therefore, surgical reaming and glenoid prosthesis alignment, perpendicular to the scapular axis, are recommended to correct the retroversion.

Plain radiographs are ineffective in assessing glenoid version due to varying radiographic techniques, complex

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and variable scapular anatomy, mobile scapula, and overlapping bones.[8] Computed tomography (CT) scans are, therefore, essential for preoperative measurement of glenoid version. Glenoid version is typically recorded as the angle between a line drawn from the medial border of the scapula to the center of the glenoid and the line perpendicular to the face of the glenoid on the axial 2-dimensional- (2D) CT slice at or just below the tip of the coracoid.[5] Despite the wide acceptance of this method, the accuracy of a 2D axial CT slice has not been well established.

To align the glenoid prosthesis to neutral version and to ensure adequate seating of the bone requires reaming to the depth of the maximum wear. The location of maximum wear, while generally in the posterior direction (which contributes to the retroversion), may not always be consistent. Correction of excessive wear medializes the glenoid prosthesis and increases the risk of perforation of the fixation pegs or keel through the anterior or posterior glenoid surface.[7] Therefore, precisely identifying the location and depth of maximum wear is important for preoperative planning.

While the accuracy of surgical navigation techniques for alignment of hip and knee arthroplasty prostheses has been established, such techniques are still in the developmental phase for shoulder arthroplasty. Current practices include measurement of glenoid version on a preoperative CT scan. However, the relative merits of 2D axial CT slices and multiplanar 2D-CT reconstructions versus a full 3-dimensional (3D) reconstruction have not been studied.

We have previously established the accuracy of 3D-CT reconstruction of the shoulder in representing the bony anatomy and in identifying the potential for perforation.[7] In this study, our primary objective was to measure the accuracy of glenoid version on axial 2D-CT slices relative to a full 3D-CT reconstruction. Secondary objectives were to determine the variability in glenoid version measurement between adjacent CT slices and to determine whether a single axial CT slice at the level of the tip of the coracoid could consistently identify the area of maximum wear.

Methods

After Institutional Review Board approval, preoperative high-resolution axial CT scans of the shoulder were obtained from 33 consecutive patients with osteoarthritis scheduled for total shoulder arthroplasty. The mean patient age was 75 years ± 8.1 (range, 56-90 years). There were 11 males and 22 females. Four patients reported previous trauma to the shoulder. Two of these 4 patients sustained fractures of the humeral neck. One was treated with closed reduction and the other with open reduction and internal fixation. No fracture or instability was reported in the other 2 patients. No glenoid bone fracture was reported in any patient. Computed tomography was performed in a GE Light-Speed RT 16 scanner (GE Healthcare, Waukesha, WI) with 0.625-mm slice thickness. Glenoid version and maximum wear of the glenoid articular surface were measured with respect to the scapular body axis on 2D-CT slices at the tip of the coracoid and at 2.5-mm intervals over a 10-mm vertical distance below the coracoid (Figs 1, *A, B*, *C*) as previously described.[5] We selected slices 2.5 mm apart in the axial direction to simulate the resolution of a typical clinical CT scan. The 3D surfaces were reconstructed from high-resolution CT scans (0.625-mm axial resolution) in a commercially available program (MIMICS, Materialise, Leuven, Belgium). The details of the accuracy and reproducibility of the reconstructed geometry have been previously reported.[7]

"True" glenoid version was measured through the center of the glenoid in the 3D-CT reconstruction on a plane perpendicular to the plane of the scapular body (Figs 1, *D*, *E*). A vertical line was drawn on the glenoid face, centered in the AP direction. A transverse plane was generated perpendicular to the midpoint and passing through the center of the glenoid and the tip of the scapular spine. Version was measured as the inclination of the face of the glenoid at the level of the transverse plane (similar to the measurement on the 2D-CT slice). The location of maximum wear was also identified as the most medial point on the articular surface of the glenoid. The medial direction was specified by a line joining the center of the glenoid to the tip of the scapular spine. The direction of the location of maximum wear relative to the center of the glenoid was recorded on a clock face with 12 o'clock denoting a pure superior direction, 3 o'clock denoting a pure anterior direction, 6 o'clock denoting a pure inferior direction, and 9 o'clock denoting a pure posterior direction (Fig 2, *A*). The clock face was reversed for the left shoulder to maintain consistency in anterior and posterior directions. After identifying the maximum wear on the 3D reconstruction, we also determined if any of the 2D-CT slices at the tip of the coracoid and over a 10-mm vertical distance below the coracoid (at intervals of 2.5 mm) passed through the area of maximum wear. Since the objective of the study was to compare the accuracy of 2 methods of measuring retroversion, we measured all types of glenoid wear (including B2 type[11]) in the same manner. To test for inter-observer error, we analyzed data measured by 4 research staff that were blinded to each other's results.

A power analysis was performed to estimate the sample size necessary to detect a difference of 5° between 2D and 3D measured version. A sample size of 32 was required to obtain a statistically significant difference with a power of 80% at a P value of .05.

Results

In this cohort of patients, the true version (as measured on 3D-CT reconstruction) was mean −8.6° (±9.8°) (Table I). The average absolute error in the version measured on the 2D-CT slice passing through the tip of the coracoid was 5.1° (range, 0° - 16°; $P < .001$). Furthermore, when slices spanning a 10-mm vertical distance below the coracoid on the same subject were analyzed[5] within, subject glenoid retroversion varied by an average of 6.7° (±5.8°).

Clinical 2D axial CT slices at the tip of the coracoid do not necessarily pass through the center of the glenoid. The average absolute error from the center of the glenoid in the superoinferior direction was 5 ± 4 mm. Additionally, the

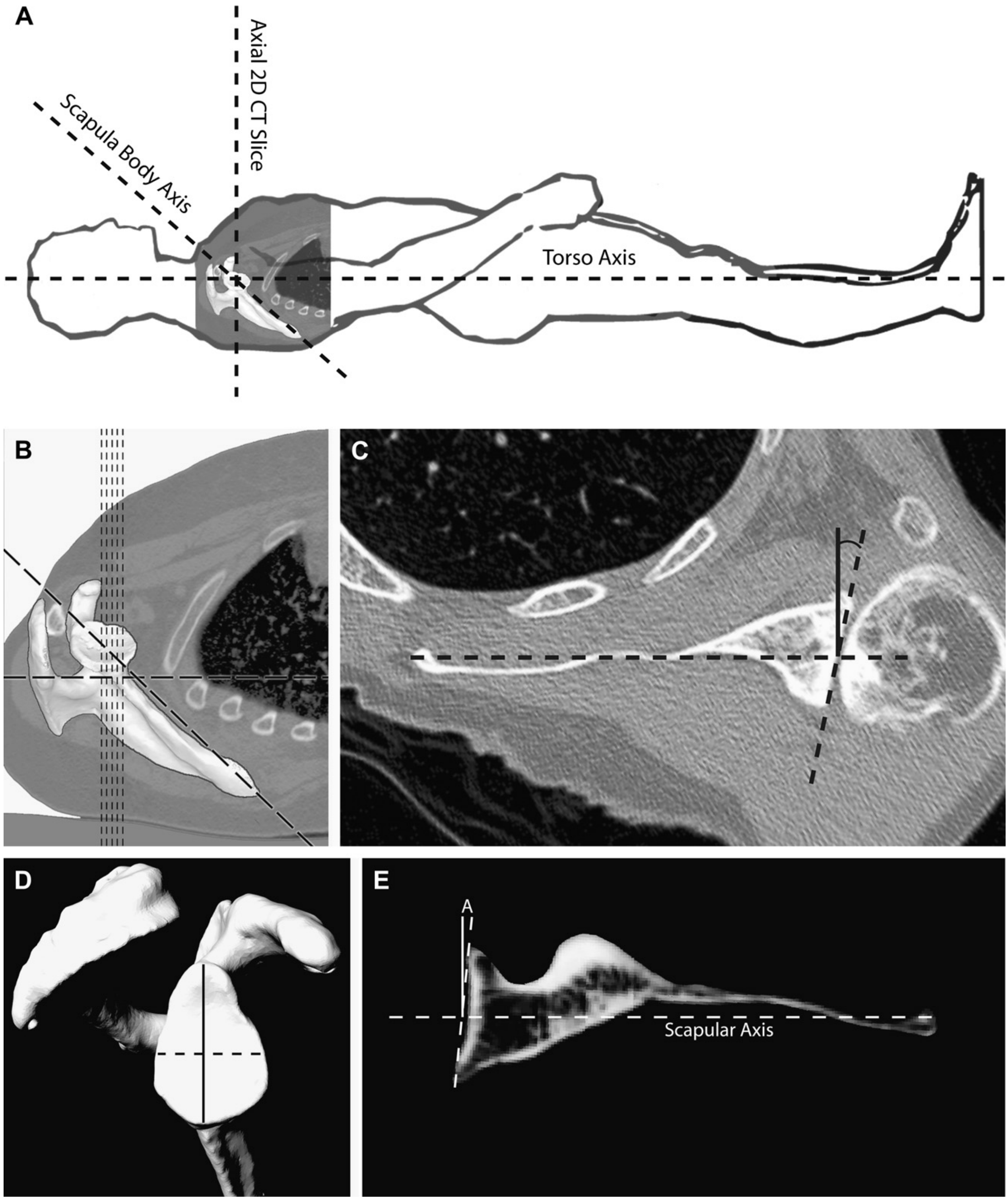

Figure 1 A standard axial CT scan aligned to the patient's body is not typically aligned to the scapula. (**A**) The vertical line shows the direction of the 2D-CT slice relative to the scapular body. (**B**) The 3D-CT reconstruction of a representative scapula and the orientation of 2D-CT slices at the tip of the coracoid and over a 10-mm vertical distance below the coracoid (at intervals of 2.5 mm). (**C**) Image of a 2D-CT slice demonstrating the method for measuring glenoid version.[5] (**D**) A vertical (solid) line was drawn on the 3D surface of the glenoid face, centered in the AP direction. (**E**) A transverse 2D plane was generated perpendicular to the mid-point of the vertical line (dotted line in **D**) and passing through the scapular axis (center of the glenoid and the tip of the scapular spine). Glenoid version angle (**A**) was measured at the level of the transverse plane as for the 2D-CT slice.

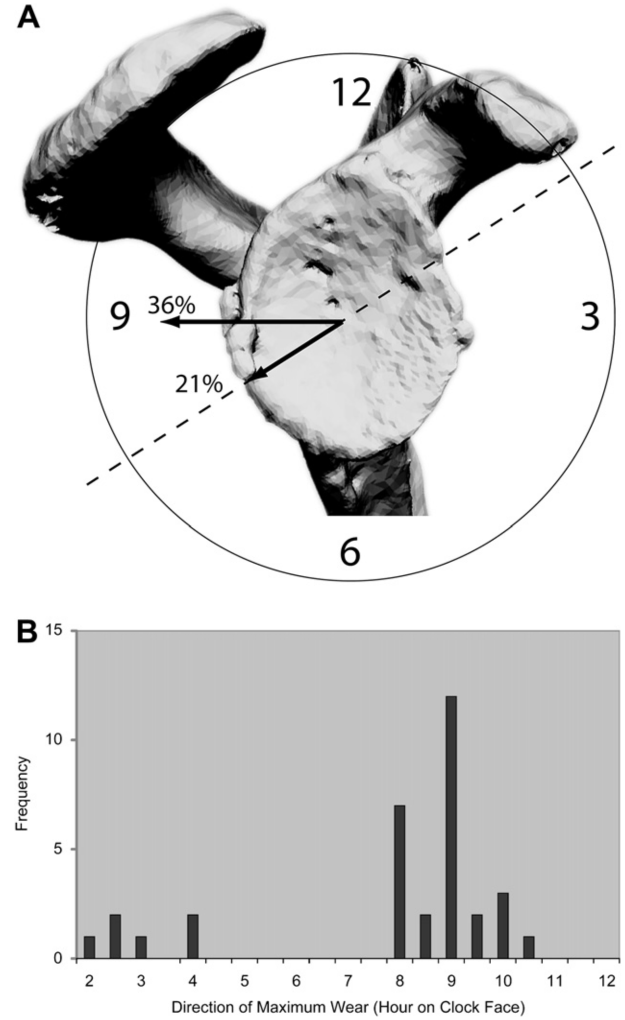

Figure 2 (**A**) Diagram illustrating the direction of location of maximum wear using the articular surface of the glenoid as a clock face. Dotted line indicates the mean inclination of the axial CT slices. Arrows depict the 2 most common directions of maximum wear (9 and 8 o'clock, respectively). The clock face was reversed for the left shoulder to maintain consistency in anterior and posterior directions. (**B**) Frequency histogram of the direction of glenoid wear. The x-axis labels refer to the direction based on the hour using the glenoid as a clock face. The clock face was reversed for the left shoulder to maintain consistency in anterior (3 o'clock) and posterior (9 o'clock) directions.

direction of the 2D axial CT slice was almost never perpendicular to the scapular body but was angled 35° (±19°) from the transverse plane relative to the scapular body.

When the high-resolution 3D-CT reconstructions were analyzed, the location of maximum wear in arthritic glenoids was most commonly posteroinferior (36% in the posterior direction [9 o'clock] and 21% in the posterior inferior position [8 o'clock], Fig 2, *A*). This maximum wear was detected accurately in only 48% of cases in the clinical 2D axial CT slices. To determine whether the error was because of the inclination of the axial slices to the scapular body or because of the offset from the center of the glenoid, we also analyzed a single transverse section through the center of the glenoid on 3D-CT reconstructions. This method would be the equivalent of having the CT reformatted to be oriented to the scapular body. The accuracy only increased to 55%, which was consistent with the fact that in 30% of the cases the maximum wear was not located in the pure anterior or posterior direction (Fig 2, *B*).

Inter-observer error analysis of 4 research staff that were blinded to each other's results revealed the following: in 91% of CT scans measured (30/33), there was a disagreement of 1° or less; in 6% of cases (2/33), there was a disagreement of 2°; and in 3% of cases (1/33), there was a disagreement of 3°. No statistical differences resulted between the mean measurements among observers.

Discussion

Glenoid retroversion due to arthritic deformity is often cited as a cause for posterior humeral subluxation.[1,4,9,11] Surgical correction of glenoid version during arthroplasty is recommended to correct pre-existing subluxation, prevent posterior instability, and reduce excessive stresses on the replaced glenoid. Therefore, a method of accurately determining glenoid version is extremely relevant for preoperative planning.

Reports of mean glenoid version in normal subjects vary between −3° and 2°.[2,5,7] The mean version for this cohort of arthroplasty patients as measured on 3D-CT reconstructions was −8.6 ± 9.8° and was comparable to previous reports.[5,10] While the average absolute error in version measured on the axial 2D CT coracoid slice was moderate (±5°), the maximum error was 16°, and in nearly 20% of cases the error was greater than 10°. Selecting slices below the tip of the coracoid introduced an additional mean variability of approximately 7° in glenoid version measured in the same subject. We could not identify a single clinical 2D slice level that was consistently more accurate.

Clinical CT scans are axial cuts aligned to the patient's torso. Because of the natural tilt of the scapula, these "axial" slices are almost never aligned perpendicularly to the scapula body. Because the mean angle between the direction of axial scan and the scapular body was 35°, true retroversion could not be accurately captured. Therefore, the inherent variability of glenoid version introduced by selecting the level of the slice is compounded by the angle of the slice relative to the scapular body.

Correction of version by eccentric reaming of the glenoid tends to only correct the wear and deformity in the transverse plane. If the maximum wear is not directly anterior or posterior, measurement of version alone underestimates the degree of correction and the extent of medialization required. The maximum wear was most commonly located in the posteroinferior direction.

Table I Comparison between 2D and 3D measurements

Glenoid version measured on 3D-CT (Mean ± SD)	Average absolute error when measured on 2D-CT (Mean ± SD)	Within-patient variation of measured version based on 2D-CT slice level (Mean ± SD)	Distance from 2D-CT slice at the tip of the coracoid and center of glenoid (Mean ± SD)	Angle between 2D-CT plane and scapular body (Mean ± SD)
−8.6° ± 9.8°	5.1° ± 9.8°	6.7° ± 5.8°	5 ± 4 mm	35° ± 19°

Beecause the axial CT slices were angled at a mean of 35° to the scapular body, we explored whether a single clinical CT slice could detect the maximum wear. However, the fact that the location of maximum wear could vary widely indicates that no single 2D-CT slice is capable of consistently identifying the depth of maximum wear and that a full 3D reconstruction is required. This result was supported by the fact that the 2D-CT image through the coracoid missed the location of maximum wear in more than half the cases.

This study reveals the complexity of identifying the alignment of glenoid prostheses to correct arthritic deformity. Attempting to align the prosthesis is complicated by the fact that an axial CT image slice represents a different plane than the intraoperative view. While surgical navigation may assist the surgeon intraoperatively in determining whether the prosthesis is aligned in a desired direction, identifying this desired direction requires careful preoperative planning. In our cohort of cases, while the mean retroversion was moderate (8.6°), in nearly 20% the retroversion was greater than 15°. Correction of severe retroversion is challenging because of the reduced volume of the glenoid vault and the increased potential for perforation induced by excessive medialization.[7] Full 3D-CT reconstructions are recommended for adequate preoperative planning, especially for cases presenting with severe arthritic deformity.

Biomechanical studies have linked glenoid version with subluxation of the humeral head.[3] It is often recommended that retroversion be corrected to correct any humeral head subluxation, as well to reduce the potential for abnormal stresses across the implant-cement-bone interface. These studies indicate that 10° of retroversion is detrimental and should be corrected.[3,6] The mean error of ±5° reported here when compounded with the error introduced by subjective visualization, and the error inherent in any surgical instrumentation becomes clinically relevant. However, our conclusion needs to be validated with clinical outcomes. This study is the first step in establishing the accuracy of clinical modalities in preoperative templating.

No clear recommendations exist for obtaining preoperative CT scans before total shoulder arthroplasty. At our institution, we routinely obtain a preoperative CT scan for glenoid version measurement, as well as for templating for prosthesis size. We have previously published results of a CT-based study demonstrating the potential for peg perforation in a glenoid prosthesis.[7] We cannot, however, recommend a CT scan in each case, because we have yet to collect evidence in the form of better clinical outcomes. We are in the process of following our patient population to assess these outcomes. This study also does not address the economic impact of a preoperative CT scan. In our institution, the additional cost of a CT scan is $252 (Medicare).

Conclusion

Standard 2D-CT slices were not as accurate as 3D reconstructions for measurements of glenoid version and for locating the direction of maximum wear. These results support the need for full 3D-CT reconstruction for preoperative planning in complex cases with significant wear and in the development of effective surgical navigation in total shoulder arthroplasty.

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