Is the Glenoid Vault Outer Cortex a more Accurate Reference Plane than Conventional Methods in Shoulder Arthroplasty?

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Abstract

**Purpose** Glenoid component positioning is an important determinant of outcome in anatomic shoulder arthroplasty. This is dependent on the accurate preparation of bony surfaces. We describe and assess a novel plane for improving the accuracy of bony preparation - the Glenoid Vault Outer Cortex plane (GvOC).

**Research question** Does the GvOC plane provide a more accurate representation of glenoid version and inclination than the standard scapular border (SB) method?

**Methods** 105 CT scans of normal scapulae were obtained. 46 females and 59 males, aged between 22 to 30 years. Accuracy of the GvOC was compared against the current ‘gold standard’ – the SB method. Measurements of glenoid inclination, version, rotation, and offset were made using both GvOC and SB planes. These were compared to ‘actual values’ obtained using an alternative method.

**Results** The mean difference between estimates of version based on the GvOC plane and the reference value were 1.8° (-2 to 5, SD 1.6) as compared to 6.7° (-2 to 17, SD 4.3) when the SB plane was used, (p<0.001). The mean difference between estimates of inclination based on the GvOC plane and the reference value were 1.9° (-4 to 6, SD 1.6) as compared to 11.2° (-4 to 25, SD 6.1) when the SB plane was used, (p<0.001).

**Conclusions** The GvOC plane produced estimates of genoid version and inclination closer to the actual with a lower variance than using the standard SB plane. This may provide a more accurate and reproducible method for surgeons when defining native glenoid anatomy.

Background

Total Shoulder Arthroplasty (TSA), whether anatomic or reverse, is a challenging procedure. Difficulty comes from the limited glenoid exposure and resulting potential challenges of glenoid preparation. This can be particularly demanding in cases where significant glenoid deformity and defects are present. The significance of this is poor glenoid preparation and resulting glenoid component malposition [1].

Glenoid component malposition can lead to poor outcome with unsatisfactory range of motion, pain, and an increased risk of loosening and subsequent implant failure and revision [2–4].

Several techniques have emerged in the literature to date such as Patient-Specific Instrumentation (PSI), CT-based planning, navigation and other computer-or robotic assisted TSA procedures. These techniques have showed reliable results in recent studies [5–8], but are often time-consuming and/or come with significant financial costs attached. Moreover, planning techniques frequently rely on the orientation of the scapula blade as the reference for optimal glenoid positioning.

Rationale
Anatomical studies report significant variability of glenoid orientation (version, inclination and rotation) relative to the scapula blade in normal non-arthritic scapulae [9], with measures of retroversion ranging from −5° to 10° [10, 11]. Considering these findings, it seems that glenoid implant positioning based on the scapula blade orientation may be a significant factor in malposition.

Our study describes and determines the glenoid vault outer cortex (GvOC) plane – a novel method for determining glenoid anatomy in TSA with a view to improving the accuracy of glenoid preparation and implant positioning.

**Study Questions**

(1) Does the GvOC plane provide a more accurate representation of glenoid version than the standard scapular border method?

(2) Does the GvOC plane provide a more accurate representation of glenoid inclination than the standard scapular border method?

**Methods**

**Study design and setting**

The authored performed a retrospective analysis of CT imaging of scapulae obtained from a series of total body CT scans performed between 2009 and 2017.

Inclusion Criteria: CT scan showing at least one scapula in full, with CT sectional slices of <3 mm, to allow for subsequent accurate 3D reconstruction. Patients had to be aged between 20 and 30 years. The purpose of this age range was to overcome any bone morphologic changes due to age-related adaptation to their physical environment, or degenerative disease distorting anatomy.

Exclusion Criteria: traumatic, degenerative or any other kind of insult which may lead to distortion of the scapula bony architecture.

3D reconstructions of 105 scapulae were created from 57 different patients (33 males and 24 females), aged 22 to 30 years-old. Forty-eight CT scans showed fully both scapulae, and 9 with only one scapulae visualized in its entirety.

All of the 105 scapulae underwent the same analysis protocol and same measurements, performed by a single observer.

DICOM data were reformatted in the three space dimensions using the OsiriX MD software (Pixmeo, Geneva, Switzerland) radiological platform. Region of Interest (ROI) points were placed onto the different borders using 3D multiplanar and volumetric reconstruction imaging.
Radiological definition of landmarks for determining the novel GvOC plane

GvOC landmarks were determined using three axial cross-sections strictly perpendicular to the glenoid vault: one axial cross-section at the level of the superior third-middle third junction, one at the middle-third and inferior third junction and one at the equatorial level of the glenoid (Fig. 1A). On each of the 3 axial views, two ROI points were placed; one at the anterior aspect and one other at the posterior aspect of the glenoid - forming a total of six points (three posterior and three anterior). The posterior ROI points placed at the deepest part of the suprascapular nerve fossa (i.e. at the bottom of the posterior slope), and the anterior ROI points were placed at the change of curvature between the slope of the glenoid and the onset of the subscapularis fossa.

The anterior slope of the glenoid is slightly curved with an anterior concavity and therefore fits with a sphere; and the onset of the subscapularis fossa also has a curved shape, with a posterior concavity, that also fits with a sphere. This anatomical relationship allowed the anterior ROI points to be accurately placed at the cross-section between both spheres that represented this change of curvature (Fig. 1B).

The six described GvOC landmarks formed a rectangular polygon, with a center and a superior-inferior direction (Fig. 2).

The novel GvOC plane was defined as the best fit line which passed through all the 6 ROI points.

Radiological Identification of Glenoid Rim and Scapula blade Landmarks

The same method as for the GvOC was used to determine the scapula blade reference (SB) and of the glenoid rim (GR), using a previously established protocol set out by Gregory et al. [12] (Fig. 2).

Variables, outcome measures, data sources, and bias

Two primary, and two secondary parameters were defined and subsequently measured in order to allow for a comparison of accuracy of the novel GvOC plane vs the traditional SB plane. Primary parameters were version and inclination. Secondary parameters were rotation of the supero-inferior axis, and the anteroposterior offset distance. The offset distance between the GvOC and the GR was calculated as the distance between the center of the GvOC and the center of the GR. The offset distance between the SB and the GR was calculated as the distance between the axis of SB and the center of the GR.

In order for the parameters to be measured for each scapula 3D files containing the ROI were transferred to the 3D Reshaper mathematical software (Technodigit, Neyron, France) where the relevant measurements were able to be determined.

Bias was determined to be a significant factor requiring measures to be undertaken to account for within in the design of the study. Intra- and inter-observer reproducibility tests were performed on the interpretation
of the results. For a single scapula, one observer (LM) carried out 10 repeated measures of each relative position parameter under investigation thus assessing intra-observer reproducibility.

In a similar manner, inter-observer reproducibility was evaluated. Ten different observers assessed the relative position parameters for a single scapula. For both intra- and inter reproducibility tests, 95% confidence interval (95% CI) were calculated, using Microsoft Excel software (Microsoft, Redmond, Washington, USA).

In order to evaluate the significance of any difference observed between orientations of the novel GvOC plane and traditional SB plane relative to the reference zero position of the glenoid plane, a Student t-test was performed for each parameter (version, inclination, rotation, and offset distance). Comparisons between GvOC and SB values for each parameter were done, and p-values were calculated with a significance threshold of 0.05.

Results

1. Does the GvOC plane provide a more accurate representation of glenoid version than the standard scapular border method?

The mean difference between estimates of version based on the GvOC plane and the reference value were 1.8° (-2 to 5, SD 1.6) as compared to 6.7° (-2 to 17, SD 4.3) when the SB plane was used, (p < 0.001). An overview of all measured parameters of accuracy are provided in Table 1.
Table 1
Relative positions of SB vs GR and GvOC vs GR in the 105 scapulae

| Measurement                   | Mean | SD  | Minimum | Maximum | Student t-test (Comparison between GvOC and SB values) |
|-------------------------------|------|-----|---------|---------|------------------------------------------------------|
| Retroversion (°)              | 6.7  | 4.3 | -2      | 17      | p < 0.001                                            |
| SB/GR                         | 1.8  | 1.6 | -2      | 5       |                                                       |
| GvOC/GR                       |      |     |         |         |                                                       |
| Superior inclination (°)      | 11.2 | 6.1 | -4      | 25      | p < 0.001                                            |
| SB/GR                         | 1.9  | 1.6 | -4      | 6       |                                                       |
| GvOC/GR                       |      |     |         |         |                                                       |
| Rotation (°)                  | 6.1  | 2.8 | 0       | 15      | p < 0.001                                            |
| SB/GR                         | 1.8  | 1.6 | -2      | 10      |                                                       |
| GvOC/GR                       |      |     |         |         |                                                       |
| Offset distance (mm)          | 3.8  | 1.2 | 1.4     | 8       | p < 0.001                                            |
| SB/GR                         | 0.3  | 0.3 | 0       | 1.6     |                                                       |
| GvOC/GR                       |      |     |         |         |                                                       |

2. Does the GvOC plane provide a more accurate representation of glenoid inclination than the standard scapular border method?

The mean difference between estimates of inclination based on the GvOC plane and the reference value were 1.9° (-4 to 6, SD 1.6) as compared to 11.2° (-4 to 25, SD 6.1) when the SB plane was used, (p < 0.001). An overview of all measured parameters of accuracy are provided in Table 1.

Other relevant findings

Mean superior inclination between GR and GvOC was 1.9° (-4 to 6, SD 1.6) (p < 0.01);

Mean rotation between GR and GvOC was 1.8° (-2 to 10, SD 1.6) (p < 0.01); Mean offset distance between GR and GvOC centers was 0.3 mm (0 to 1.6, SD 0.3) (p < 0.001). Secondary measures of accuracy are shown alongside the primary measured parameters of accuracy in Table 1.
Intra-observer reproducibility results to account for bias are presented in Table 2. Results showed statistically consistent results between measures for every type of measurements in one scapula (p < 0.01). Inter-observer reproducibility results are presented in Table 3 and also showed statistically reliable measures between observers.

| Measurement                  | Mean | SD | Minimum | Maximum | 95% CI |
|------------------------------|------|----|---------|---------|--------|
| Retroversion (°) SB/GR       | 1.1  | 0.6| 0       | 2       | 0.001  |
| Retroversion (°) GvOC/GR     | 0.8  | 0.6| 0       | 2       | 0.001  |
| Superior inclination (°) SB/GR | 0.9  | 0.7| 0       | 2       | 0.001  |
| Superior inclination (°) GvOC/GR | 0.5  | 0.8| -1      | 2       | 0.001  |
| Rotation (°) SB/GR           | 10.9 | 1.0| 9       | 12      | 0.002  |
| Rotation (°) GvOC/GR         | 3.2  | 0.6| 2       | 4       | 0.001  |
| Offset distance (mm) SB/GR   | 2.0  | 0.1| 1.8     | 2.2     | 0.08   |
| Offset distance (mm) GvOC/GR | 0.3  | 0.1| 0.2     | 0.5     | 0.05   |
Table 3
Inter-observer reproducibility tests for SB/GR and GvOC/GR planes position calculations in one scapula

| Measurement                  | Mean | SD  | Minimum | Maximum | 95% CI |
|------------------------------|------|-----|---------|---------|--------|
| Retroversion (°)             | 1.3  | 0.9 | 0       | 3       | 0.002  |
| SB/GR                        | 0.8  | 0.6 | 0       | 2       | 0.001  |
| GvOC/GR                      |      |     |         |         |        |
| Superior inclination (°)     | 1.1  | 1   | 0       | 3       | 0.002  |
| SB/GR                        | 0.6  | 0.9 | 0       | 3       | 0.002  |
| GvOC/GR                      |      |     |         |         |        |
| Rotation (°)                 | 11.5 | 1.1 | 10      | 13      | 0.002  |
| SB/GR                        | 3.6  | 1.2 | 2       | 6       | 0.002  |
| GvOC/GR                      |      |     |         |         |        |
| Offset distance (mm)         | 2.1  | 0.15| 1.9     | 2.4     | 0.09   |
| SB/GR                        | 0.3  | 0.1 | 0.2     | 0.5     | 0.05   |
| GvOC/GR                      |      |     |         |         |        |

Discussion

Background and rationale

We describe in this paper a novel plane the GvOC. This plane is able to reliably and consistently be found, and is more accurate when compared to the traditional SB plane currently used commonly to define glenoid anatomy in TSA. The GvOC may be an alternative plane which allows for more accurate glenoid preparation and subsequently improve final implant positioning and outcome.

Results of the analysis of the 3D CT reconstructions from the scapula utilised showed that the GvOC plane when calculated is very close to the same plane as the normal non-eroded GR. This is evidenced by the mean value of angles between these planes being very low: 1.8° of retroversion (vs 6.7° between GR and SB), 1.9° of superior inclination (vs 11.2° between GR and SB), and 1.8° of rotation (vs 6.1° between GR and SB). Moreover, the mean anteroposterior offset distance between the center of these planes is close to zero: 0.3 mm (vs 3.8 mm between GR and SB).

A key stage during TSA is glenoid preparation and implantation. This demands complete and careful exposure, bony preparation and then implant placement. The difficulty of achieving this is well documented in the literature [12, 7, 9, 1]. When this is not achieved resulting in a poorly positioned glenoid component the literature reports poor outcome[2]. Walch et al. - a group extensively published in
this area - reports a 32% rate of definite radiographic loosening after TSA for primary osteoarthritis [4]. It has been reported that optimal bony fixation of the glenoid implant is directly correlated to better radiological and clinical results, and that glenoid implant placement in TSA should target the center of the glenoid vault - aiming for maximal bone stock [12, 1]. Many authors agree on the difficulty to locate precisely the center of the glenoid vault, and consequently the risks of insufficient fixation strength, and of cortical perforation by the component [1, 13, 14].

In order to improve glenoid implant positioning, recent technologies have emerged and are now in widespread use, such as CT scan-based planning, multiplanar & 3D planning, patient specific instrumentation (PSI), along with computer-assisted and navigated procedures. [6, 15–19]

These new techniques have shown encouraging results [6, 8, 15, 17, 20]. However, many present a common significant limitation: the high variability of the bony landmarks (i.e. the scapula blade or the Friedman plane defined as by a line drawn from the mid-point of the glenoid fossa to the medial end of the scapula blade) used to predict the pre-eroded position of the glenoid surface layer.

Rouleau et al.[9] compared glenoid version measurement in 116 patients with shoulder computed tomography (CT) scans based on the scapula blade (3D) or defined by Friedman method (2D). They concluded that there was no advantage on 3D CT Scan (as compared to 2D) to assess version in terms of reliability of measures. They argue that while in the axial plane - when the scapula blade is almost linear leading to a reference plane passing through the glenoid vault - the repeatability of the measures is acceptable; however, this is not the case when the scapula blade has a curved shape causing the reference line to be in an off-centred position related to the vault of the glenoid.

The glenoid vault has also been studied as a potentially more reliable alternative measuring method for glenoid version[21–23], as well as being a safe fixation site for the glenoid implant itself [1, 13, 24]. However, determining the glenoid vault from the complex inner cortex geometry is challenging [24]. Thus, the planning of the implant position is often based on the unreliable Friedman plane and is subsequently manually readjusted so that the implant fixation fits with the glenoid vault inner cortex (i.e. the maximal bone axis). This might explain some recent published data suggesting inaccurate results when using CT scan-based planning, alongside multiplanar & 3D planning [18].

There is therefore a clear need for an accurate plane which can be reliably located. The novel GvOC examined in this study may be reliable landmark for glenoid implant positioning while maintaining the specific advantages of planned and/or computer-assisted procedures, whilst avoiding their shortcomings as discussed.

The next stage of research on the GvOC should focus on the evolution of the GvOC in the aging patient’s scapulae, as well as the intra- and post-operative relevance of the a GvOC-based guiding system for glenoid preparation and component implantation.

Limitations
The major limitation of this study is the single-observer protocol utilised, however reproducibility tests were performed showing good inter-observer and intra-observer reproducibility in the measures. Another limitation a lack of clinical data from the included patients whose ages ranged between 20 and 30 years old. We have assumed that the given young age range of our scapulae for analysis, patients had not developed any glenoid erosion or other pathology that may alter the bony architecture – however this may not have been the case. Reassuringly our studies report values of glenoid rim orientation with respect the scapula blade corresponding to previous published date in normal patients [9, 10, 21].

Finally, the most important limitation is that age could possibly lead to changes in the relationship between GvOC and GR. Although it is worth noting this appears to have not been taken into consideration in any glenoid preparation guiding system in the literature. The possible bone morphologic changes due to age-related adaptation to the mechanical environment to which they are subjected, needs to be investigated further.

1. Does the GvOC plane provide a more accurate representation of glenoid version than the standard scapular border method?

The mean difference between estimates of version based on the GvOC plane and the reference value were 1.8° (range −2 to 5, SD 1.6, P < 0.001) as compared to 6.7° (range −2 to 17, SD 4.3, P < 0.001) when the SB plane was used. The estimates of version derived from our data using the SB are similar to those reported in the literature. Hoenecke et al in California, USA, have suggested an absolute error in glenoid version of 5.1° (range, 0–16°, P < 0.001). [25] This was in a slightly smaller sample of size of 33 scapulae – but from a notably older cohort scheduled to undergo arthroplasty with likely existing glenoid deformity from degenerative disease.

2. Does the GvOC plane provide a more accurate representation of glenoid inclination than the standard scapular border method?

The mean difference between estimates of inclination based on the GvOC plane and the reference value were 1.9° (range −4 to 6, SD 1.6, P < 0.001) as compared to 11.2° (range −4 to 25, SD 6.1, P < 0.001) when the SB plane was used. Data comparing two commonly used surgical planning platforms - BluePrint and SurgiCase - for glenoid preparation and positioning suggest a difference of in glenoid inclination of 5.1°. [26] Whilst this is lower than the 11.2° it is still in excess of 1.9° measured for the GvOC in this study.

Other relevant findings
The data presented from our study is in line with Rispoli et al. who published results [27]: in 20 consecutive computed tomography scans obtained preoperatively in patients with primary osteoarthritis. The glenoid center point was chosen on the glenoid surface and then projected back into the glenoid vault along the scapular axis and perpendicular to glenoid inclination. They reported that the difference from the projection of the glenoid surface center point to the center point at a 1.5-cm depth into the glenoid vault in the antero-posterior direction (i.e. what we defined as the offset distance) was 1.7 mm. In our study the difference was 2 mm. In addition, they realised that the rotational axis of the glenoid rim matches with the axis of the vault although no data were given. In our studies, we report a mean rotation between GR and GvOC of 1.8° (+/-2°) However, Rispoli et al. analysed eroded glenoids, and therefore were not able to determine correspondence between vault and pre-eroded surface layer inclination or retroversion.

**Conclusions**

The novel GvOC plane described corresponded better to the orientation of the glenoid surface than did the standard SB plane. This may help to improve accuracy in TSA by improving glenoid preparation and final implant position. The GvOC plane can be used in anatomic or reverse TSA to determine the pre-eroded orientation of the arthritic glenoid. In additional, the novel plane described and evaluated in this study may represent a reliable landmark able to further improve accuracy alongside current navigation, PSI and other guidance technologies.

**Abbreviations**

**GR:** Glenoid rim

**GvOC:** Glenoid Vault Outer Cortex plane

**PSA:** Patient-Specific Instrumentation

**ROI:** Region of interest

**SB:** Scapula border

**TSA:** Total Shoulder Arthroplasty

**Declarations**

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Conflicts of interest/Competing interests

Each author certifies that he or she has no commercial associations (e.g. consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article.

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Consent to participate

Not applicable - covered within IRB decision CLEP Decision N°: AAA-2018-08006

Consent for publication

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Availability of data and material

All data and other relevant materials for the manuscript can be supplied on request.

Code availability

Not applicable

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