Original article

Effect of scapular pillar anatomy on scapular impingement in adduction and rotation after reverse shoulder arthroplasty

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Abstract

Background: Notching of the scapular pillar is the main radiographic complication seen during follow-up of reverse shoulder arthroplasties. Several recommendations pertaining to the implantation technique and glenoid component design have been suggested. No studies have investigated potential anatomic risk factors for inferior scapular impingement.

Hypothesis: A specific anatomic shape of the scapular pillar promotes the development of notching.

Materials and methods: The Aequalis Reversed® (Tornier Inc., Edina, MN, USA) prosthesis was implanted into 40 cadaver scapulae. We measured maximal range-of-motion (ROM) in internal rotation, external rotation, and adduction. The anatomic specimens were then imaged using two-dimensional computed tomography (CT) and the scapular neck angle, surface area under the scapular pillar, and distance from the central glenosphere peg to the inferior glenoid rim were measured. Associations between these CT parameters and ROM values were assessed using statistical independence tests.

Results: ROM values were greatest when the surface area under the scapular pillar was above 0.8 cm² (P<0.5). This feature combined with a scapular neck angle less than 105° produced the largest ROM values (P<0.5).

Discussion: The scapular neck angle alone is not sufficient to identify a scapular morphology that increases the risk of notching. The surface area under the scapular pillar, in contrast, discriminates between scapulae with and without a high risk of notching. The surface area under the scapular pillar is influenced by the inferior glenoid offset.

Conclusion: We were unable to define a specific scapular shape at high risk for notching. The prevention of notching should rely chiefly on a rigorous glenoid component implantation technique, with particular attention to the inferior offset.

Level of evidence: III, experimental study.

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1. Introduction

Reverse shoulder arthroplasty was developed by Grammont et al. [1] in 1985 and has since then been proven effective in older patients with eccentric gleno-humeral osteoarthritis. Boileau et al. [2] reported significant improvements in pain scores and forward arm elevation in the plane of the scapula, which had increased by 70° after the mean follow-up of 40 months. The two main adverse outcomes after reverse shoulder arthroplasty are decreased range-of-motion (ROM) with the elbow by the side [3–5] and notching of the scapular pillar [6].

Recommendations regarding the surgical technique have been made to prevent these adverse outcomes. The first criterion identified to ensure optimal implantation of the glenoid component is inferior positioning of the glenoid baseplate as described by Nyfeler et al. [7] and Kelly et al. [8], according to the 12-mm rule. If the drill guide used to prepare the glenoid cavity is placed 12 mm away from the inferior glenoid rim, the supero-inferior position of the glenoid implant will be appropriate to prevent the development of notching, regardless of the shape of the scapula. The second technical criterion is lateralisation of the centre of rotation achieved either by using lateralising implants as suggested by Frankle et al. [9], Kalouche et al. [10], and Valenti et al. [11]; or by

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implanting a lateraled bone graft according to the BIO-RSA (Bony Increased Offset-Reverse Shoulder Arthroplasty) concept developed by Boileau et al. [12]. Nevertheless, lateralisation would be expected, in theory, to increase the loads on the bone-glenoid baseplate interface [13], thereby potentially increasing the risk of glenoid component loosening in the event of prothetic lateralisation or of non-union in the event of bony lateralisation.

A number of improvements in the material have been introduced, and glenospheres are now available in various diameters and designs. Gutiérrez et al. [14–16] obtained better elevation in the plane of the scapula with glenospheres that had a lateralisating effect, whereas notching prevention was most effective with glenospheres that were positioned off-centre. In previous works [17,18], our group showed that a large-diameter glenosphere with BIO-RSA lateralisation was the most effective combination for delaying inferior scapular impingement, while allowing well-balanced rotation ROMs with the elbow by the side.

In contrast to this variety of suggested solutions, the influence of scapular shape has received little research attention. The studies conducted to date focused chiefly on determining the best sites for implanting the inferior baseline fixation screws. Middernacht et al. [19] described a position with posterior offset of the scapular pillar relative to the surgical axis of the glenoid cavity. Torrens et al. [20] identified posterior position of the most prominent part of the scapular pillar as a relevant feature and separated scapulae into two groups depending on whether the neck was long or short. These studies suggest to support a posterior direction of the inferior glenoid baseplate screw. In contrast, Humphrey et al. [21] advocated an anterior direction of this screw, after demonstrating the existence of an anterior buttress of the scapular pillar. Finally, these studies provide a volumetric description of the scapular pillar, in the antero-posterior direction, but fail to identify specific scapular morphological features associated with the development of notching after reverse shoulder arthroplasty.

The primary objective of our work, which relied on two-dimensional computed tomography (CT), was to analyse scapular pillar morphology in order to determine its influence in the risk of inferior notching and the rotation ROMs. Our secondary objective was to verify that the 12-mm rule devised by Kelly et al. [8] was independent from scapular anatomic features.

2. Materials and methods

2.1. Materials

2.1.1. Shoulders and prosthesis

We studied 40 cadaver shoulders (20 from left and 20 from right upper limbs) that had no detectable evidence of prior injury (no internal fixation material or malunions) or overt osteoarthritis (no glenoid cavity deformities to the naked eye). Mean age at death was 79.1 years (range: 61–95 years) and there were 21 men and 19 women. We had no information on the height or weight of the donors.

Before CT, the Aequalis Reversed II® (Tornier Inc., Edina, MN, USA) prosthesis was implanted into each shoulder.

2.1.2. Computed tomography (CT)

We used a Somatome® Definition AS® machine (Siemens S.A.S., France).

2.2. Methods

2.2.1. Prosthesis implantation and range-of-motion (ROM) measurements

The reverse shoulder prosthesis was implanted according to a detailed and reproducible protocol, by a single operator, on the cadaver specimens. Each specimen included the scapula-humeral girdle with the clavicle, forearm, and hand.

A modular metallic holder (Sawbones, Malmö, Sweden) was devised. A vise was clamped onto the scapula and an articulated arm was attached to the rest of the upper limb via an intramedullary nail screwed into the humeral implant. This device allowed us to replicate shoulder movements in all planes. ROMs were measured using protractors in the coronal and horizontal planes. The goal of the assembly was to allow modifications of the degree of humerus elevation while enabling ROM measurements.

On the glenoid cavity side of the shoulder, a baseplate of 25 mm in diameter was combined with a 36-mm centred glenosphere, after preparation of the glenoid cavity around a threaded drill guide held perpendicularly to the joint surface and in compliance with the 12-mm rule described by Kelly et al. [8]. On the humeral side, we used a stem measuring 6.5 mm in diameter with a metaphysis measuring 36 mm in diameter and an insert of the same diameter. Humeral retroversion was adjusted using a guidewire positioned relative to the axis of the forearm.

Once preparation of the shoulder prosthesis assembly on the metallic articulated holding device was complete, a crucial preliminary to performing the various measurements was adjustment of glenoid cavity alignment to ensure that the centre of rotation of the gleno-humeral joint was on the same axis as that of the metallic holder (Figs. 1 and 2). The plane of reference was the plane of the scapula: rotation was considered neutral when the forearm with the elbow flexed to 90° was perpendicular to the plane of the scapula.

For each of the 40 cadaver shoulders bearing the reverse prosthesis, we measured the maximal ROM values in forward elevation in the plane of the scapula, adduction, internal rotation, and external rotation [17,18]. The maximal ROMs were defined as ROMs at which superior, inferior, anterior, and posterior impingements occurred. Rotation ROMs were measured with the humerus in 20° of abduction. This angle was defined based on the glenohumeral joint angle, which reflects the position of the glenosphere relative to the humeral implant. In a study by Falaise et al. [22], the mean gleno-metaphyseal angle of 46.9° in patients with notching indicated 20° of humerus abduction; whereas the mean angle of 37.5° in patients without notching indicated 52° of humerus abduction with a strictly vertical orientation of the glenoid. We therefore selected this low value to ensure detection of impingements during rotation.

2.2.2. Computed tomography (CT)

After removal of the prostheses, each scapula was imaged by CT. All specimens were in exactly the same position on a stiff support. A laser beam was aimed at the middle of the central peg anchoring the glenoid baseplate before image acquisition (Fig. 3).

The image acquisition protocol was the same for all CT scans. We used a standardised protocol appropriate for bone imaging, with a slice thickness of 0.6 mm, 0.3 mm increments, and muliplanar reconstruction. The total radiation dose delivered was 140 mGy, i.e., the same as the dose used to examine living patients.

2.2.3. Image analysis and processing

The CT scans of each scapula were obtained in DICOM (Digital imaging and communications in medicine) format. They were visualised and analysed using Osirix® software (version 3.7.1, GNU General Public License).

2.2.4. Data collection

We elected to study only two-dimensional CT acquisitions. This choice was based on the difficulties encountered in identifying reliable parameters that can be used and measured on three-dimensional acquisitions.

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For each scapula, data were collected twice by the same observer at an interval of 1 month. The measurements were obtained after defining a reference axis through the middle of the central metaglenoid peg in the coronal, sagittal, and horizontal planes (Fig. 4). We also measured the following variables in the coronal plane (Fig. 5):

- cranio-caudal height of the scapular glenoid cavity;
- distance from the middle of the central peg anchoring the glenoid baseplate to the inferior rim of the prepared bony glenoid, or peg-glenoid rim distance (PGRD), after application of the 12-mm rule described by Kelly et al. [8];
- scapular neck angle formed by the line connecting the superior and inferior poles of the prepared glenoid cavity and the line drawn from the inferior glenoid cavity pole to a point located 10 mm away on the scapular neck prominence, as described by Simovitch et al. [23];
- surface area demarcated by the scapular neck and pillar (SAUSN), the 36-mm glensphere segment overhanging the inferior pole of the glenoid cavity, and the horizontal line from the edge of the glensphere to the bony prominence of the scapular pillar.

2.2.5. Statistical analysis

Inter-observer reproducibility was evaluated using the least squares method, with computation of the correlation coefficient R and of the coefficient of determination R².

Steps of 0.10 mm for distances, 0.5° for angles, and 0.04 mm² for surface areas were used for the computations. The relationships between adduction and rotation ROMs, the scapular neck angle, and the SAUSN were evaluated using the Chi² test for independence; however, when the sample size was less than 5, Fisher’s exact test was used. Values of P less than 0.05 were considered significant. The above-described least squares method was used to assess the relation between PGRD, pillar angle, and SAUSN.

Statistical tests were performed using Stat View software (version 4.1, Abacus Concepts Inc., Berkeley, CA, USA).

3. Results

3.1. Range-of-motion (ROM) in adduction, internal rotation, and external rotation (at 20° of abduction) after prosthesis implantation

For the ROM measurements, we replicated the degree of anatomic retroversion (17.5° on average) of each cadaver shoulder during implantation of the reverse prosthesis (Table 1). The results are reported as the means with the 95% confidence intervals:

- adduction: $-16.25 \pm 2.85^\circ$, indicating an adduction deficit relative to the axis of the glenoid baseplate (zero reference position);
- internal rotation: $31.1 \pm 10.2^\circ$;
- external rotation: $33.8 \pm 11.1^\circ$.

3.2. Results from the two-dimensional computed tomography (CT) acquisitions of the 40 scapulae

3.2.1. Descriptive data

The results are reported as the means with the 95% confidence intervals (Table 1):
The three ROMs studied were significantly improved when the SAUSN was greater than 0.80 cm² (Fig. 6).

3.2.3. Influence of scapular neck angle on the surface area demarcated by the scapular neck and pillar (SAUSN)

The correlation coefficient used to evaluate the influence of the scapular neck angle on the SAUSN was modest, equal to 0.56, but the association was highly significant (P < 0.001). Thus, the scapular neck angle explained nearly 40% of the SAUSN. When the SAUSN was less than 0.8 cm², the mean scapular neck angle was 102.9°; whereas a SAUSN equal or greater than 0.8 cm² was accompanied by a mean scapular neck angle of 94.6° (Fig. 7a).

Combining a scapular neck angle cut-off of 105° and a SAUSN cut-off of 0.8 cm² effectively separated two different types of scapular characterized respectively by a mean neck angle of 109.9° with a mean SAUSN of 0.36 cm² and by a mean neck angle of 92.7° with a mean SAUSN of 0.77 cm². We designated these two types as having favourable and unfavourable neck morphologies, respectively (Fig. 7b).

3.2.4. Influence of scapular type on range of motion (ROM) in adduction and rotation

Scapular type as defined above based on the neck angle and surface under the pillar was significantly (P=0.04) associated
3.2.5. Influence of the peg-glenoid rim distance (PGRD) on scapular neck angle and surface area demarcated by the scapular neck and pillar (SAUSN)

The PGRD was not significantly associated with the scapular neck angle.

In contrast, the glenoid prosthesis overhang under the inferior bony glenoid rim computed based on the PGRD explained nearly 30% of the SAUSN; the correlation coefficient was $-0.29$ and the association was very highly significant ($P=0.0004$) (Fig. 9).
notching. The wide array and modularity of commercially available glenoid implants help to prevent the development of this complication, while also improving ROMs in rotation, which are often limited after reverse shoulder arthroplasty [14–18]. Apart from the data reported by Torrens et al. [20], no information was available on potential associations between scapular notching, ROM limitations, and predisposing scapular anatomic features. Assessing such associations was the primary objective of our study. Our findings allowed us to define two types of scapula based on combined measurements of the scapular neck angle and SAUSN. ROMs were significantly better for scapulae having both a neck angle smaller than 105° and a SAUSN greater than 0.8 cm².

We first assessed the influence of scapular anatomy using the descriptive criterion reported by Simovitch et al. [23], namely the scapular neck angle. Whereas this group found a significantly greater frequency of notching in scapulae with higher neck angle values, we found no significant association between neck angle and ROMs in adduction or rotation. Thus, using only the scapular neck angle does not allow the identification of anatomic scapular types at high risk for notching.

The second descriptive criterion selected for our study was the SAUSN. This was the only criterion that separated two scapular types: those with a SAUSN greater than 0.8 cm² and those with a SAUSN equal to or smaller than 0.8 cm². A SAUSN greater than 0.8 cm² was associated with greater ROMs in adduction and rotation.

Thus, different results were obtained with these two descriptive criteria. Nevertheless, the two criteria are closely connected, with a correlation coefficient of about 40%. This discrepancy in the results may be ascribable to influences on the SAUSN not only of scapular anatomy (scapular neck angle or length), but also of the technical prosthesis implantation conditions. In our experimental protocol, we used the 12-mm rule described by Kelly et al. [8], which indirectly reflects the height of the glenoid implantation, thereby governing the inferior glenesphere overhang and consequently the value of the SAUSN. Simovitch et al. [23] stated that appropriate cranio-caudal glenesphere positioning, reflecting inferior prosthetic offset, was the main criterion for preventing notching, being more important than the scapular neck angle. Similarly, a cadaver study by Nyffeler et al. [7] demonstrated that inferior glenoid component anchoring was crucial to improve adduction ROM. In our study, we found a correlation of about 30% between inferior glenoid implant position and the SAUSN.

Thus, the scapular neck angle and cranio-caudal glenoid component position emerge as two major parameters for increasing the SAUSN, thereby minimising the risk of notching. We found that the combination of a scapular neck angle of less than 105° and a SAUSN greater than 0.8 cm² defined a favourable scapular geometry associated with better ROMs in the various planes. In contrast, the scapular geometry characterized by a neck angle greater than 105° and a SAUSN less than 0.8 cm² was unfavourable, that is, associated with smaller ROM values. Nevertheless, there have been reports that applying the 12-mm rule described by Kelly et al. [8] can, in some cases, increase the SAUSN, thus cancelling out the effects of an unfavourable scapular neck angle. Thus, only the 12-mm rule to determine the inferior glenoid offset may be able to counteract a scapular geometry at high risk for notching. Support for this possibility comes from our finding that the prosthetic glenesphere overhang relative to the bony glenesphere rim computed in our study was constant, with a mean of 4.51 ± 0.41 mm, regardless of scapular geometry.

A single published study, by Torrens et al. [20], focused on morphological scapular features of relevance to the implantation of a reverse shoulder prosthesis. This descriptive study showed considerable variability in scapular geometry. Two groups were defined, long-neck and short-neck, respectively, although no cut-off was identified. In addition, two scapular pillar types were distinguished based on an angle complementary to the scapular neck angle described by Simovitch et al. [23]: type I scapulae had a mean value of 52° and type II scapulae a mean value of 64°. However, no effort was made to assess correlations between these descriptive features. In addition, the scapulae were not implanted and no clinical data were available. Torrens et al. [20] concluded that the surgical technique must be customised to the specific needs of each individual when implanting a reverse shoulder prosthesis.

A strength of our study is the collection of scapular anatomy data from a substantial number of cadaver specimens bearing a reverse prosthesis and used to obtain accurate ROM measurements.
Any technical biases inherent to the prosthetic implantation, such as inferior tilt and glenoid retroversion, were limited. Under these conditions, the two parameters selected in our study, namely, neck angle and SAUSN, appeared useful for evaluating scapular anatomy and the main technical criterion, i.e., the 12-mm rule of Kelly et al. [8].

Our study has several limitations. ROMs were measured at the anatomic retroversion, which differed for each of the implanted and tested shoulders. Several studies [18,25,26] indicate that the degree of humeral implant retroversion influences the risk of scapular notching. Our decision to use two-dimensional CT imaging is also open to criticism. We selected the CT slice through the central peg of the glenoid baseplate at the point of maximal diameter. This criterion does not ensure that the slice goes through the most prominent part of the scapular pillar, where notching is most likely to occur. Impingement may not occur at a single site of the scapular pillar. In an arthroscopic evaluation, Boughebri et al. [27] showed...
that, during external rotation, impingement occurred posteriorly at first then shifted gradually to an inferior position. Thus, a three-dimensional CT assessment as performed by Torrens et al. [20] may be more appropriate for describing antero-posterior pillar anatomy and understanding the pathophysiology of notching. However, we were unable to find a satisfactory tool for assessing the pillar on three-dimensional acquisitions. Most notably, the SAUSN cannot be measured on three-dimensional models. A volumetric evaluation would probably be more satisfactory but also less widely available and more difficult to use in everyday practice.

5. Conclusion

Our study confirms the major role for optimising inferior glenoid overhang in preventing impingement on the scapular pillar after the implantation of a reverse shoulder prosthesis. The 12-mm rule devised by Kelly et al. [8] allows to achieve this objective. The use of this rule, in combination with a favourable scapular geometry, defined in our study as a neck angle smaller than 105°, further improves ROMS in the various planes, thereby minimising the risk of subsequent scapular notching.

Disclosure of interest

Julien Berhouet, Pascal Garaud, Jordan Nicot, Jesse Banah, Eric Waynberger declare that they have no conflicts of interest concerning this article.

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