SHOULDER ARTHROPLASTY: GLENOID WORRIES

Anatomical and biomechanical
considerations of the glenoid

Anne Karelse

Thesis submitted for the degree of Doctor in Health Sciences 2015

Department of Orthopaedics and Traumatology
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Table of Contents

Introduction

Shoulders are similar to other joints subject to aging and wear, and at one stage a shoulder surgeon must deal with the request for help from a patient with painful degeneration of the shoulder joint. This pain and the functional impairment can be so severe that it obviates the need for replacement of the joint. Shoulder arthroplasty is currently an established treatment for any type of osteoarthritis and it can provide reliable pain relief and an improved to almost normal function of the shoulder. The last few decades the total shoulder arthroplasty has made a striking improvement in longevity and functional outcome. The main complication jeopardizing this success is the loosening of the glenoid component, which can be associated with increased pain, decreased function and the need for revision surgery.

The aim of this thesis is to create insight in the factors and mechanisms influencing glenoid loosening with the intention to hand guidelines in surgical approach and preparation of the glenoid for optimal component placement.

Chapter 1 is a short introduction to the anatomy, biomechanics, pathology and prothesiology of the shoulder joint.

Chapter 2 is a literature study clarifying the concept and mechanism of glenoid loosening and providing an overview of the parameters influencing failure of the glenoid component.

Chapter 3 is a three-dimensional CT scan study on the orientation (version and inclination) of the original non-pathological glenoid surface. The arthritic process causes erosion of the glenoid, often asymmetric resulting in a posterior tilt of the surface. In total shoulder arthroplasty it is essential to restore the orientation of the original (or native) glenoid surface, failure to do so is associated with prosthetic instability and endangers the longevity of the prosthesis. In this study the glenoid surface is defined as a plane and different planes are measured. We hypothesize that the plane with the least variation represents the 'true' glenoid plane and is the most reliable to use in prosthetic surgery.

Chapter 4 is a basic science study of the effect of reaming on the glenoid surface and bone volume. Reaming is performed to correct the orientation of the glenoid surface to the native plane and to create a smooth and solid underlying surface for fixation of a prosthesis. In cases of posterior erosion it is common use to ream down the anterior side to correct the orientation, but since the relatively small size of the glenoid and its conical shape there is a limit to the amount of reaming. We study the effect of different types of reamers (flat and convex) on a series of glenoids with differently orientated surfaces created from Sawbone foam blocks. The loss of bone volume, the size of the remaining surface area and the reaming depth are measured and evaluated.

Chapter 5 is a basic science study questioning the accuracy of the reaming procedure. We investigate if it is feasible to ream glenoids with different erosion patterns in a reproducible way. The influence of different reamers, surgeon's experience and glenoid erosion patterns on the quality of the reamed surface is evaluated.

Chapter 6 is a CT scan simulation study focusing on the influence of the inclination of a glenoid component. The magnitude of the shear forces exerted by the rotator cuff on a virtual glenoid component in different positions of inclination is discussed.

Chapter 7 is an anatomy study describing two consistent bony pillars of the scapula that can be used as a fixation point in case of severe erosion of the glenoid in primary, but more often, revision surgery.

Chapter 8 is an evaluation of the results of a clinical study of arthroscopic soft tissue interpositioning arthroplasty, using either a dermal allograft or a meniscal allograft, as an alternative treatment for severe osteoarthritis of the shoulder joint in young and active patients.

Chapter 9 displays future considerations on guidance in prosthetic surgery of the shoulder.

Chapter 10 is a summary with conclusions.

Chapter 1 The shoulder joint

1.1 Anatomy

The shoulder is a complex joint with a subtle equilibrium between mobility and stability. In the glenohumeral joint the proximal humerus articulates with the glenoid surface surrounded by labrum, capsule, ligaments, tendons and muscles of the rotator cuff. The interaction between the static (bone, cartilage, labrum, capsule and glenohumeral ligaments) and dynamic stabilizers (rotator cuff) of the glenohumeral joint permits a wide range of motion of the shoulder.[1] (Figure 1 and 2)

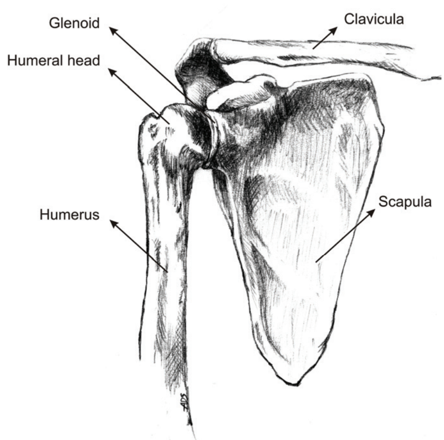

Figure 1: Bony anatomy; the humerus articulates with the scapula in the glenohumeral joint.

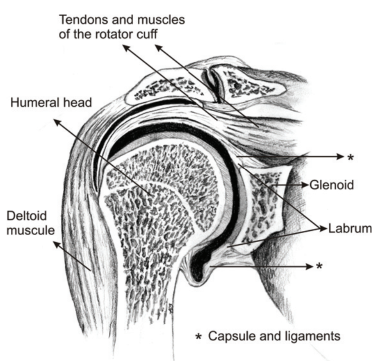

Figure 2: Labrum, capsule, ligaments, tendons and muscles surround the glenohumeral joint.

The bony anatomy of the proximal humerus and the glenoid show a large variation. The humeral head has the shape of an ellipse, approaching a sphere, with 4 geometrical variations relative to the humeral shaft; the inclination, version, medial offset and posterior offset.[2,3,4] The glenoid is a shallow fossa with a diverse curvature, size and shape, with a length larger than the width. (Figure 3)

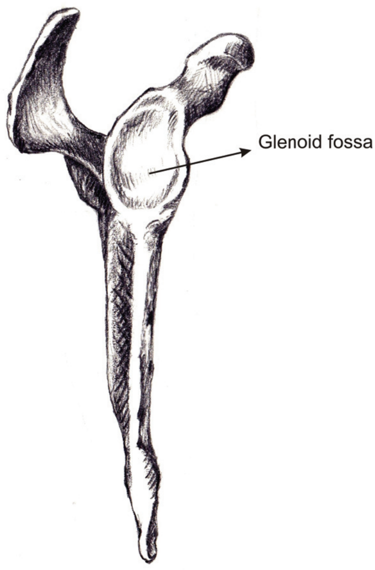

Figure 3: The glenoid fossa

The orientation of the glenoid is determined by the version and the inclination. The version is the angulation of the glenoid in the transverse plane (Figure 4) and is most frequently measured according to the method of Friedman. This method defines version as the angle between the glenoid fossa line and the perpendicular to the line between the center of the glenoid and the medial end of the scapula (90 – α degrees). (Figure 5a) This ranges in healthy individuals from 14 ° of retroversion to 12° of anteversion, with a mean of 3° retroversion. The inclination is measured similarly in the coronal plane and ranges from -8° to 16 ° (a negative number corresponds to an inferiorly directed and a positive number to a superiorly directed glenoid), with a mean of 4°. [5,6] (Figure 5b)

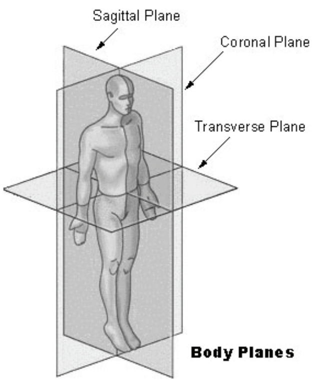

Figure 4: Planes of the body

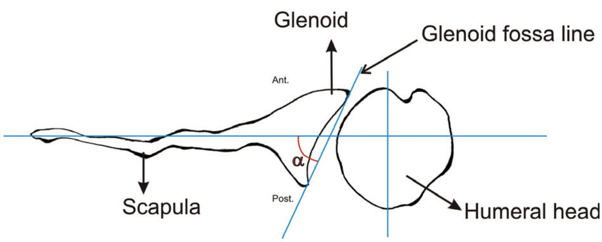

Figure 5a: Version of the glenoid = (90- α) degrees.

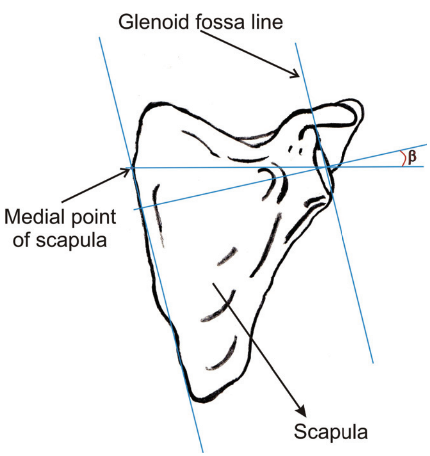

Figure 5b: Inclination of the glenoid = β

These dimensions are angles between lines and do represent two-dimensional anatomical findings. The wide variation of the measurements is partly explained by anatomical variation and partly by positional errors. Outcomes of version measurements on two dimensional (2 D) CT images vary significantly with scapular rotation and positioning of the patient.[7, 8] The use of three dimensional (3 D) reconstruction images to determine the orientation of the native glenoid is more precise and independent of the position of the scapula.[9,10,11]

1.2 Biomechanics

The gleno-humeral articulation is composed of a convex humeral head on a concave glenoid fossa, which acts as a fulcrum. These are close fitting and have nearly identical curvatures and identical centers of rotation in a normal shoulder. The radius of curvature of the glenoid is slightly larger than the humeral head curvature allowing rotation but also translation of the humeral head in the glenoid. The articular cartilage and labrum facilitate in conforming the glenoid to the humeral head, aiding in joint stability and evenly distribution of joint pressure.[1]

The force couples of the rotator cuff (the transversal couple is the balance between the subscapularis anteriorly and the infraspinatus and teres minor posteriorly and the coronal couple is the balance between the deltoid muscle and the force vector of the subscapularis, infraspinatus and teres minor distal to the center of rotation) serve as the primary stabilizing mechanism providing compression of the humeral head in the glenoid concavity during the normal range of motion.[12,13] (Figure 6 and 7)

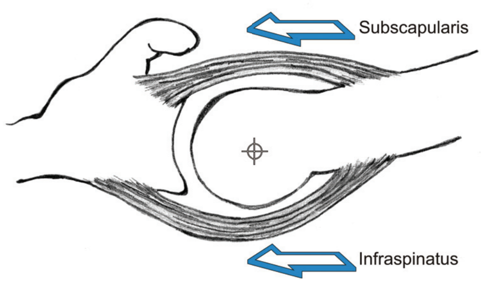

Figure 6: Transverse force couple

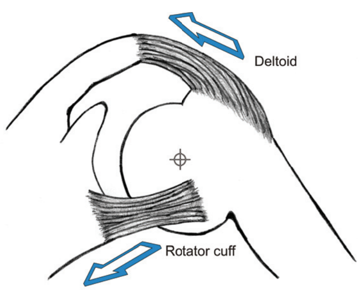

Figure 7: Coronal force couple

Codman described the shoulder as a simple bony structure with a very complex muscular mechanism, of which the function and accuracy of motion in every direction depends on the muscles, which must be absolutely coordinated and always work together to follow as the fulcrum (glenoid) changes positions.[14] (Figure 8)

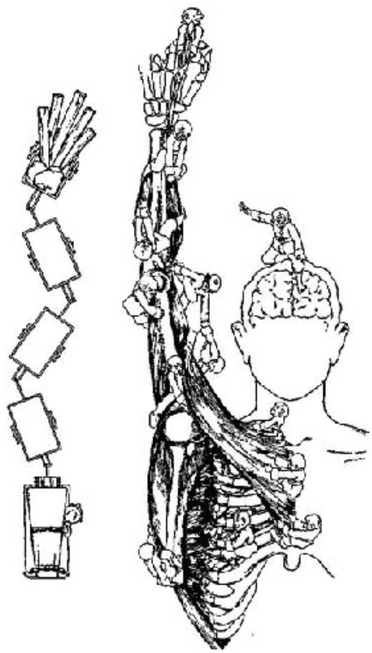

Figure 8: Codman figure: cooperation of all muscles.

He compared this with a car and a trailer where the back of the car represents the glenoid surface, with the location of the towing hook on the back of the car representing the spinning point, the ball of the towing hook representing the glenohumeral articular center of rotation and the trailer which represents the humerus. Change in position of the back of the car (glenoid surface) changes the center of rotation of the trailer immediately effecting the position of the trailer. Moreover if the back of the car (glenoid surface) is positioned obliquely (as in retroversion of the glenoid) it will be more difficult to control the position of the trailer (c q the humeral head) Furthermore a direct conflict between car and trailer can arise if the slope is too steep, this reduces overall freedom of movement.

1.3 Pathophysiology

In degenerative glenohumeral joints the loss of the smooth articular cartilage and the erosion of the subchondral bone can result in a change of the glenohumeral contact area and an increase of local joint pressures contributing to the progression of bone erosion.[15] (Figure 9) In primary omarthrosis this erosion is typically central or posterior. Posterior erosion can lead to biconcavity of the glenoid and can be associated with subluxation of the humeral head. In these circumstances where the orientation of the native glenoid surface is changed, the center of rotation of the glenohumeral joint can be altered causing a disbalance of the force couple.[16] Disruption of the force couple as in rotator cuff tears compromises the concavity compression and can affect the load transmission in the glenohumeral joint.[13]

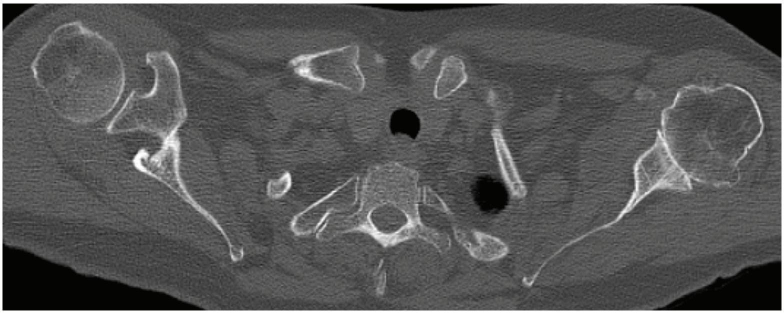

Figure 9: CT scan image showing a normal glenohumeral joint on the left side, and a degenerative joint on the right side, with loss of the joint space and flattening of the joint surface.

1.4 Prothesiology

It was Jules Pean in 1892 who replaced the humeral head of a shoulder by a prosthesis for the first time, long before the first hip or knee replacement.[17] The indication was a painful shoulder destroyed by tuberculous arthritis and the implant had to be removed due to infection 2 years later. It took until the 1950 ‘s before Doctor Charles Neer introduced the concept of the unconstrained shoulder prosthesis.[18,19, 20] (Figure 10)

Figure 10: Neer Shoulder Prosthesis: Stemmed humeral component and a polyethylene glenoid component.

This evolved from hemiarthroplasties, where only the humeral head was replaced, to total shoulder replacements, with implementation of a glenoid component.[21] Currently the third generation unconstrained total shoulder arthroplasty consists of a stemmed or stemless metal humeral component with modularity for the humeral head in size, offset, inclination and version, and a polyethylene component for the glenoid. (Figure 11)

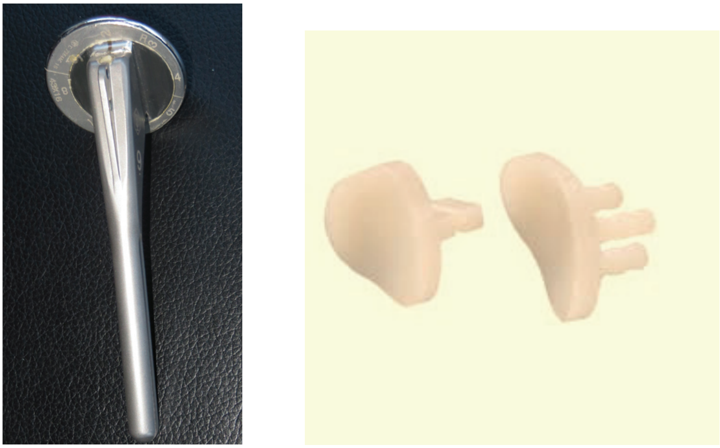

Figure 11: Left: Stemmed humeral component with modularity for the humeral head. Right: Keeled and pegged polyethylene component

These third-generation total shoulder prostheses have the theoretical advantage of a more accurate reconstruction of the glenohumeral centre of rotation. In the future this can be improved with the introduction of elliptical humeral heads, which are a better approximation of normal geometry allowing more anatomical movement.[22]

Anatomical and biomechanical studies have had great implications with regards to prosthetic design. Theoretically, prosthetic replacement should restore normal geometry hence restoring tissue balance and center of rotation. Small alterations in anatomy result in altered glenohumeral kinematics as shown by Matsen.[15] Every single degree of glenoid retro-/anteversion, varus/valgus angulation will displace the center of rotation of the mean humeral component by 0.5 mm, and vice versa.[16]

It is impossible to reproduce a glenoid component with the same mechanical properties and geometry of the native glenoid with labrum and cartilage since a polyethylene component is much stiffer. If the radius of curvature of the glenoid equals the humeral component, as in a conforming design, there will only be rotation, no translation and excellent stability. In motion this can cause eccentric compression of the humeral head on one side creating a tensile loading on the opposite side of the glenoid. This eccentric loading of the glenoid is called the rocking horse phenomenon potentially causing wear and loosening of the glenoid component.
In a non-conforming design there is a mismatch between radii of curvature of glenoid and humerus allowing the humerus to translate slightly. This decreases the contact area and increases local contact stress, leading to asymmetrical or eccentric loading and the rocking horse phenomenon (with again potential risk of polyethylene wear and loosening).
(Figure 12)

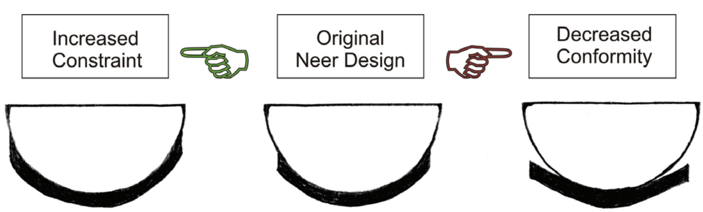

Figure 12: Center: Original unconstrained Neer design. Right: Decreased conformity leads to decreased stability and decreased constraint. Left: Increased conformity leads to increased stability and increased constraint.

The overall results of the unconstrained total shoulder replacement have been very satisfactory, and patients with primary osteoarthritis (having an intact rotator cuff) have the best functional outcome.[21, 23, 24] Reported survivorship of the Neer cemented, all-polyethylene glenoid component ranges from 93% to 97% at 10 years and 84% to 87% at 15 years.[25, 26] The results of total shoulder arthroplasty are superior to hemiarthroplasty in primary osteoarthritis, with a higher satisfaction, better range of motion and the primary benefit being the superior pain relief. Despite the increased technical difficulties and potential problems associated with the placement of a glenoid component the rate of revision surgery is significantly lower for total shoulder arthroplasty compared to hemiarthroplasty. (Figure 13)

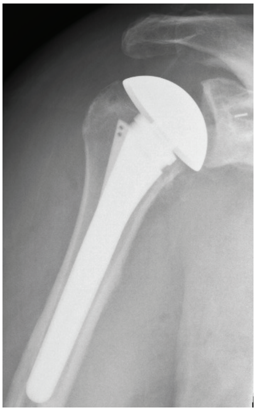

Figure 13: Total shoulder replacement: Stemmed humeral component and a polyethylene glenoid with a metal marker in the central peg to verify the position.

In patients with osteoarthritis with sufficient glenoid bone stock and an intact rotator cuff the total shoulder arthroplasty appears to be the surgical treatment of choice.[26, 27, 28, 29, 30, 31] The glenoid component remains the weakest link.

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Chapter 2 Glenoid failure

2.1 Introduction

Loosening of the glenoid component is the most frequent middle- and long-term complication of total shoulder arthroplasty. An extensive review of the literature on failure of the glenoid component brought up a lack of agreement on definitions of loosening and failure and it revealed a labyrinth of variables as potential risk factors for the occurrence of loosening. To improve the quality of future studies we should first of all agree on definitions of outcome (loosening and failure) and variables (potential risk factors of loosening). The first aim of this thesis is to create insight and organization of these topics. [2,4,9,13,24,26,36,37,38,41,46,47,50,63, 85,92,102,103,114,120,]

2.2 Biomechanical failure

In prosthetic surgery the reconstruction of the normal geometry should restore the center of rotation and the soft tissue tension. (Figure 1) Small alterations in anatomy result in altered glenohumeral kinematics and with the knowledge that every single degree of glenoid retro-/anteversion, varus/valgus angulation will displace the center of rotation of the humeral component by 0.5 mm, it is obvious that an anatomical reconstruction needs to be performed within a minimal margin of error.[75, 82] (Figure 2)

Figure 1: The center of rotation and the soft tissue tension should be restored to retain the net humeral reaction force within the glenoid.

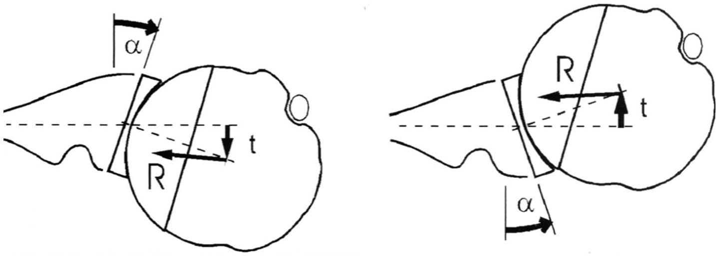


Figure 2: Influence of glenoid component version (α) on anteroposterior humeral head translation (t) and orientation of the resultant force vector (R). The centre of the humeral component is displaced posteriorly by 0.5mm per degree of retroversion and vice versa.

The primary and most important mechanism of glenoid loosening is biomechanical failure, with the exception of inflammatory pathology (biological failure). The biomechanical failure can be defined as a disturbance of the subtle equilibrium of the transversal or the coronal force couple at the shoulder. Disruption of the force couples compromises concavity compression and affects load transmission in the glenohumeral joint. [86, 89]

The mechanism of glenoid loosening is the repetitive eccentric loading of the humeral head on the glenoid, the so-called rocking horse phenomenon, causing tensile stresses at the bone-implant or bone-cement-implant interface initiating causing loosening. (Figure 3 a and b) Any unbalance in the glenohumeral unit at the glenoid side, the humeral side or in the force couple of the rotator cuff (either transverse or coronal) potentially creates eccentric loading leading to the rocking horse phenomenon. (Figure 4)

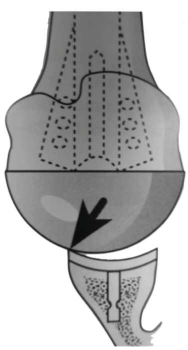


Figure 3 a: Eccentric (or edge) loading

Figure 3 b: Superior migration of the humeral component causes eccentric loading.

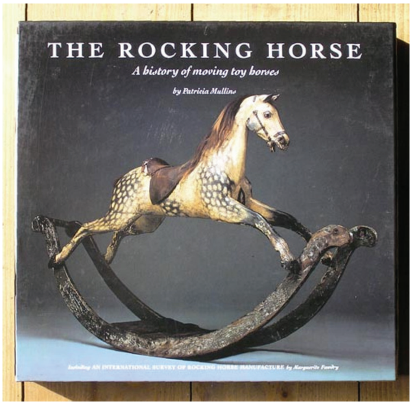


Figure 4: A rocking horse.

Biological failure is the second mechanism of loosening, and either an infectious disease, or a particle disease causes this. The latter is due to the different stiffness of the ultra high molecular weight polyethylene (UHMWPE) compared to the humeral head or the glenoid bone stiffness. This difference will always lead to some eccentric loading, more prominent in conforming designs, and to a lesser degree in non-conforming designs.

The effect of eccentric loading is more significant if the implant fixation is suboptimal or if the soft tissue status of the shoulder is altered. [41, 50, 122] Even an isolated weakening or partial tear of the supraspinatus tendon will negatively influence this unbalance, but to a lesser extent as medium to large rotator cuff tears.[46] These tears cause eccentric loading in the antero-posterior direction, but also in the supero-inferior direction due to lack of resistance to the upwards pull of the deltoid muscle leading to superior migration of the humeral head.[40, 118] Tight capsular structures and retracted rotator cuff tendons can also negatively influence the eccentric loading[1]

2.3 The definition of glenoid loosening

The most frequent middle- and long-term complication of unconstrained total shoulder arthroplasties is glenoid loosening, but the concept of loosening has received many different definitions. [2, 4, 9, 19, 38, 41, 47, 50, 85, 92, 102, 114] Loosening can be defined according to radiological appearance, progression and clinical data as follows:

1. Radiolucent lines. The majority of radiolucent lines at the bone-cement interface appear from day

one after surgery suggesting reflection of surgical technique rather than failure of the implant and these are not necessarily of clinical significance. The reported incidence in the literature is 30 to 96 %.[9, 10, 13, 36, 79, 102, 103, 121]

2. Radiological loosening. Between 0 and 44% progress to radiological loosening. This is defined as an increase of radiolucent lines, as a complete radiolucent line of 2 mm or more around the implant, or as implant migration.[114] (Figure 5)

3. Clinical loosening. Clinical loosening is the progression of radiolucent lines and/or migration of a component, associated with increased pain and decreased function of the shoulder. Progression to clinical loosening is clearly increasing with a follow-up of five years or longer.[47]

4. Revision. This is considered to be the endpoint for clinical glenoid loosening. Between 8 to 10% results in actual revision of loose implants at longterm follow-up (10 to 15 years).[10, 36, 47, 114, 121]

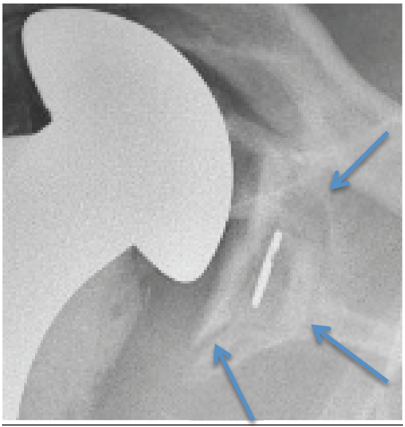


Figure 5: A complete radiolucent line (arrows) around the keeled polyethylene glenoid implant.

2.4 The causes of glenoid loosening.

Failure of a shoulder arthroplasty in general is likely to be multifactorial; patients have on average 4 contributing factors leading to dissatisfaction after a shoulder arthroplasty.[41] Largely the contributing factors to loosening mechanisms can be divided into 3 groups (Table 1):

1. Implant related, with design features of the components, fixation methods, material properties and the glenohumeral relationship as main categories.
2. Patient specific factors include the pathology of the glenohumeral joint and the bony morphology of the glenoid.

3. Surgical factors: individual skills and experience in surgical technique seem to play a crucial role in the outcome of arthroplasties.

1. Implant related factors	
1.1. Design: size and shape	Oval, circular, elliptical Convex or flat backed Keeled or pegged Step-off implant or vaulted
1.2. Fixation methods	Cemented or uncemented Metal backed or Full Polyethylene
1.3. Material properties	Type of Polyethylene
1.4. Glenohumeral relationship	Conformity Morphology of the humeral head Orientation of the humeral head
2. Patient Specific factors	
2.1. Pathology of the glenohumeral joint	Soft tissue related Bone related Combination
2.2. Morphology of the native glenoid	Egg, pear or comma shaped Dysplasia
2.3. Orientation of the native glenoid plane	Version Inclination
2.4. Erosion of the glenoid	Concentric or eccentric Subluxation of the humeral head
3. Surgical factors	
3.1. Experience	Years of experience Number of surgeries
3.2. Amount of correction	How to determine?
3.3. Method of correction	Downreaming Type of reamer Guidance Augmented glenoids
3.4. Preparation of the bone	Motorised, hand reaming Type of reamer
3.5. Cementing technique	
3.6. Soft tissue handling	

Table 1. Parameters influencing glenoid loosening.

2.4.1 Implant related factors

2.4.1.1 Design of the glenoid prosthesis.

Size and shape should ideally match the underlying bone. Optimal support by subchondral bone centrally and cortical bone at the peripheral rim enhances resistance to off-center loading. An oversized component creates overhang, and loading at one side can lead to lift off of the opposite side, whereas an undersized component lacks support of the cortical rim and is prone to subsidence. [121] Anatomy studies show that approximately 30 % of glenoids have an ovoid or elliptical shape and 70 % is pear or egg-shaped. (Figure 6) Fewer mismatches will be encountered if a pear-shaped design is used. A height to width ratio of approximately 1.3 to 1 improves the antero-posterior and supero-inferior fit.[18]

Figure 6: A pear-shaped glenoid.

Curved back prostheses withstand off center loading better than flat backed. (Figure 7) A curved backed prosthesis shows half the distraction (defined as movement between bone and prosthesis on the unloaded side) of a flat backed if a dynamic physiological rocking horse test is performed.[3] In curved backings stresses are transmitted more in compression than in shear (vector parallel to the surface) and consequently stress concentration at the edges is avoided. The frequency of radiolucent lines in the immediate postoperative period is lower for the curved back than for the flat backed glenoids. [107]

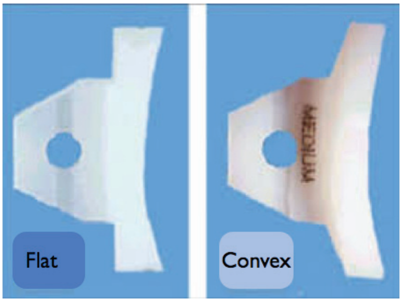


Figure 7: Flat and curved backed glenoid.

A striking observation is the difference between keeled and pegged designs. (Figure 8) Literature predominantly states that radiolucency's and incomplete component seating occur more frequently in association with keeled components compared to pegged components.[44, 73, 112] Even with modern cementing techniques, pegged glenoid components remain radiographically superior to keeled glenoid components.[6, 33] This seems biomechanically self evident since a platform is more stable with more supporting legs. Similar stability of cemented all-polyethylene keeled and in-line three-pegged glenoid components during the first two years after surgery is found, but the pegs being in line resembles the effect of a keel and might explain this finding. [90] A recent meta-analysis of the effect of glenoid design produced evidence that pegged components were associated with less loosening and less risk for revision compared with keeled components. [115]

Figure 8: A pegged (left) and a keeled (right) glenoid component with a curved back.

Augmented or step-off implants have been created to assist the surgeon in correcting the version, but clinical data are still pending.[58] (Figure 9)

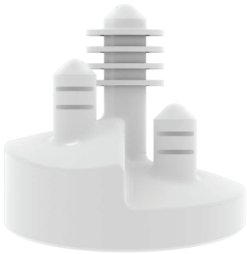


Figure 9: Augmented glenoid implant.

2.4.1.2 Fixation methods of the glenoid prosthesis

Cemented Polyethylene components.

All implants seem to fail at the implant-cement interface and failure starts at the inferior part of the fixation, irrespective of the design.[97] This failure is caused by a weak and brittle implant-cement interface, especially in off-center loading of the prosthesis. Fatigue, breakage and fragmentation, and secondary third degree body wear, eventually lead to failure. Optimal glenoid surface preparation and cementing techniques are required to allow a perfect fit and avoid radiolucent lines. The cementing procedure is associated with bone necrosis from the exothermic reaction of polymethylmethacrylate and the area of bone at risk is correlated with the amount of cement used. [21] If too much cement is seated behind the prosthesis there is an increased risk of damage to the supporting bone, and a chance of lateralization of the prosthesis changing the center of rotation, eventually leading to a rocking horse phenomenon.

Cemented metal-backed components.

Glenoid failure can be delayed or prevented by improving the implant/cement interface strength. Changing the cemented PE to a cemented metal-backed component made no difference regarding the appearance of lucent lines; 83 % of lucent lines were visualized after 2 years of follow-up. [108] The use of a cemented metal-backed implant reduces the load carried by the bone, with increased stresses in the cement indicating potential for failure. [88]

Uncemented metal-backed components.

Metal-backed ingrowth prostheses were thought to offer a strong immediate fixation without the appearance of radiolucent lines. This turned out to be true but did not translate into better long-term fixation. On the contrary, a high rate of failure was found in most clinical studies.[10, 39,43,109,124] Recent systematic reviews showed more than three times higher revision rates for metal-backed than for PE glenoids. [26, 85] Revisions of the PE components were in 77 % performed because of loosening of the implant. Reasons for revision of the metal-backed components were more diverse and differed between failure, breakage and wear of the material, and rotator cuff deficiency. The rigidity of the metal is thought to enlarge the stress on the PE inlay with more rapid wear, even progressing to metal on metal contact, metal wear and osteolysis. [104] Overstuffing the joint with metal-backed glenoids places excessive tension on the rotator cuff, explaining the high percentage of rotator cuff failure. Overstuffing also lateralizes the center of rotation and causes eccentric loading of the joint. Adjustments of the design and fixation methods (adding screws) of metal backed prostheses show better medium-term results. [17, 24, 25] (Figure 10 a and b)

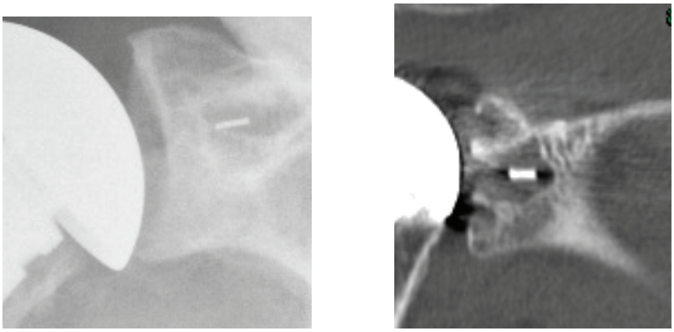
a b

Figure 10 a: Total Shoulder Prosthesis with a metal backed glenoid component, b: examples of a metal backed glenoid component with a polyethylene insert.

Uncemented polyethylene components.

The adverse effect of cement on the underlying bone triggered the search for alternatives. A cementless fluted peg stem achieved superior osseous integration and fixation in a weight bearing animal model, compared to a conventional cemented keeled design.[128] (Figure 11) It was hypothesized that the use of a PE component with a central peg with fins allowing bone ingrowth would avoid cement usage. (Figure 12) Results are satisfying on the short term but longer follow up is necessary. [29,126,127]

Figure 11: Anchor pegged glenoid: cementless fluted peg aims at bone ingrowth between the fins.



a b

Figure 12: Bone ingrowth is recognised between the fins of the peg, on X ray (a) and CT scan (b).

2.4.1.3 Material properties

Wear debris of the polyethylene glenoid component has been observed in arthroplasty in general and the biologic response to this debris with osteolysis of the underlying bone contributes to aseptic loosening of an implant. The potential for wear is influenced by the design and the material properties. The osteolytic potential from a cross- linked ultrahigh-molecular weight polyethylene (UHMWPE) glenoid component is significantly lower than from a conventional type.[127] In the shoulder conforming designs with a cemented polyethylene component with a thickness of at least 6 mm, have a more favourable wear rate. [56].

2.4.1.4 Glenohumeral relationship.

Conformity

Conformity between the radius of curvature of the humeral head and the glenoid (similar radius) has been subject of change and discussion. Non-conforming or mismatch is defined as the difference in the radius of curvature between the humeral head and glenoid components. A non-conforming design allows larger interface motions than a conforming design because the humeral head is translating on the glenoid. This increases the rocking horse effect with a risk of less ingrowth of the glenoid prosthesis. [87, 105] However other studies show that in conforming designs the stress at the periphery is larger than in hybrid or non-conforming designs. [32, 111, 132] It seems that a hybrid design, with a conforming center and a non-conforming periphery, has favourable characteristics with lower stress at the periphery and a greater contact area with the humeral head offering better stability. [8, 84, 132] Clinical evaluations are sparse and not correlated with clinical results or failure. There is a relationship found between mismatch and radiolucent lines with significant lower (better) radiolucency scores associated with radial mismatches between 6 and 10 mm. [122] Observation of retrieved components showed that non-conforming glenoids were reshaped to conforming.[70] The value of mismatch is questionable; maybe it tolerates surgical mistakes better, whereas conforming designs need a perfect correction of the center of rotation, non-conforming designs are more forgiving. Mobile glenoid bearings are under development and theoretically they offer the advantage of conformity between the glenoid and humeral component, while allowing a translation movement in the coupling of the mobile bearing. Clinical data have to be awaited.

The morphology of the humeral head

Failure to match the shape and size of the prosthetic humeral head has important biomechanical consequences. It results in malpositioning of the joint line and this implies a change in the center of rotation and this can lead to eccentric loading of the glenoid. [11] The size of the head is defined by the radius of curvature (ROC) and by the head height. [130] With a ROC smaller in the anteroposterior than in the superoinferior dimension, the humeral head can be imaged as an elliptical shape. The native head is spherical in the center and becomes non-spherical with a gradual decrease of 2 mm in the anteroposterior dimension.[11, 63] A custom made non-spherical humeral head replicates the native humeral head more accurately than a spherical head does, with a better rotational range of motion, joint kinematics and translation. [66] No clinical results of this potential method to reduce the eccentric loading are available today.

The orientation of the humeral head

Correct sizing and placement of the humeral head affect the center of rotation; mistakes can lead to off-center loading. [125] To resemble the native center of rotation one should try to obtain the best offset, version, inclination and size. A stemmed humeral component offers the best reproducible positioning. [52]

2.4.2 Patient specific factors

2.4.2.1 Pathology of the glenohumeral joint

Any underlying or associated pathology of the glenohumeral joint affecting the integrity of soft tissue and/or bone can compromise component fixation and restoration of soft tissue tension. Soft tissue related disorders include inflammatory diseases, periarticular ossification, capsular contractures or fibrosis (post irradiation, after burns, multiple surgery or trauma). A dysfunctioning rotator cuff whether it is because of partial, small or massive tears can create an unbalance inducing the rocking horse mechanism. Structural bony deficits as osteoporosis, subchondral cysts and arthritic diseases can weaken the glenoid bone. (Figure 13)

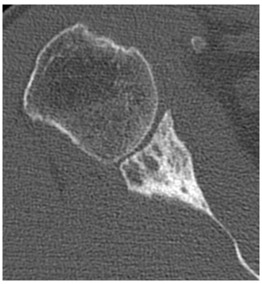


Figure 13: Subchondral cysts in the glenoid.

2.4.2.2 Morphology of the native bony glenoid

The morphology of the glenoid cavity is described as elliptical or ovoid (30%), pear, egg or inverted comma shaped (70%).[18] Congenital dysplasia is rare, but the lack of bone stock and orientation of the glenohumeral joint line requires special attention.[35, 101, 123] (Figure 14)

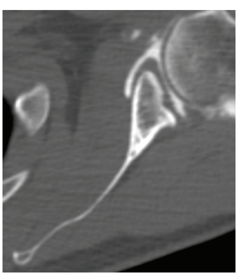


Figure 14: Dysplastic glenoid.

2.4.2.3 Orientation of the native glenoid plane

The most important anatomical factor predisposing to failure of the glenoid component is the preoperative orientation of the glenoid and its direct influence on the postoperative orientation of the glenoid prosthesis. The possibility and feasibility to correct to the native glenoid orientation determine the longevity of prostheses.

Codman already expressed the importance of the orientation of the glenoid surface and the effect of change on the center of rotation.[133] However, there is no clear definition of the original glenoid plane. This is partly due to the diverse morphology of the glenoid and to the variety in angulation in normal shoulders, with a version ranging from 14 ° retroversion to 12 ° anteversion, and an inclination ranging from -8° to 16°. [22, 31, 42]

Version and inclination measurements are made relative to the line between the most medial scapular point and the middle of the glenoid, the transverse axis of the scapula as defined by Friedman. [42] Measurement techniques seem to matter; the outcome of 2 D CT measurements of glenoid version according to Friedman varies with rotation of the scapula. [12, 14, 83] In case of deformation there is no agreement on measurement method as different reference lines can be used to describe the joint surface of the glenoid. For eroded glenoids the intermediate glenoid line is the most reliable method on 2 D CT scans.[95] (Figure 15) More accurate measurement of glenoid version and inclination, without positional errors, requires a full 3 D CT reconstruction and analysis.[55, 72, 98] Three dimensional reconstruction studies of the pattern of erosion in asymmetrically eroded glenoids showed that the orientation of maximum erosion is situated more inferiorly, and that 2 D CT is insufficient to evaluate this erosion.[7, 110] With this technique, planes instead of lines are introduced to quantify erosion, and it is clear that the erosion is different to the original plane of the glenoid. (Figure 16)

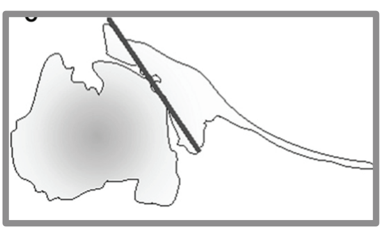


Figure 15: The intermediate glenoid line (from the anterior to the posterior edge of the eroded glenoid).

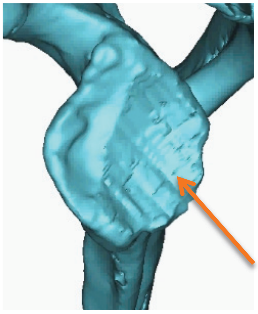


Figure 16: 3 D reconstruction image shows erosion (arrow) of the posteroinferior glenoid.

Several methods have been described to define the native glenoid plane;

1) Place 3 points on the glenoid fossa; one on the superior aspect of the glenoid, one on the anterior-inferior aspect and on the posterior- inferior aspect, to define a plane that best represents the orientation of the glenoid. Three points, one on the inferior tip, one on the center of the vault and one on the trigonum scapulae define the scapular plane. The relationship of scapular plane to the plane of the glenoid defines version and inclination.[27] (Figure 17)

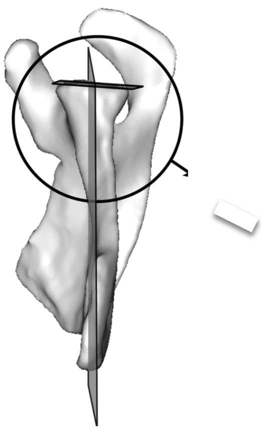


Figure 17: 3 D image showing the scapular plane and the glenoid plane.

2) A 3-dimensional glenoid vault model mimics the contralateral shoulder to assist in predicting the native glenoid plane relative to the coronal and transverse plane of the body of the scapula.[99] This plane represents the normal plane of the body for that individual person. (Figure 18)

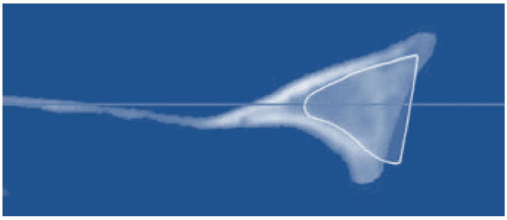


Figure 18: A 3 D vault model printed from the normal shoulder is superimposed on the eroded glenoid. This predicts the native glenoid bone.

3) The inferior glenoid plane defined by the most anterior, posterior, and inferior points of the rim of the glenoid appears to be the most reliable glenoid plane, with the most constant degree of version.[30, 116] (Figure 19) This finding supports the use of this plane as the most appropriate plane to restore normal anatomy. The inferior plane of the glenoid can be reconstructed by using 3 different points situated in a sector of 60° at the rim of the anterior part of the glenoid.[117] This can be helpful in severely eroded glenoids, where bony surgical reference points are altered or even lost.

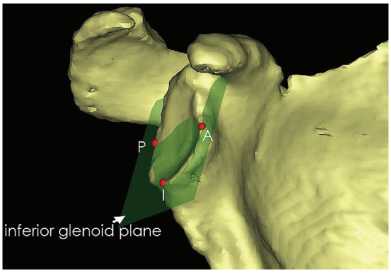


Figure 19: The most anterior, posterior and inferior points on the glenoid rim define the inferior glenoid plane.

We are familiar with the concept of the inferior glenoid circle from instability surgery.[16, 59] At the inferior glenoid a constant shape of a nearly perfect circle with a low variability can be distinguished.[31,78] (Figure 20) It is possible to use this circle as an anatomic guide in prosthetic glenoid surgery. This has been adapted in the reversed prosthesis, in which the baseplate can be designed as a circle fitting the inferior glenoid rim.[76] A recent CT simulation study investigates the biomechanical consequences of the inclination of a glenoid component and concludes that positioning of the glenoid component in the inferior circle might reduce the risk of a rocking horse phenomenon because the shear forces exerted on the glenoid by the rotator cuff (the transversal force couple) appear to be lesser for the inclination of the inferior circle. [68] However in the anatomic total shoulder replacement the orthopaedic surgeon still tends to use the surface of which the center is defined as the crossing line between the most superior and inferior point of the glenoid (Saller's line) and the largest antero-posterior distance. (Figure 21)

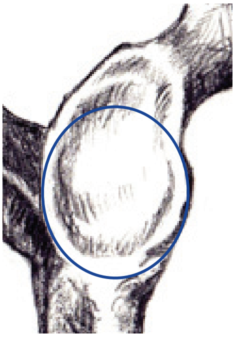


Figure 20: At the inferior glenoid the shape of a circle is distinguished.

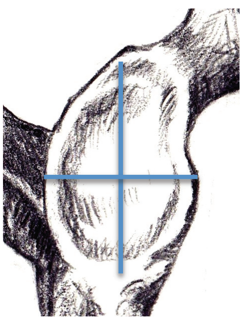


Figure 21: The cross point between Saller's line and the largest anteroposterior diameter as the classical anatomical center of the glenoid.

2.4.2.4 Erosion of the glenoid

In primary glenohumeral osteoarthritis the erosion of the glenoid is either concentric or eccentric. Walch classified glenoid morphology taking into account two factors, the pattern of the erosion, and the degree of posterior subluxation of the humeral head.[123] (Figure 22) (Figure 23)

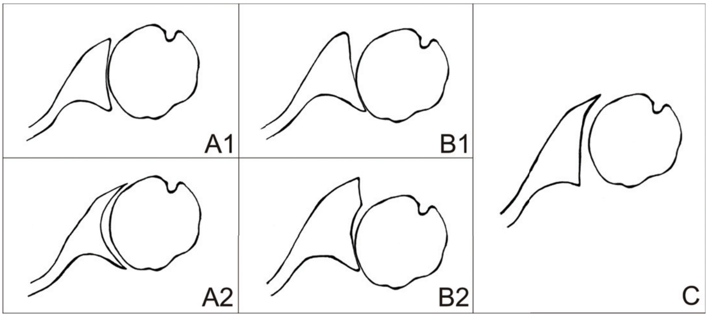


Figure 22: In type A glenoids the humeral head is centered and the erosion is central. The severity of the erosion is either minor (A1) or major (A2). In type B there is asymmetric posterior wear of the glenoid associated with posterior subluxation of the humeral head. In type B1 the erosion is minor with joint space narrowing, subchondral sclerosis and osteophytes. In type B2 the erosion is major and the glenoid has become biconcave. Type C is defined as a dysplastic glenoid with retroversion of more than 25 °, the head remains centered.

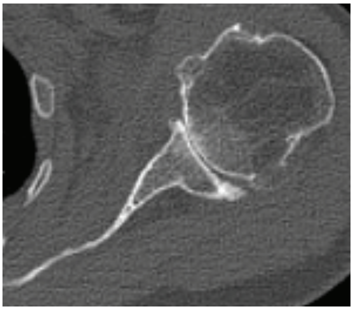


Figure 23: Type A1 eroded glenoid.

It is unclear whether posterior subluxation of the humeral head is the cause or the result of posterior glenoid wear, or even if there is a strong linear relationship. It is shown that posterior humeral head translation increases with the amount of retroversion[15] and that it is most frequent in biconcave glenoids[54] but other studies could not confirm this.[5, 45] The relationship between the humeral head alignment and glenoid retroversion is linear if measured from the plane of the scapula, but no correlation is found if measured in relation to the glenoid plane.[96, 110] The extent and direction of the erosion, and the humeral head subluxation are important obstacles to correct the proper alignment of the prosthesis.[48] (Figure 24) It is the malalignment and/or malpositioning of the glenoid component and the persistent subluxation of the humeral head in a total shoulder prosthesis that can lead to asymmetrical loading and predisposes to loosening.[10, 50, 57,62,102,120]

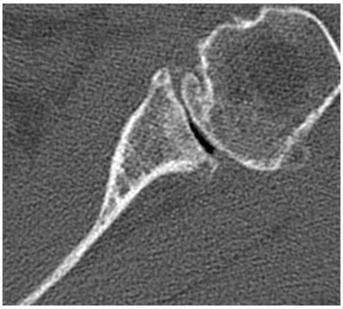


Figure 24: Type B2 glenoid: biconcave and a posterior subluxed head.

Biomechanical testing of implants on cadavers and CT simulation studies have shown that placement of the glenoid component in retroversion significantly decreases contact area, increases contact pressure and changes joint reaction force. The contact point moves posteriorly and, as a result, the center of rotation; this increases the stress in cement and glenoid bone in the posterior part of the glenoid. [37, 57, 82, 100] These biomechanical parameters all contribute to the undesirable eccentric loading. Clinical studies confirm these findings and show a strong correlation between loosening and malalignement.[50] There is a negative influence of retroversion and biconcavity on the outcome of TSR's regarding loosening and instability.[53, 120] The correction of version not necessarily corrects the static posterior subluxation of the humeral head.[45] Soft tissue tensioning and deformity of the humeral head and other unknown factors are thought to play a role here.

2.4.3 Surgical factors

2.4.3.1 Experience

Individual skills and experience in surgical technique seem to play a crucial role in the outcome of shoulder arthroplasty. Individual skill is the inborn ability and handiness of a person, a natural sense of 3 D orientation enabling one to convert 3 D images to a surgical scene. Experience is acquired competence; its improvement is expressed as the surgical learning curve and proportional to the number of surgeries performed. If a high-volume surgeon performs surgery in a high-volume hospital patients are likely to have a better outcome in hemiarthroplasty and total shoulder arthroplasty, measured by a decreased mortality rate, shorter length of hospital stay, decreased hospital charges, less readmissions and reduced postoperative complication rate.[49, 65,74] A significant decrease in complications over time concerning TSA 's can, at least partly, be explained by the increase of experience.[19] Increased experience grows with the awareness of functional outcomes and decrease of complications and this modifies indications, results and complications for the reversed total shoulder over time.[119] Furthermore the choice whether or not to opt for a glenoid component is related to the experience of the surgeon. High-volume surgeons are shown to have better outcomes after shoulder arthroplasty and perform a total shoulder arthroplasty more frequently for osteoarthritis. The risks of the technically more complex TSA procedure and the benefits of better long-term outcomes with TSA are outweighed to the experience and the comfort level of the surgeon.[64]

2.4.3.2 The amount of correction

If correction of the native glenoid orientation is the desirable objective different questions raise. How to define the native glenoid plane and its center? In subdivision 2.3 the lack of consensus was already mentioned. What is the amount of correction aimed for? Optimal correction should restore the native orientation, but since the latter is unknown it is impossible to state an absolute quantity of correction. Moreover, this can only be argued if the premorbid glenoid anatomy is presumed to be normal to start with. A CT study using the vault model confirmed that patients with primary glenohumeral osteoarthritis do not have an abnormal premorbid version and inclination predisposing them to arthritis.[93] The average version in non-pathological specimen is 3° of retroversion, and on the base of this value most surgeons recommend correction to neutral. The average inclination is 4 °, with a superiorly directed surface, but similarly a correction to neutral inclination is adopted.[60, 67] With the known variation of version and inclination between individuals, and within individuals, the error made if corrected to neutral is of a similar magnitude and spreading, and, therefore, inadequate in at least a certain amount of cases.

Obviously there is a lacuna in the determination of the native premorbid glenoid position and the orientation of the diseased glenoid, and subsequently in the determination of the optimal correction. This correction should focus on the restoration of the native glenoid plane and the force couples of the rotator cuff, but also on the preservation of a strong subchondral plate.

2.4.3.3 The methods of correction

Downreaming the anterior side is relatively simple and used frequently by most surgeons. This is acceptable for most cases with mild (< 6 mm) posterior wear.[80] Excessive reaming can result in weakening of the subchondral bone, loss of bone volume and surface area of the glenoid vault. The lack of solid strong bone to support the prosthesis enhances the chances of loosening, and the occurrence of both tilting and subsidence of the prosthesis is associated with reaming of the glenoid.[121] There is either diminished bone support, or risk of perforation.[113] Retroversion of 15 degrees or more cannot be corrected by down reaming without compromising implantation of a glenoid component with peripheral pegs.[23] Obviously other designs of the prosthesis (keel or in line pegs) can reduce perforation potential in certain cases, in other words: choose a prosthesis that fits.[113] CT simulation studies showed that correction of 10 degrees of retroversion requires more than 5 mm of reaming of the anterior side, and this risks significant glenoid decortication and bone loss.[80] For a maximal implant- bone surface area contact correction of more than 5 degrees is not recommended. The initial reamer placement is a determining factor in bone volume removal; erring to the posterior side creates more bone loss.[129]

Reaming appears to be a difficult exercise even in experienced hands, and the reproducibility of reaming is questioned. Iannotti and Karelse state that optimal placement of a component can only be achieved when there is minimal deformity, and correction of moderate to severe deformity appear to be not consistent.[61, 69] Three-dimensional preoperative planning improves the accuracy of guide pin placement and results in a better correction of the version and inclination.[60] This confirms the presumption that the surgeon needs guidance, and it explains the increasing interest in patient specific instruments and navigation systems.

Computer assisted surgical navigation might be the solution according to several surgeons.[34, 71,77] Disadvantages of these techniques include the intraoperative tracking system, which is vulnerable to technical mistakes, and failure of the tracking devices.
Patient specific instrumentation can avoid the use of these tracking devices. Suero and Hendel showed a custom made jig to be accurate for optimal implant positioning.[51, 106]
Augmented glenoids are developed to conserve more of the anterior glenoid bone and create less muscle shortening than with eccentric reaming.[58, 94] Further clinical studies are necessary to validate this concept.

2.4.3.4 Preparation of the glenoid bone.

Both the contact area and the bone quality of the glenoid are important factors for good primary fixation. The remaining cartilage is removed, and the bone is prepared in order to create a congruent surface of strong subchondral bone. Careful preparation of the glenoid surface helps to stabilize the component, improving its resistance to eccentric loading. Preparation of the glenoid surface by motorized reaming outperforms hand reaming or curettage and creates a superior smooth glenoid surface.[28] Different types of reamers are available; flat and convex, K-wire or nipple guided. A glenoid reaming study showed that there is a significant difference in congruity after convex and flat reaming. The flatness after reaming with a flat reamer is better than the sphericity after reaming with a convex reamer. However there is no difference in sphericity or flatness of the surface whether the reamers are used guided by a central K-wire or by a nipple. The length of the reamer plays a significant role: with the short reamer the congruence of the surface is better.[69]

2.4.3.5 Cementing technique

Cemented all PE glenoid components remain the gold standard. Many variations exist in the technique of cementation and the lack of definition of ' the modern cementing technique' makes it difficult to interpret the reported results.[131] Cement pressurization leads to better penetration in the glenoid bone in cadavers and it reduces the rate of early radiolucency's around the glenoid in TSA.[6, 20, 91] The fixation of a pegged glenoid component is better if the holes are filled with cement under pressure by use of a syringe than with pure finger pressure.[81] Pressurization of cement is only possible if there is containment of the prosthesis within the vault.[113]

2.4.3.6 Soft tissue handling

A frequently mentioned statement is ' Implanting a shoulder prosthesis is substantially soft tissue surgery'. Indeed of great importance is careful handling of the soft tissues. A complete resection of labrum and capsule to liberate the entire rotator cuff, in particular the subscapularis tendon, is necessary to regain freedom of motion and balance the transverse force couple. The postoperative rehabilitation should be adjusted to the quality of the soft tissue.

2.5 Conclusion

This review describes the available knowledge on the different parameters influencing glenoid failure, as well as the actual gaps with the aim to constructively contribute to the debate on how to prevent glenoid loosening. The implant related parameters are features of the design of prosthetic components, and are mainly determined by the biomechanical engineers and developers. The patient related parameters; the anatomy and pathology of the glenohumeral joint are inherent to the patient and cannot be altered. The physician influences the surgical parameters: method of correction, technique of preparation of the glenoid bone, cementing techniques and handling of the soft tissues. These actions are affected by individual skills and experience of the surgeon.

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2.6 Article 1. Parameters influencing glenoid loosening.

From this extensive literature search a review article is distilled and submitted to the Bone and Joint Journal.

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Log no. 36080

Title: Parameters influencing glenoid loosening.

Abstract

Failure of the glenoid component is the most frequent complication of total shoulder arthroplasty. Reviewing the literature on glenoid component failure we can define glenoid loosening as the appearance of radiolucent lines, radiological loosening, clinical loosening and revision as the end stage. Three different categories of influencing parameters are distinguished; implant related, patient related and surgeon related.

Level of evidence: Review article.

Keywords: glenoid, prosthesis, loosening, experience, retroversion, erosion.

Introduction

There is a lack of organization in existing studies on outcome and complications of total shoulder arthroplasty. Therefore it is difficult to gain substantial evidence regarding the rate and risk factors for the occurrence of glenoid loosening which remains the most common cause of prosthetic failure. To improve the quality of future studies agreement should exist on definitions of glenoid loosening and on the potential risk factors. The aim of this review is to organize the available knowledge on glenoid failure. [1,2,3,4]

Biomechanical failure

In prosthetic surgery the reconstruction of the normal geometry should restore the center of rotation and the soft tissue tension. Every single degree of glenoid retro-/anteversion, varus/valgus angulation will displace the center of rotation of the humeral component by 0.5 mm, and vice versa, so anatomical reconstruction needs to be performed within a minimal margin of error.[5] The transversal and the coronal force couple (Figure 1a and b) of the shoulder serve as the primary stabilizing mechanism, providing compression of the humeral head in the glenoid concavity. Biomechanical failure can be defined as a disturbance of the equilibrium of the force couples, and it is the primary mechanism of glenoid loosening[6], with the exception of biological failure, which has either an infectious or a particle disease ethiology. The mechanism of glenoid loosening is the repetitive eccentric loading of the humeral head on the glenoid, the so-called rocking horse phenomenon, causing tensile stresses at the bone-implant or bone-cement-implant interface initiating failure of fixation.[7] Any unbalance in the glenohumeral unit at the glenoid side, the humeral side, or in the force couples of the rotator cuff potentially creates eccentric loading leading to the rocking horse phenomenon and this is more significant if the implant fixation is suboptimal or if the soft tissue status of the shoulder is altered as in rotator cuff deficiency or if capsular contractures.

The definition of glenoid loosening

According to radiological appearance, progression, and clinical data, loosening can be defined as follows; [3,9,10,11,12]

1. Radiolucent lines. The majority of radiolucent lines appear at the bone-cement interface from day one after surgery suggesting reflection of surgical technique rather than failure of the implant and these are not necessarily of clinical significance. The reported incidence in literature is high, up to 30 to 96 %.
2. Radiological loosening. Between 0 and 44% progress to radiological loosening defined as an increase of radiolucent lines, as a complete radiolucent line of 2 mm or more around the implant, or as implant migration. (Figure 2 a and b)
3. Clinical loosening. Clinical loosening is the progression of radiolucent lines and/or migration of a component, associated with increased pain and decreased function of the

shoulder. Progression to clinical loosening is clearly increasing with a longer follow-up of five years and more.

4. Revision. This is considered to be the endpoint for clinical glenoid loosening. Between 8 to 10% results in actual revision of loose implants.

<u>The causes of glenoid loosening.</u>

Failure of a shoulder arthroplasty is likely to be multifactorial; patients have on average 4 contributing factors leading to dissatisfaction after a shoulder arthroplasty.[13] Causes of loosening can be divided into 3 groups (Table 1):

1. Implant related
2. Patient specific
3. Surgical factors

1. Implant related factors	
1.1. Design: size and shape	Oval, circular, elliptical Convex or flat backed Keeled or pegged Step-off implant or vaulted
1.2. Fixation methods	Cemented or uncemented Metal backed or Full Polyethylene
1.3. Material properties	Type of Polyethylene
1.4. Glenohumeral relationship	Conformity Morphology of the humeral head Orientation of the humeral head
2. Patient Specific factors	
2.1. Pathology of the glenohumeral joint	Soft tissue related Bone related

	Combination
2.2. Morphology of the native glenoid	Egg, pear or comma shaped Dysplasia
2.3. Orientation of the native glenoid plane	Version Inclination
2.4. Erosion of the glenoid	Concentric or eccentric Subluxation of the humeral head
3. Surgical factors	
3.1. Experience	Years of experience Number of surgeries
3.2. Amount of correction	How to determine?
3.3. Method of correction	Downreaming Type of reamer Guidance Augmented glenoids
3.4. Preparation of the bone	Motorised, hand reaming Type of reamer
3.5. Cementing technique	
3.6. Soft tissue handling	

Table 1. Parameters influencing glenoid loosening.

1. Implant related factors

1.1 Design of the glenoid prosthesis.

Size and shape should perfectly match the underlying bone. An oversized component creates overhang possibly leading to lift off, an undersized component lacks support of the cortical rim and is prone to subsidence.[12] Approximately 30 % of glenoids has an ovoid or elliptical shape and 70 % is pear or egg-shaped. Fewer mismatches will be encountered if a pear-shaped design is used. A height to width ratio of approximately 1.3 to 1 improves the antero-posterior and supero-inferior fit.[14] Curved back prostheses withstand eccentric loading better than flat backed because stresses are transmitted more in compression than in shear and consequently stress concentration at the edges is avoided.[15] The frequency of radiolucent lines is lower for the curved back than for the flat backed glenoids.[16] A recent meta-analysis shows that pegged components are associated with less loosening and less risk for revision compared with keeled components. [17] Radiolucency's and incomplete component seating occur more frequently in keeled components compared to pegged components, even with modern cementing techniques.[10, 11,18,19] Augmented or step-off implants have been created to assist the surgeon in correcting the version, but clinical data are still pending.[20]

1.2 Fixation methods of the glenoid prosthesis

Cemented Polyethylene (PE) components.

All implants seem to fail at the implant-cement interface and failure starts at the inferior part of the fixation, irrespective of the design.[21] Fatigue, fragmentation and secondary third degree body wear, worsened by eccentric loading of the prosthesis, eventually lead to failure. Cementing is associated with bone necrosis from the exothermic reaction of polymethylmethacrylate and the area of bone at risk is correlated with the amount of cement used.[22]

Cemented metal-backed components.

Changing the cemented PE to a cemented metal-backed component made no difference regarding the appearance of lucent lines; 83 % of lucent lines were visualized after 2 years of follow-up.[23] The use of a cemented metal-backed implant reduces the load carried by the bone, with increased stresses in the cement indicating potential for failure.[24]

Uncemented metal-backed components.

Metal-backed ingrowth prostheses were thought to offer a strong immediate fixation without the appearance of radiolucent lines. This turned out to be true but did not translate into better long-term fixation. On the contrary, a high rate of failure and revision surgery was found.[9, 25,26] The rigidity of the metal is thought to enlarge the stress on the PE inlay with more rapid wear. Overstuffing of the joint places excessive tension on the rotator cuff, lateralizes the center of rotation, and condemns the joint to eccentric loading. Adjustments of the design and fixation methods (adding screws) of metal backed prostheses show improved medium-term results.[27, 28]

Uncemented polyethylene components.

Clinical and radiological results of fully uncemented PE components with a central peg with fins allowing bone ingrowth are satisfying on the short term, but longer follow-up is necessary.[29] Radiostereometric analysis has shown early micromotion of these implants, and this might lead to failure of osseointegration.[30]

1.3 Material properties

The potential for wear from a cross- linked ultrahigh-molecular weight polyethylene (UHMWPE) glenoid component is significantly lower than from a conventional type.[31] Conforming designs with a PE thickness of at least 6 mm that are cemented have a more favourable wear rate.[32]

1.4 Glenohumeral relationship.

Conformity

A non-conforming design allows larger interface motions than a conforming design and this can increase the rocking horse effect with a risk of less ingrowth of the prosthesis.[33, 34]

However other studies show that in conforming designs the stress at the periphery is larger than in hybrid or non-conforming designs, leading to edge loading and a rocking-horse effect.[35] Observation of retrieved components showed that non-conforming glenoids were reshaped to conforming.[36] The value of mismatch is questionable; maybe it tolerates surgical mistakes better, whereas conforming designs need a perfect correction of the center of rotation, non-conforming designs are more forgiving.

The morphology of the humeral head

Failure to match the shape and size of the prosthetic humeral head results in malpositioning of the joint line and this implies a change in the center of rotation leading to eccentric loading of the glenoid. The native humeral head can be imaged as an elliptical shape, and is spherical in the center and becomes non-spherical in the anteroposterior dimension.[37, 38] A custom made non-spherical humeral head replicates the native humeral head more accurately than a spherical head does, with better joint kinematics.[39] No clinical results of this potential method to reduce the eccentric loading are available until now.

The orientation of the humeral head

To resemble the native center of rotation we should try to obtain the best offset, version, inclination and size. A stemmed humeral component offers the best reproducible positioning.[40]

2. Patient specific factors

2.1 Pathology of the glenohumeral joint

Any underlying or associated pathology of the glenohumeral joint affecting the integrity of soft tissue and/or bone can compromise component fixation and restoration of soft tissue tension. These include inflammatory diseases, rotator cuff lesions, periarticular ossification, capsular contractures or fibrosis. Structural bony deficits as osteoporosis, subchondral cysts and arthritic diseases can weaken the glenoidal bone.

2.2 Morphology of the native bony glenoid

The morphology of the glenoid cavity is described as elliptical or ovoid (30%), pear, egg or inverted comma shaped (70%). [14] Congenital dysplasia is rare, but the lack of bone stock and orientation of the glenohumeral joint line requires special attention. [41,42]

2.3 Orientation of the native glenoid plane

Codman already expressed the importance of the orientation of the glenoid surface and the effect of change on the center of rotation.[43] Several methods have been described to define the native glenoid plane. The 3 D vault model mimics the contralateral shoulder to assist in predicting the native glenoid plane relative to the coronal and transverse plane of the body of the scapula. [44] Verstraeten found that the inferior glenoid plane, defined by the most anterior, posterior, and inferior points of the rim of the glenoid, has the most constant degree of version, and he concludes this is the most reliable glenoid plane to use in prosthetic surgery.[45, 46] We are familiar with the concept of the inferior glenoid circle from instability surgery[47], and a recent CT simulation study concludes that positioning of the glenoid component in the inferior circle might reduce shear forces and consequently the risk of a rocking horse phenomenon.[48] Measurement methods of the orientation(version and inclination) seem to matter. Outcomes of version measurements on 2D CT images vary significantly with scapular rotation and positioning of the patient.[49] The use of 3D reconstruction images to determine the orientation of the native glenoid is more precise and independent of the position of the scapula.[50, 51] (Figure 3 and b)

2.4 Erosion of the glenoid

In primary glenohumeral osteoarthritis the erosion of the glenoid is either concentric or eccentric. The Walch classification takes 2 factors into account; the pattern of the erosion, and the degree of posterior subluxation of the humeral head.[42] (Figure 4) Posterior humeral head translation increases with the amount of retroversion and it is most frequent in biconcave glenoids but it is unclear whether the posterior subluxation is the cause or the result of posterior glenoid wear. [52,53,54,55] Placement of the glenoid component in retroversion significantly changes the center of rotation, and increases the stress in cement and glenoid bone in the posterior part of the glenoid.[56, 57] Clinically there is a negative influence of retroversion and biconcavity on the outcome of TSR's regarding loosening and instability.[58, 59] The correction of version not necessarily corrects the static posterior subluxation of the humeral head.[53]

3. Surgical factors

3.1 Experience

If a high-volume surgeon performs surgery in a high-volume hospital patients are likely to have a better outcome after hemiarthroplasty and total shoulder arthroplasty, measured by a decreased mortality rate, shorter length of hospital stay, decreased hospital charges, less readmissions and reduced postoperative complication rate.[60, 61] The choice whether or not to opt for a glenoid component is related to the experience of the surgeon. High-volume surgeons perform a TSA for osteoarthritis more frequently and have better outcomes. The risks of the technically more complex TSA procedure and the benefits of better long-term outcomes after TSA are outweighed to the experience and the comfort level of the surgeon.[62]

3.2 The amount of correction.

In non-pathological specimen the average version is 3° retroversion, the average inclination is 4 °, with a superiorly directed surface, and on the base of these values correction to neutral is recommended. [63,64] Because of the large variation of version and inclination the error made if corrected to neutral is of a similar magnitude, and therefore inadequate in at least a certain amount of cases. Obviously there is a lacuna in the determination of the native premorbid glenoid and the orientation of the diseased glenoid, and subsequently in the determination of the optimal correction.

3.3 The methods of correction.

Downreaming the anterior side is relatively simple and used frequently by most surgeons. CT simulation studies show that correction of 10 degrees of retroversion requires more than 5 mm of reaming of the anterior side, and this risks significant glenoid decortication and bone loss. [65] Retroversion of 15 degrees or more cannot be corrected by down reaming without compromising implantation of a glenoid component with peripheral pegs[.66.] Excessive reaming can result in weakening of the subchondral bone, and the occurrence of both tilting and subsidence of the prosthesis is associated with reaming of the glenoid.[12] The initial reamer placement is a determining factor in bone volume removal; erring to the posterior side creates more bone loss.[67]

Reaming appears to be a difficult exercise and optimal placement of a component can only be achieved when there is minimal deformity, and correction of moderate to severe deformity appears to be not consistent. [68,69] Three-dimensional preoperative planning improves the accuracy of guide pin placement and results in a better correction of the version and inclination.[63] Computer assisted surgical navigation might be the solution according to different surgeons, however the intraoperative tracking system is vulnerable to technical mistakes and failure. [70,71,72] Patient specific instrumentation can avoid the use of these tracking devices. Suero and Hendel showed a custom made jig to be accurate for optimal implant positioning.[73, 74] Bone grafting of the posterior defect is used for the more severe cases of bone deficiency (more than 20 degrees of retroversion) and is technically a demanding procedure leading to varying results.[75] Augmented glenoids and custom made glenoids are developed to conserve more of the anterior glenoid bone and create less muscle shortening than with eccentric reaming. [20]

3.4 Preparation of the glenoid bone.

Both contact area and bone quality of the glenoid are important factors for good primary fixation. Motorized reaming outperforms hand reaming or curettage and creates a superior smooth glenoid surface.[76] Different types of reamers are available and the flatness after reaming with a flat reamer is shown to be better than the sphericity after reaming with a convex reamer.[69]

3.5 Cementing technique

Many variations exist in the technique of cementation and the lack of definition of ' the modern cementing technique' makes it difficult to interpret the reported results.[77] Cement pressurization leads to better penetration in the glenoid bone in and it reduces the rate of early radiolucency's around the glenoid in TSA.[78]

3.6 Soft tissue handling

Of great importance is the handling of the soft tissues with a complete resection of labrum and capsule to liberate the entire rotator cuff, but in particular the subscapularis tendon, in order regain freedom of motion and to balance the transverse force couple. The postoperative rehabilitation should be adjusted to the state of the soft tissue.

Conclusion

This review article describes the available knowledge on the different parameters influencing glenoid failure, as well as the actual gaps with the aim to constructively contribute to the debate on how to prevent glenoid loosening. The implant related parameters are features of the design of prosthetic components, and these issues are mainly in the hands of the biomechanical engineers and developers. The patient related parameters; the anatomy and pathology of the glenohumeral joint are inherent to the patient and cannot be altered. The surgical parameters are under the influence of the physician, and his or her actions are greatly influenced by individual skills and experience of a surgeon.

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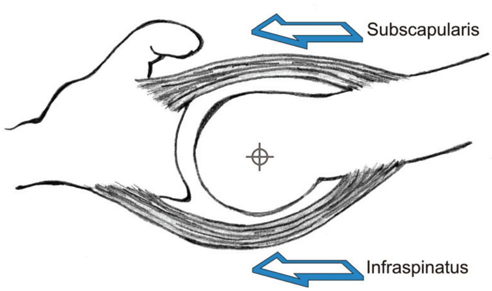

Figure 1a: Transverse force couple.

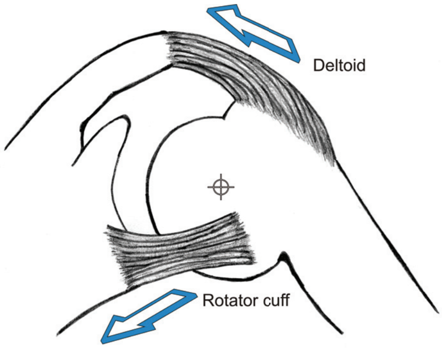

Figure 1b: Coronal force couple.

Figure 2a: A complete loosening line of 2 mm.

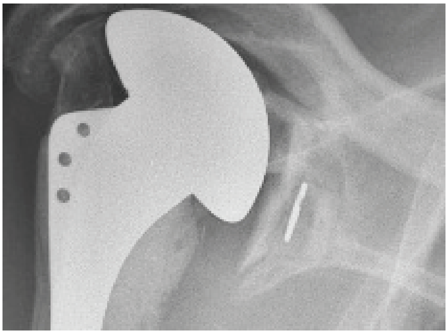

Figure 2b: Loosening lines surrounding the keeled glenoid component.

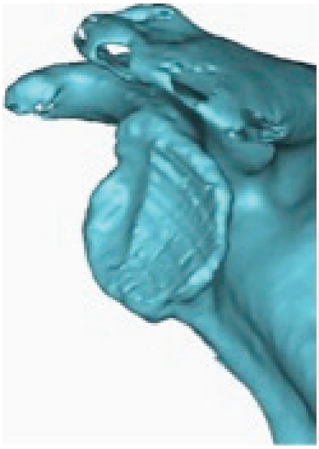

Figure 3a: 3 D image of a biconcave glenoid.

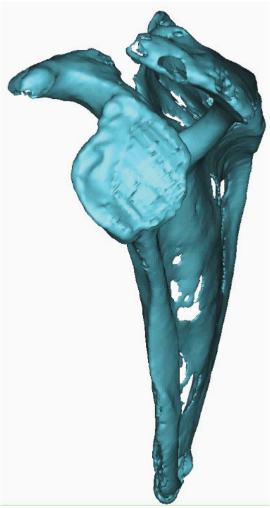

Figure 3b: 3 D image of a biconcave glenoid.

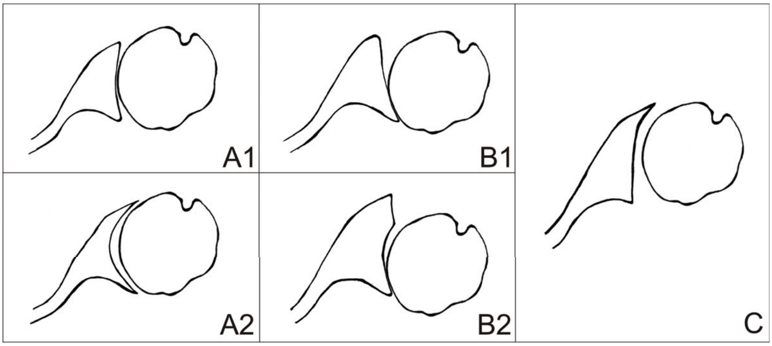

Figure 4: Walch classification: Type A: Central erosion (minor (A1) or major (A2)), head centered. Type B: asymmetric posterior wear (minor (B1) or major or biconcave (B2)), head posteriorly subluxed. Type C: Dysplastic glenoid, retroversion > 25 °, head centered.

Chapter 3 The native glenoid plane

3.1 Introduction

At first sight one can describe the glenohumeral joint as a ball in a socket comparable to the hip joint. This type of joint has a certain inherent bony stability, and the size of the ball and the depth of the socket determine the range of mobility. The radius of curvature of the glenoid and humeral head are nearly identical, however the glenoid fossa is so small that it covers only a small part of the humeral head. The resemblance with a golf ball on a tee is made and this displays the instability of this configuration, and presumes the importance of the surrounding soft tissues to maintain the ball in the socket, or to keep the socket positioned under the ball. (Figure 1)

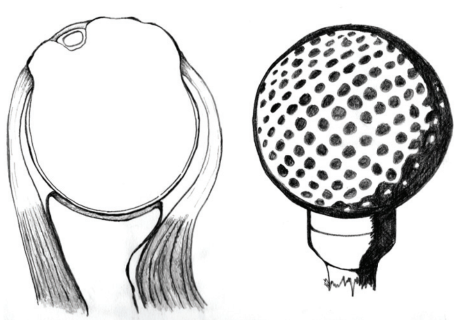

Figure 1: The humeral head stabilized on the glenoid by the soft tissues. Its bony configuration resembles a golf ball on a tee.

Codman already emphasized the importance of the orientation of the glenoid surface and how a change of its orientation immediately changes the center of rotation and position of the humeral head. It is this original non-pathologic glenoid surface we need to describe as an anatomic entity, preferably as a plane, with a shape (round, oval or other), a size (height and width, or radius) and an orientation (version and inclination). Only after determining these parameters, a pathological glenoid can be reconstructed to its native shape and position. There is still a lot of controversy around this plane: is it a circle or an oval, or other? De Wilde and Huysmans found a constant shape of a nearly perfect circle with a low variability at the inferior glenoid.[1, 2] (Figure 2)

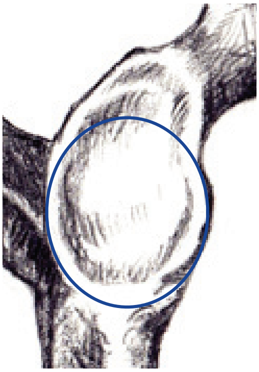

Figure 2: The shape of the inferior glenoid can be described as a circle.

If the glenoid plane can be defined as a circle this would provide us with a center (as every circle has a center), and this could serve as a point of fixation (conform to the location of the trailer hook of Codman).

We performed a three-dimensional CT reconstruction study in which we investigate the normal 3 D relationship of different glenoid planes with the scapular plane. The aim of the second study of this thesis is to define a constant and reproducible anatomical plane of the glenoid so that we know what plane we intend to reconstruct during surgery.

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3.2 Article 2. Reliability of the glenoid plane

J Shoulder Elbow Surg (2010) 19, 414-422

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Reliability of the glenoid plane

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Hypothesis: The purpose of this study was to investigate the 3-dimensional (3-D) orientation of the glenoid and scapular planes. Different definitions of the glenoid plane were used and different planes measured, and we hypothesed that the 3-D plane with the least variation would be best to define the most reliable glenoid plane.

Methods: We studied 150 CT scans from nonpathological shoulders from patients between 18 and 80. The scapular plane and 5 different glenoid planes were determined: inferior, anterior, posterior, superior, and neutral. All plane versions and inclination angles were measured. Because all examinations were done in a standardized position to the coronal, sagittal, and transverse planes of the body, the scapular plane could be defined versus the coronal, sagittal, and transverse planes of the body.

Results: The version (mean, 3.76) of the inferior glenoid plane showed a significantly lower standard deviation than the version of the anterior ($P < .001$), posterior ($P = .001$), and superior ($P = .001$) glenoid plane (ANOVA). For inclination all planes have a similar variance. The scapular plane was different between gender ($P = .022$) and correlated with age.

Conclusion: This study showed that the retroversion of the inferior glenoid is reasonably constant. The osseous anthropometry of the inferior glenoid can offer a reproducible point of reference to be used in prosthetic surgery of the shoulder.

Level of evidence: Level II; Basic Science Study; Anatomical Survey

Keywords: Glenoid cavity; anthropometry; plane of reference; variability; retroversion; prosthetic surgery; inferior glenoid circle; scapular plane

Restoration of the glenoid plane is essential in total shoulder arthroplasty. Failing to restore the inclination and the version of the glenoid is associated with prosthetic instability and jeopardizes the longevity of the prosthesis.[25] Correct restoration of the glenoid plane balances the forces across the glenoid and prosthetic components, thereby improving stability and functional outcomes.[14,19,30,33] The definition of the glenoid plane itself is not clear. This can be explained by the fact that the morphology of the glenoid is extremely diverse.[8] Furthermore, the angulation of the glenoid has a wide range of variety in healthy individuals with a version ranging from 14° of retroversion to 12° of anteversion,[3,5,10,22,24] and an inclination ranging from 8° to 15.8°.[5,12]

At the inferior glenoid a constant shape of a true circle can be distinguished.[8,13,16] The plane of this inferior glenoid circle is less variable and can be used as an anatomic

Ethical approval: Ethical approval was cleared from the ethics committee University Hospital Ghent - Chairman Prof. dr. R. Rubens (EC/2009-099/ Svdm: The normal glenohumeral relationships: a 3-Dimensional CT-scan stduy of the humeral and glenoid planes in one hundred and fifty normal shoulders).

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1058-2746/2010/$36.00 - see front matter © 2010 Journal of Shoulder and Elbow Surgery Board of Trustees.
doi:10.1016/j.jse.2009.10.005

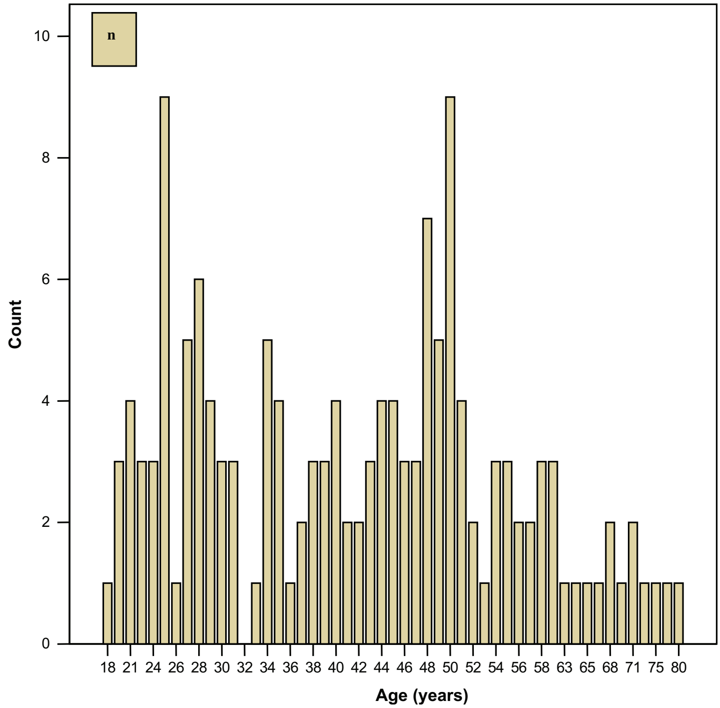

Figure 1 Age distribution of the patients.

guide[17,21] in prosthetic glenoid surgery. However, the orthopaedic surgeon tends to use the plane with the center defined as the crossing line between the most superior and inferior point of the glenoid (Saller's line) and the largest antero-posterior distance.[1,26] Recently a standardized 3-dimensional (3-D) glenoid vault model mimicking the contralateral shoulder was introduced to assist in restoring the plane of the glenoid in the coronal and transversal plane of the body.[6,27,28] It is assumed that this plane represents the normal plane of the body for that individual person.[16] The normal anatomy of the 3-D positioning of the glenoid plane in a population is still unknown.

The purpose of this study is to investigate the normal 3-D relationship of the glenoid plane and scapular plane, and we try to define the most reliable glenoid plane, which should be most suitable for prosthetic surgery. Different definitions of the glenoid plane were used and different planes were measured and we hypothesed that the 3-D plane with the least variation would be best to define the ''true'' glenoid plane.

Material and methods

We examined 150 computed tomography (CT) scans of nonpathologic shoulders of patients who were examined with an arthro-ct scan for pathology of the contra lateral shoulder. The patients were between 18 and 80 years old (mean, 41.75). There were 68 females and 82 males. The age distribution is found in Figure 1.

Ethical approval was given. The patients received no extra irradiation, because it is difficult to impossible to positioning one shoulder more central in the CT-scan tunnel to be able to narrow the window, resulting in less irradiation.

The patients included had a CT scan examination of the contralateral (pathologic) shoulder for instability (30), AC-joint arthritis (33), rotator cuff tears (33), [partial (5), full thickness (28)], calcifying tendinitis (12), frozen shoulder (8), subacromial impingement (17), tendinitis of the long head of biceps brachii (12), and fractures of the proximal humerus (5).

The shoulder was included if any pathology was excluded first by clinical examination and according to the patients history. If any structural bony pathology (like cysts and visual bony deformations of clavicula, scapula or humerus, as well as the SC, AC, and GH-joint) or soft tissue pathology (like swellings or muscular fatty degeneration of the rotator cuff and/or deltoid) were seen, the casus was not included.

The CT-scan settings are: type of scanner: Somatom Volume Zoom – Siemens (Siemens Business Park, Marie Curiesquare 30 - Square Marie Curie 30; 1070 Brussel – Bruxelles). Matrix: 512/ kV:140/eff. mAs: 350. The scan field of view (SFOV) is always 500. Field of view (FOV): adapted to the individual patient: max. 500 for both shoulders and minimally for 1 shoulder 150.

In an effort to minimize the influence of the individual positioning, all CT scans were made with the patient positioned as

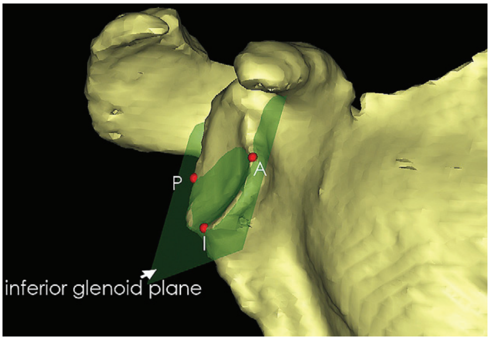

Figure 2 Inferior glenoid plane was determined by setting 3 points on the rim of the inferior quadrants of the glenoid: an inferior (I), anterior (A), and posterior (P) glenoid point.

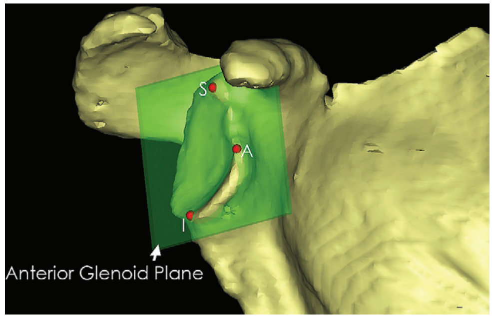

Figure 3 Anterior glenoid plane was determined by setting 3 points on the rim of the anterior quadrants of the glenoid: an inferior (I), superior (S) and anterior (A) glenoid point.

described by the senior author[17] in dorsal recumbency and with a thoracobrachial orthosis to keep the arm adducted in the coronal plane and the forearm flexed in the sagittal plane of the body. The glenohumeral joint was scanned with 2-mm interval slices. Three independent investigators imported CT-images (dicom) into a medical imaging computer software (Mimics® 11.02 for Intel X86 Platform V11.2.2.1 1992-2007, Materialise n.v., Haasrode Belgium) to create 3D images of the shoulder joint. Both bones of the joint could be separated digitally and virtually manipulated to determine the bony reference points for purposes of measurement.

The 5 different glenoid planes were created as follows. Four points were indicated at the glenoid rim: a superior point (S) and a inferior point (I) at the greatest length of the glenoid (= identical to the points used to determine Saller's line), an anterior point (A) and a posterior point (P) at the greatest width of the glenoid. The inferior glenoid plane was determined by 3 points: the anterior point (A), the posterior point (P), and the inferior point (I) (Figure 2). The anterior glenoid plane was determined by 3 points: the superior (S), the inferior (I), and the anterior (A) (Figure 3). The posterior glenoid plane was determined by 3 points: the superior (S), the inferior (I) and the posterior (P) (Figure 4). The superior glenoid plane was determined by 3 points: the superior (S), the anterior (A), and the posterior (P) (Figure 5). The neutral glenoid plane was determined by only 2 points: the superior (S) and the inferior (I), and is perpendicular to the scapular plane (Figure 6). The scapular plane is the plane determined by 3 points: a lateral scapular point in the surgical center of the glenoid [this is the crosspoint (C) between the line between de most anterior point (A) and the most posterior point (P) and the line between the most superior point (S) and the most inferior point (I)], a medial scapular point (MS) at the most medial point of the spina scapula and the inferior scapular point (IS) at the most inferior point of the scapula) (Figure 7).

From these planes, different angles were measured:

A. Angles measured within the scapula.
A. a. angles between lines:

2-dimensional (2-D) glenoid version (GV): the angle between the line from the most anterior point (A) to the most posterior point (P) and the line of the scapular plane, calculated conform the method of Churchill[5] (Figure 8).

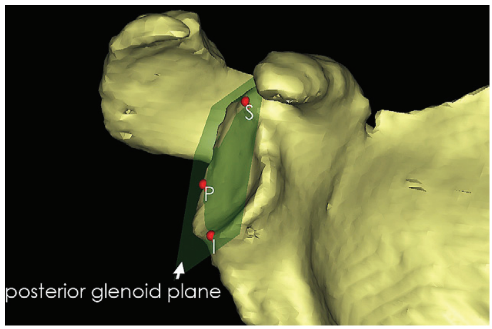

Figure 4 Posterior glenoid plane was determined by setting 3 points on the rim of the posterior quadrants of the glenoid: an inferior (I), superior (S), and posterior (P) glenoid point.

2-D glenoid inclination (GI): the angle between the line from the most superior point (S) to the most inferior point (P) and the line between the most medial scapular point (MS) and the middle of the glenoid (crosspoint (C), measured conform the method of Churchill[5] (Figure 9).

A. b. angles between planes:

3-D glenoid retroversion: the angle between the scapular plane and the different glenoid planes (superior, inferior, anterior, posterior, and neutral).

3-D glenoid inclination: the angle between the perpedicular to scapular plane including point C and point MS and the plane of different glenoid planes (superior, inferior, anterior, posterior, and the neutral plane).

B. Angles of the different glenoid planes (neutral, superior, anterior, posterior, and inferior) and the scapular plane versus the coronal, sagittal, and transversal planes of the body (Spatial parameters).

Because all measurements are related to the scapular plane, all patients were positioned similar to minimize error due to a different scapular orientation. This allowed us to measure the

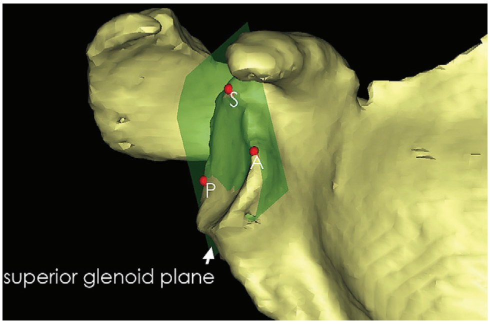

Figure 5 Superior glenoid plane was determined by setting 3 points on the rim of the posterior quadrants of the glenoid: a superior (S), anterior (A), and posterior (P) glenoid point.

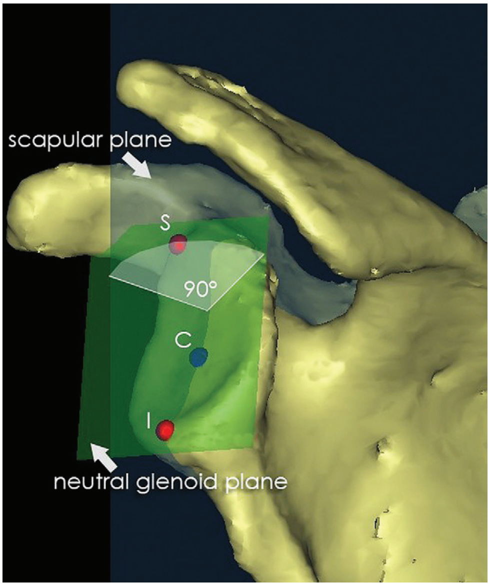

Figure 6 Neutral glenoid plane was determined by setting 2 points on the rim of the superior and inferior quadrant of the glenoid: an inferior (I) and superior (S) glenoid point. This plane is perpendicular to the scapular plane.

scapular plane and different scapular angles. We defined the angle of the scapular and coronal planes as the coronal scapular angle (CSA) (Figure 10, *A*), the angle of the scapular and sagittal planes as the sagittal scapular angle (SSA) (Figure 10, *B*), and the angle of the scapular and transversal planes as the transversal scapular angle (TSA) (Figure 10, *C*). This means that CSA is comparable to the angle measured in the transversal plane of the body in a normal CT-setting. For the SSA, this means that this angle is comparable to the angle of the glenoid plane (AG).[9]

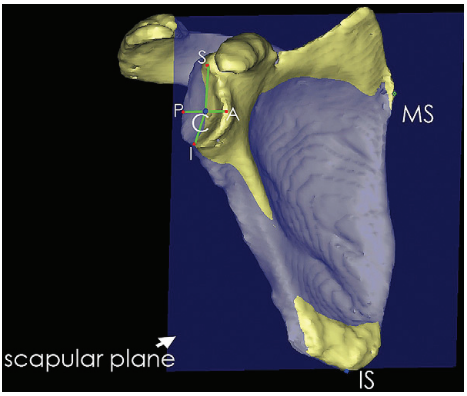

Figure 7 Scapular plane was determined by selecting 3 points on the scapula: a lateral scapular point in the center of the glenoid (C) which is the cross-point of the line between the most superior (S) and inferior (I) glenoid point (Sallers line) and the line between the most anterior (A) and most posterior (P) point of the glenoid; a medial scapular point (MS) at the most medial point of the spina scapula; and the inferior scapular point (IS) at the most inferior point of the scapula.

Statistical analysis

Statistical testing was performed (ANOVA) to detect significant differences in the measured angles.

Comparative man/women

A Mann-Whitney *U* test (MWU) was used to detect the distribution of angle measurements between males and females.

Correlation

Spearman correlations were used to explore the correlation with age. Regression models for each of the angle measurements were used to verify the interaction between age and gender and to obtain (potentially) age- and gender specific normal distributions of the angle. P values smaller than .05 were considered significant. Terms with $P < .10$ were kept in the regression model. No corrections for multiple testing were performed, as the aim is to detect any indication that the construction of normal values for the angle measurements should be done gender and/or age-specific.

Accuracy, reliability, and repeatability

Twenty different glenoids were analyzed by 2 independent investigators in order to determine the interobserver variability. To measure the intraobserver variability, 20 specimens were analyzed twice by the same person. To determine

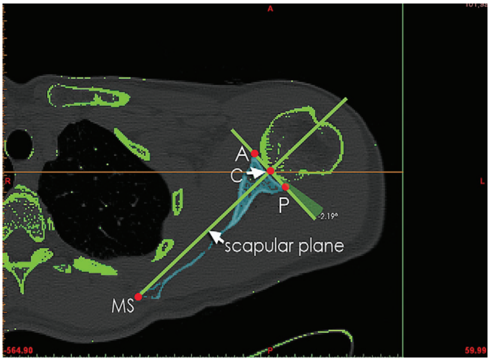

Figure 8 2-D glenoid version: angle between the line from the most anterior point (A) to the most posterior point (P) and the scapular plane [formed by the most medial scapular point (MS) and the center of the glenoid (C)].

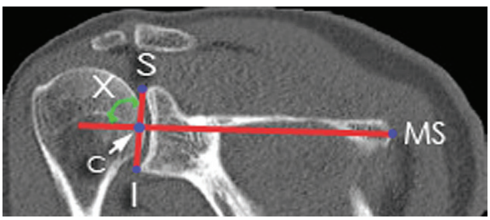

Figure 9 2-dimensional glenoid inclination (GI). According to the method of Churchill, angle between the line from superior point (S) to inferior point (P) and the line between the line from the most medial scapular point (MS) and the middle of the glenoid [crosspoint (C)] −90°.

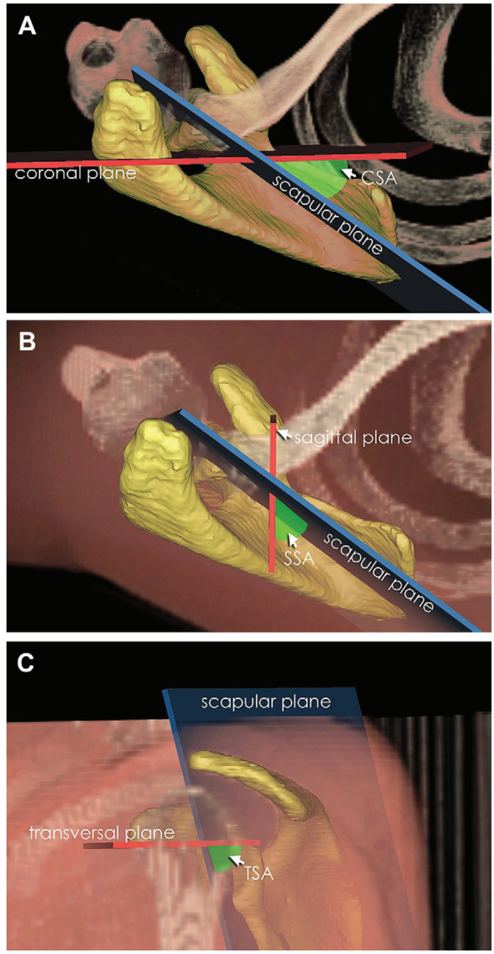

Figure 10 3-dimensional angles. (**A**), The coronal scapular angle (CSA) = the angle of the scapular plane and the coronal plane. (**B**), The sagittal scapular angle (SSA) = the angle of the scapular plane and the sagittal plane. (**C**), The transversal scapular angle (TSA) = the angle of the scapular plane and the transversal plane.

these variabilities, the interclass and intraclass correlation coefficients were used[29] (ICC, Wilcox on Signed Ranks test).

Results

A. Angles measured within the scapula
A. a. angles between lines.

2-D glenoid version (GV): the descriptive statistics are mean = −3.78°; Min = −13.74°; Max = 4.89°; SD = 3.50°.

2-D glenoid inclination (GI): the descriptive statistics for the method of Churchill[5] are mean = 10.89°; Min = 1.02°; Max = 24.91°; SD = 4.46°.

A. b. angles between planes.

Descriptive statistics

3-D glenoid retroversion: the descriptive statistics of the different glenoid planes (superior, inferior, anterior, and posterior) to the scapular plane can be found in Table I. The angle between the neutral plane is, of course, always 90°.

3-D glenoid inclination: the descriptive statistics of the different glenoid planes (superior, inferior, anterior, and posterior) to the scapular plane can be found in (Table II).

B. Angles of the different glenoid planes (neutral, superior, anterior, posterior, and inferior) and the scapular plane versus the coronal, sagittal, and transversal planes of the body (spatial parameters).

3-D angle of the different glenoid planes: the descriptive statistics of the different glenoid planes (neutral, superior, inferior, anterior, and posterior) can be found in Table III.

Table I Descriptive statistics of the version angles of the different glenoid planes. Negative values are retroversion, positive values are anteversion

Glenoid plane versus scapular plane	N	3-D version (degrees) range	Minimum	Maximum	Mean	Std. deviation
Anterior	150	28.26	.03	28.29	11.7135	5.88238
Inferior	150	16.59	−11.70	4.89	−3.7641	3.35027
Posterior	150	22.91	−25.38	−2.47	−14.0438	4.60318
Superior	150	24.27	−12.02	12.25	−2.0078	4.41418

Table II Descriptive statistics of the inclination of the glenoid planes. Negative values have a caudal directed angle (downslope) and positive values have a cranial directed angle (upslope)

Glenoid plane versus ⊥scapular plane	N	3-D inclination (degrees) range	Minimum	Maximum	Mean	Std. deviation
Neutral	150	23.89	1.02	24.91	10.8941	4.45579
Anterior	150	25.59	.00	25.59	9.7711	4.90862
Posterior	150	26.42	.01	26.43	12.1466	4.66731
Inferior	150	31.36	5.97	37.33	21.2241	5.22018
Superior	150	25.36	−8.76	16.60	3.2625	4.80235

3-D angle of the scapular plane: the descriptive statistics of the different glenoid planes CSA, SSA, and TSA can be found in Table IV.

Comparative statistics

The 3-D retroversion of the inferior glenoid plane showed a significantly lower standard deviation than the version of the anterior ($P < .001$), posterior ($P = .001$), and superior ($P = .001$) glenoid plane (ANOVA). Figure 11, *A* shows a normal distribution of the inferior glenoid version and Figure 11, *B* shows its Q-Q plot.

For the 3-D retroversion of the posterior glenoid plane ($P = .036$) significantly different values were found between men (mean, −13.2507) and woman (mean, −14.9748) (MWU test), implying that a less retroverted posterior glenoid plane is found in men.

No significant difference between all calculated inclination angles was found (ANOVA).

A significant difference between men (mean, 20.3009) and woman (mean, 22.3078) was found (MWU) for the 3-D inclination ($P = .035$) of the inferior glenoid plane: in men, less inclination is found.

A significant difference between the defined different glenoid planes is found, $P < .001$ (MWU).

Correlation statistics

A correlation with age was found for 3-D retroversion of the anterior glenoid plane ($R = -0.162$, correlation at the .05 level) and superior glenoid plane (.186, correlation at the .05 level) implying that both planes are more retroverted in the elderly (Spearman correlation).

No significant correlation could be calculated between the 3-D inclination angles and age or gender (Spearman correlation).

B. Angles of the scapular plane versus the coronal, sagittal, and transversal planes of the body (spatial parameters).

Comparative

The mean SSA in women is 53.3119°, in men: 55.4463°. The difference is significant ($P = .022$) (MWU) and implies that the scapular plane is more protracted in women.

Correlation

For the SSA ($R = .171$, correlation at the .05 level) and TSA ($R = -.224$, correlation at the .01 level) a significant correlation with age was found: in the elderly, the protraction and anteflexion of the scapular plane increases (Spearman correlation).

Accuracy, reliability and repeatability

Inter- and intraobserver variability was very high, with an intra-class correlation coefficient of 0.98 and an intraclass coefficient of 0.99 (ICC, Wilcoxon Signed Rank Tests).

Table III Descriptive statistics of the different glenoid plane (superior, anterior, posterior, inferior, and neutral) versus the coronal, sagittal, and transversal plane of the body

a. Glenoid planes - Transversal plane

	N	Minimum	Maximum	Mean	Std. deviation
Anterior glenoid vlak - transversaal vlak	150	65.6	90.0	83.054	5.0179
Inferior Glenoid vlak - transversaal vlak	150	50.3	89.7	69.202	7.1800
Posterior glenoid vlak - transversaal vlak	150	55.01	88.97	73.5167	6.90878
Superior glenoid vlak - transversaal vlak	150	69.3	90.0	83.634	4.3615
Gemiddeld glenoid vlak - transversaal	150	63.38	89.94	79.5105	6.20665
Valid N (listwise)	150				

b. Glenoid planes - Sagittal plane

	N	Minimum	Maximum	Mean	Std. deviation
Anterior glenoid vlak - sagittaal vlak	150	31.44	78.36	54.0653	7.71738
Inferior Glenoid vlak - sagittaal vlak	150	31.7	67.3	48.254	5.8391
Posterior glenoid vlak - sagittaal vlak	150	16.75	62.14	35.3538	6.09866
Superior glenoid vlak - sagittaal vlak	150	23.27	57.88	39.0705	5.70850
Gemiddeld glenoid vlak - sagittaal	150	30.7	61.7	44.904	4.8934
Valid N (listwise)	150				

c. Glenoid planes - Coronal plane

	N	Minimum	Maximum	Mean	Std. Deviation
Anterior glenoid vlak - coronaal vlak	150	13.37	63.72	37.2932	8.00143
Inferior Glenoid vlak - coronaal vlak	150	35.79	64.83	49.8086	5.31474
Posterior glenoid vlak - coronaal vlak	150	28.28	78.97	60.6745	6.52316
Superior glenoid vlak - coronaal vlak	150	32.79	67.46	52.0086	5.84530
Gemiddeld glenoid vlak - coronaal	150	34.75	59.85	47.6495	4.66447
Valid N (listwise)	150				

Discussion

We used a 3-D reconstruction software program (Mimics®) that enabled us to define the orientation of the scapular and glenoid planes versus the coronal, sagittal, and transversal planes of the body in a patient positioned in dorsal recumbency. According to the literature, this is the first study that defines the 3-D orientation of the scapular and glenoid plane *in vivo*. The knowledge of this orientation can be important in future studies of the range of motion of the shoulder,[4] instability,[24] and rotator cuff tears.[1,23,31,32]

The osseous measurements of this 3-D CT-scan reconstruction are consistent with the literature. The 2-D retroversion of the superior and inferior plane are comparable with the known osteology.[3,5,11,17,20-22,26] The reason why the version of the anterior and posterior planes are not comparable with the literature is that the maximum anteroposterior diameter of the glenoid is not taken into account. The same phenomenon is seen comparing the 2-D inclination with the known literature.[1,11,12,17,20] A different absolute value is found regarding the inclination of the inferior or superior plane; a comparable value is found with the neutral, anterior, and posterior planes.

Standardizing the positioning of the patient in the scanner minimizes the error of positioning both scapulae in a different coronal plane. The thoracobrachial orthosis forces the elbow (and the shoulder) to be positioned at the same transversal level and brings the upper arms (and caput humeri) in the same rotation. In a previous study,[9] we could demonstrate that this positioning reduces the variability of the *in vivo* measurements to the variability of the osseous anthropometric results. Unfortunately, neither the length, weight, nor body mass of the patients are taken into account, nor are the length and the orientation of the clavicula. These shortcomings can be considered as the major weakness of this study, which can thereby not pretend to analyze the impact of the morphology of the clavicle and thoracic cage on the positioning of the scapula.

Although this study has a very high intra- en interobserver accuracy, a similar variation is found between our measurements and the literature confirming the known variation of these measurements.[3,5,11,17,20-22,26] Only 1 exception is found for this statement: this study defines the inferior glenoid plane as the plane with the least variability regarding the retroversion of the glenoid ($P \leq .001$). Conforming to the literature, this plane is the plane of the inferior glenoid circle,[8,13,16,21] which seems to be a constant finding of the

Table IV Descriptive statistics of the scapular plane versus the coronal, sagittal and transversal plane of the body

Angle of the Scapular plane and the coronal, sagittal, and transverse plane	N	Range	Minimum	Maximum	Mean	Std. Deviation
CSA	150	21.0	35.4	56.4	44.876	3.9937
SSA	150	40.33	37.72	78.05	54.4645	6.72804
TSA	150	37.97	46.59	84.56	67.6457	7.11497

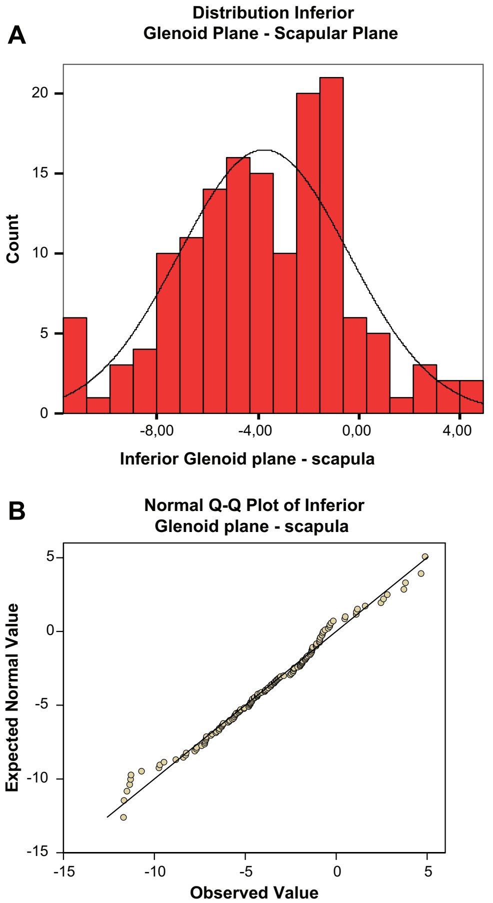

Figure 11 Distribution of the version of the inferior glenoid plane. (**A**), Normal distribution of the inferior glenoid version (IGF). (**B**), Q-Q plot to demonstrate the normal distribution of the IGF.

normal glenoid morphology. The variability of the inclination of this plane is similar to the variability of the other planes. The inferior plane is situated more distally so a greater influence of variables as morphology of the clavicle and the thoracic cage can be expected.

Because this study calculates a statistically significant difference between all the different planes of the glenoid, it seems important to define the most reliable one if the surgeon wants to reconstruct normal anatomy. This might be difficult when normal anatomy is distorted, as is the case in about two thirds of the rotator cuff sufficient omarthrosis, which shows a posteroinferior defect of the glenoid.[12] Probably new parameters need to be defined[6] or computer aided surgery will be indicated to mimic as close as possible normal glenoid anatomy.

The results show that the scapular plane is more protracted in women than in men, and that protraction and anteflexion of the scapular plane increase in the elderly. This might be explained by the degree of thoracic kyphosis, which increases with age, and affects the thoracic morphology and, therefore, scapular orientation.[7,18]

The scapular positioning influences the glenoid plane as well.[9,18] Nevertheless, this study could not find particular relationships between the scapula and glenoid. We demonstrated a less inclinated inferior glenoid plane in men than in woman, and maybe this can be seen as a causal factor in the higher incidence of rotator cuff tears in men.[1,34]

This study found less retroversion of the posterior glenoid plane in men than in woman, and this can be probably explan why degenerative osteoarthritis of the shoulder is less frequently found in men than in women.[2,15] The anterior and superior glenoid planes are more retroverted in the elderly, but aging cannot explain this as none of the scans showed degenerative articular signs. Maybe it is a consequence of aging of the rotator cuff.[34] These statements need to be confirmed by studies comparing inclination and version in nonpathologic shoulders to the values in shoulders with rotator cuff tears and degenerative osteoarthritic lesions.

Conclusion

This study shows that the inferior plane of the glenoid formed by the most anterior, posterior, and inferior points of the rim of the glenoid has a constant degree of retroversion. This finding supports the use of this plane as the most appropriate plane to restore normal anatomy. This is important in prosthetic surgery, where the restoration of the glenoid anatomy is crucial for the longevity of the prosthesis and functional outcomes.

Disclaimer

The other authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article and have no potential conflicts of interest related to this manuscript.

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Chapter 4 Consequences of reaming of the glenoid

4.1 Introduction

The native glenoid plane is subject to degeneration, and wear and erosion patterns are determined by the primary pathology. Walch classified glenoid morphology in function of the pattern of the erosion, and the degree of posterior subluxation of the humeral head.[1] (Figure 1)

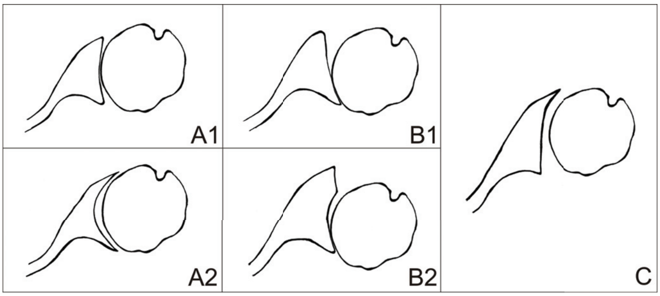

Figure 1: Walch classification. (For index see Chapter 2, Figure 22)

Recognizing and quantifying glenoid bone erosion and its orientation are important if we want to be able to restore the native glenoid plane in total shoulder arthroplasty.
Just as definition and measurement of the native plane is controversial, so is measurement of the plane of a deformed glenoid and this is greatly influenced by the instruments and the methods used (2 or 3 D CT). [2-6] A universal tool and method of measurement of the glenoid plane would be a step forward in handing and handling guidelines for correction of the native glenoid plane, but until now there is no agreement. Version measurement according to Friedman is shown to be reliable on a 2 D CT scan. [7] However in the presence of posterior erosion or even biconcavity it becomes more difficult to determine the glenoid surface and it is the intermediate glenoid line drawn from the anterior to the posterior edge of the glenoid fossa without considering irregularities, shown to be most reliable to represent the glenoid surface. [8] Three-dimensional CT reconstruction studies of both type A and type B glenoids provided further insight in the erosion patterns in osteoarthritis. The advantage of 3 D imaging is the possibility to evaluate and quantify the bony erosion without positional errors and the possibility of evaluating planes instead of lines. Walch and coworkers found that in type A glenoids the arthritic process flattens and enlarges the glenoid, involving incorporation of osteophytes. [9] Beuckelaers et al quantified the direction and amount of posterior erosion of type B glenoids with 3 D reconstructions in a population with primary glenohumeral arthritis.[10] (Figure 2)

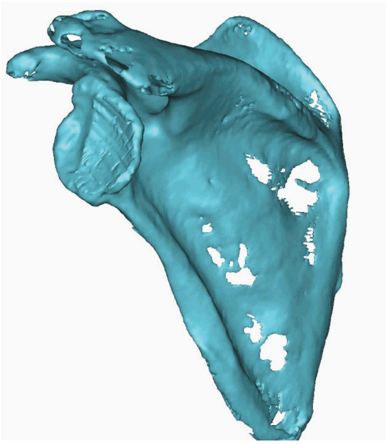

Figure 2: 3 D reconstruction image showing posterior erosion leading to biconcavity of the glenoid.

They found important posterior erosion of the glenoid (B1 and B2) and concluded that the amount of erosion of B1 glenoids could be underestimated using 2 D CT evaluation because the orientation of the maximum erosion in type B1 glenoids appeared to be situated more inferiorly. They used the native inferior circular plane as the reference plane. Verstraeten et al showed that this circular inferior plane has the lowest variability to the scapular plane in non-pathological shoulders.[11] This plane can be accurately reconstructed using 3 points on the anterior rim of the native glenoid, which is practically not affected by the degenerative disease.[12]
Needless to say that correction of the deformed plane is not without difficulties. Reaming down the high anterior edge is often performed. This sacrifices bone stock and medialises the joint line with the risk of peg perforation. Would it be better to accept a residual increased degree of version whilst minimizing bone loss and preserving maximal subchondral bone for support? [9,13] However if the version is not corrected then similarly the center of rotation is not corrected and this can lead to a rocking horse phenomenon. The aim must be to ream for an optimal and maximal correction with a minimum amount of bone loss. The aim of the third study is to determine the effect of reaming on the remaining surface area and on the bone volume of the glenoid vault?

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4.2 Article 3. Consequences of reaming with flat and convex reamers for bone volume and surface area of the glenoid. A basic science study.

Journal of Orthopaedic Surgery and Research

Consequences of reaming with flat and convex reamers for bone volume and surface area of the glenoid. A basic science study.

--Manuscript Draft--

Manuscript Number:	
Full Title:	Consequences of reaming with flat and convex reamers for bone volume and surface area of the glenoid. A basic science study.
Article Type:	Research article
Abstract:	Background: The effect of reaming on bone volume and surface area of the glenoid is not precisely known. We hypothesize that 1. Convex reamers create a larger surface area than flat reamers, 2. Flat reamers cause less bone loss than convex reamers, and 3. The amount of bone loss increases with the amount of version correction. Methods: Reaming procedures with different types of reamers are performed on similar sized uniconcave and biconcave glenoids created from Sawbone foam blocks. The loss of bone volume, the size of the remaining surface area and the reaming depth is measured and evaluated. Results: Reaming with convex reamers results in a significantly larger surface area than with flat reamers for both uniconcave and biconcave glenoids (p = 0.013 and p =0.001). Convex reamers cause more bone loss than flat reamers, but the difference is only significant for uniconcave glenoids (p = 0.007). Conclusions: In biconcave glenoids convex reamers remove a similar amount of bone as flat reamers, but offer a larger surface area while maximizing the correction of the retroversion. In pathological uniconcave glenoids convex reamers are preferred because of the conforming shape.
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Consequences of reaming with flat and convex reamers for bone volume and surface area of the glenoid. A basic science study.

Abstract

Background: The effect of reaming on bone volume and surface area of the glenoid is not precisely known. We hypothesize that 1. Convex reamers create a larger surface area than flat reamers, 2. Flat reamers cause less bone loss than convex reamers, and 3. The amount of bone loss increases with the amount of version correction.

Methods: Reaming procedures with different types of reamers are performed on similar sized uniconcave and biconcave glenoids created from Sawbone foam blocks. The loss of bone volume, the size of the remaining surface area and the reaming depth is measured and evaluated.

Results: Reaming with convex reamers results in a significantly larger surface area than with flat reamers for both uniconcave and biconcave glenoids ($p = 0.013$ and $p = 0.001$). Convex reamers cause more bone loss than flat reamers, but the difference is only significant for uniconcave glenoids ($p = 0.007$).

Conclusions: In biconcave glenoids convex reamers remove a similar amount of bone as flat reamers, but offer a larger surface area while maximizing the correction of the retroversion. In pathological uniconcave glenoids convex reamers are preferred because of the conforming shape.

Keywords: Glenoid, reaming, erosion, version, shoulder, prosthesis.

Background

Glenohumeral osteoarthritis is often associated with glenoid bone deformation and deficiency due to chondral and bone erosion. The erosion is concentric in approximately 60 % and eccentric in over 30% according to Walch [1]. In total shoulder arthroplasty the increased retroversion and erosion of the glenoid are associated with a higher rate of loosening of the glenoid component [2], [3]. Optimal positioning of the glenoid prosthesis seems to be essential to achieve good long-term results. To obtain this the surgeon should aim to correct the retroversion, while minimizing glenoid bone loss and creating a maximal and congruent contact surface area to support the prosthesis [2], [4], [5]. In glenoids with concentric erosion, type A according to Walch, this brings few difficulties. With limited reaming a congruent surface with a maximum contact area of supporting bone offers optimal initial stability to the implant. In contrast, in type B glenoids with eccentric erosion this causes more problems [6], [7]. It has been suggested to correct the retroversion to as close to the native version as possible (to within 5°), however, the exact amount of correction has not been clearly defined. Eccentric downreaming can correct less severe retroversion, but the amount of reaming is limited by the glenoid bone volume and by the medialization of the joint line.

It is not known how much bone is exactly removed by reaming or how this reaming affects the glenoid supporting area with respect to the pathology of the glenoid. The purpose of this study is to quantify bone loss and contact surface area of uniconcave and biconcave glenoids after reaming with different types of reamers. We hypothesize that 1. Convex reamers create a larger surface area than flat reamers, 2. Flat reamers cause less bone loss than convex reamers, and 3. The amount of bone loss increases with the amount of version correction.

Methods

Bone Models

Seventy-two glenoid bone models were created from Sawbones foam blocks: 36 with a uniconcave shape and 36 with a biconcave shape, hereby mimicking type A and type B2 glenoids according to the Walch classification [1]. The Sawbones solid rigid polyurethane foam (Sawbones, Malmo, Sweden) has material properties similar to subchondral glenoid bone [8]. The dimensions of an original female biconcave glenoid (82 year old woman with glenohumeral osteoarthritis) were used to create the B2 glenoid models. The dimensions of the B2 glenoid were obtained from a CT-scan of the glenoid. The radius of the inferior circle of the native glenoid was 15 mm [9], [10]. The retroversion measured according to Friedman [11] was 12°. From this CT scan an STL (Standard Tesselation Language) surface was extracted using Mimics (Materialise, Haasrode, Belgium), which was used to prepare the CAD (Computer Aided Design) drawings and generate CAM (Computer Aided Manufacturing) commands for the milling process in NX 7.5 (Siemens PLM, Plano, TX, USA). In this way, the STL surface of the patient was replicated onto the Sawbones blocks. The A model glenoids were ovoid in shape [12], [13] and were not CT-based, but were chosen comparable in size to the B models, measuring 30 mm in width, 39 mm in length and with a depth of 5 mm. The version is neutral, 0°. Again, starting from a STL surface of the CAD drawing CAM (computer aided manufacturing) commands were generated for the milling process in NX 7.5 (Siemens PLM, Plano, TX, USA). Both type A and B2 glenoids were milled from the polyurethane blocks using a 3-axis milling machine (Haas, Oxnard, CA, USA) (Fig. 1a and b). Automation of the milling process ensured all fabricated glenoid blocks were exact within manufacturing tolerance (10 µm) (Fig. 2a and b).

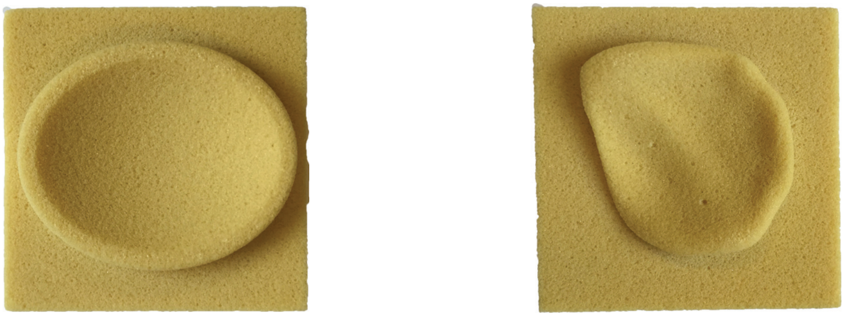

Figure 1 a. Uniconcave type A glenoid bone block, b. Biconcave type B2 glenoid bone block.

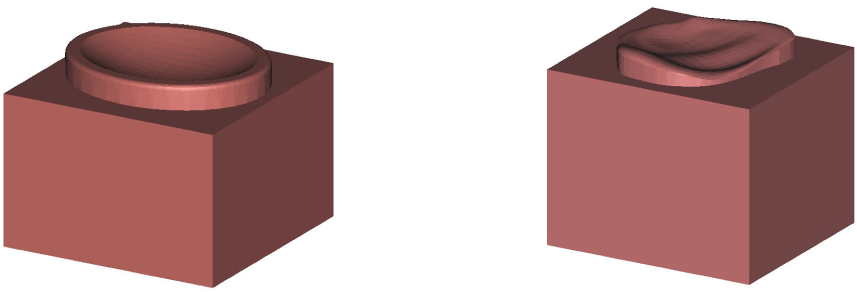

Figure 2 a. Uniconcave type A glenoid bone block, b. Biconcave type B2 glenoid bone block

Methodology

A set up is prepared with the bone blocks positioned vertically at surgical working height. The reaming procedure we used was validated in 2013 [14]. Three surgeons, three authors, perform the reaming representing an experienced, intermediate and inexperienced surgeon with respectively over 50, over 20 and under 20 total shoulder arthroplasties performed per year. Each surgeon individually defines the preferred center of the glenoid for the reaming procedure using a flat semicircular guide (Zimmer, Warsaw, Indiana). The surgeons individually determine the direction of reaming to obtain the intended correction of version. For the A glenoids the aim is to keep the version neutral. The B2 glenoids have a retroversion of 12 ° and the aim is to corrected this as close to neutral as possible. For the A glenoids reaming is performed until the reamer is over its entire surface in contact with glenoid bone, creating a smooth bone bed. For the B2 glenoids reaming is performed similarly taking into account a correction to a neutral version (Fig. 3). Four different reamers with the same radius are used. A convex reamer guided by a K-wire (Global AP, diameter: 33 mm, Depuy, Warsaw, Indiana), a convex reamer guided by a nipple (Global Advantage, diameter 33mm, nipple 6 mm, Depuy, Warsaw, Indiana), a flat reamer guided by a K-wire (custom made, diameter 30 mm) and a flat reamer guided by a nipple (diameter 30 mm, nipple 6 mm, Zimmer, Warsaw, Indiana). All reamers are used with the companies' instruments with a set arm length (18 cm). Each surgeon reams three A and three B2 glenoids with the four different reamers. This results in 24 reaming procedures per surgeon, 72 all together.

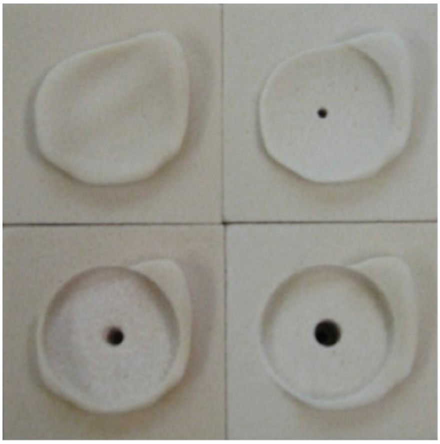

Figure 3. Reamed B2 glenoids.

Parameters

All bone blocks are scanned using 3D Laser CMM (Coordinate Measuring Machine) (MC16, Coord3, Turin, Italy) before and after reaming. The 3D CMM uses a laser to scan the surface of the blocks resulting in a dense point cloud of points lying on that surface. These resulting point clouds are processed using GOMInspect (Braunschweig, Germany) and STL's are built in 3-Matic (Materialise, Haasrode, Belgium) based on these point clouds. These STL's are used in the further analyses. All bone models are aligned in the software to the same identical coordinate system ("world coordinate system"), ensuring comparability between the parameters of different blocks. The parameters extracted for all reamed bone blocks are: the loss of bone volume, the size of the remaining surface area and the reaming depth. The bone volume removed is calculated based on the STL's of the respective block taken before and after reaming, similar to the procedure described by Youngpravat [15]. The three direction angles are calculated with respect to the local anatomical X, Y and Z-axis ("anatomical coordinate system") of the A and B2 glenoids defined according to Verstraeten [16] (Fig. 4). Defining the angles with respect to this local anatomical coordinate system allows for a uniform and clinically relevant interpretation of the angles for A and B2 blocks. Repeatability of the parameter extraction procedure is verified for all parameters with 10 repetitions per parameter and results in a mean standard deviation of 0.23% on the parameter values.

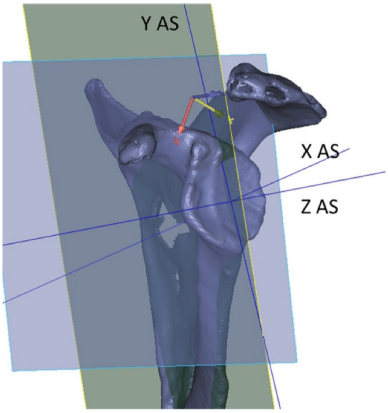

Figure 4. Anatomical coordinate system with X and Y-axis in the plane of the glenoid, and the Z-axis perpendicular to this plane.

Statistics

Statistical analyses are performed using IBM SPSS Statistics, version 21 (SPSS Inc., Chicago, IL, USA). Hypothesis testing between two groups is performed using a t-test if both groups to be compared were normally distributed according to a Shapiro-Wilk test or using a Mann-Whittney U test if one of the groups failed to pass the normality test. When more than 2 levels per factor are compared, an ANOVA analysis is carried out if the normality assumption is satisfied or a Kruskal-Wallis test if this assumption is not fulfilled. Regression analyses are carried out to assess the relationship between continuous parameters (e.g. direction angles) and relevant outcomes (e.g. bone loss). Significance is assessed at the 5% level.

Results

A glenoids

Convex reamers cause significantly more bone loss than flat reamers ($p = 0.007$) (Table 1, Fig. 5). Reaming with convex reamers results in a significantly ($p = 0.013$) larger surface area than flat reamers (Table 2, Fig. 6) and a significantly greater average depth of reaming ($p < 0.001$). We find no significant difference in bone loss ($p = 0.174$), surface area ($p = 0.521$), and depth ($p = 0.278$) between reaming with a K-wire or a nipple guided reamer, for both flat and convex reamers. The regression between bone loss and the three direction angles is not significant ($p = 0.4$). Hence, none of the three direction angles show a significant relation to the bone loss: X direction angle ($p = 0.566$), Y direction angle ($p = 0.108$) and Z direction angle ($p = 0.568$). The regression between the surface area and the three direction angles is not significant ($p = 0.058$): X direction angle ($p = 0.083$), Y direction ($p = 0.070$) and Z direction ($p = 0.219$). The regression of bone loss to the depth of reaming shows a significant relation ($p < 0.001$, $R^2 = 0.469$). Every mm of additional reaming depth accounts for an extra 215 mm^3 of bone loss for the given A glenoid samples.

B2 glenoids

There is no significant difference in bone loss between flat and convex reamers ($p = 0.855$). Reaming with convex reamers results in a significantly larger surface than with flat reamers ($p = 0.001$). The average depth of reaming is significantly greater with convex reamers than with flat reamers ($p < 0.001$). There is no significant difference in bone loss ($p = 0.174$) and depth ($p = 0.449$) between reaming with a K-wire or a nipple guided reamer, both for flat and convex reamers. A significant difference however exists in the reaming area ($p < 0.001$) between reaming with a K-wire or a nipple guided reamer for flat reamers. No significant difference in reaming area is recorded for K-wire versus nipple-guided wires for convex reamers ($p = 0.529$). The regression between bone loss and the X direction angle is significant ($p = 0.002$, $R^2 = 0.249$). The regression coefficient shows that every angle degree of correction along the X-axis results in an additional bone loss of 56 mm^3 for the B2 bone samples used. The Y direction angle ($p = 0.943$) and the Z direction angle ($p = 0.288$) show no significant relation to the bone loss. There is a significant difference in reaming angle between surgeon 1 and 2 for the X direction angle ($p = 0.14$) and between surgeon 1 and surgeon 3 ($p < 0.001$). No significant difference can be found between surgeon 2 and 3 ($p = 0.296$). Surgeon 3 corrects to an average X direction angle of 83.9° (+-2.257), surgeon 2 corrects to an average X direction angle of 85.67° (+-3.33) and surgeon 1 corrects to an average X direction angle of 89.58° (+-3.83°). The regression between the surface area and the three direction angles is not significant ($p = 0.817$): X direction angle ($p = 0.459$), Y direction ($p = 0.792$) and Z direction ($p = 0.856$). The regression of bone loss to the depth of reaming shows a significant relation ($p = 0.001$, $R^2 = 0.290$). Every mm of additional reaming depth accounts for an extra 235 mm^3 of bone loss for the given B2 glenoid samples.

Bone loss (mm3)	Reamer	Glenoid	N	Mean	SD
	convex	A	18	1686	352
	flat	A	18	1381	343
	convex	B2	18	1779	447
	flat	B2	18	1807	473

Table 1. Bone loss in A and B2 glenoids for convex and flat reamers.

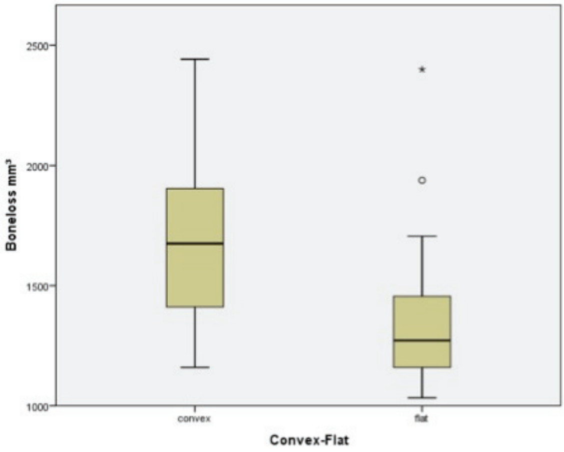

Figure 5. Bone loss in A glenoids for convex and flat reamers

Surface area (mm2)	Reamer	Glenoid	N	Mean	SD
	convex	A	18	864	14
	flat	A	18	744	24
	convex	B2	18	794	38
	flat	B2	18	730	42

Table 2

Surface area in A and B2 glenoids for convex and flat reamers.

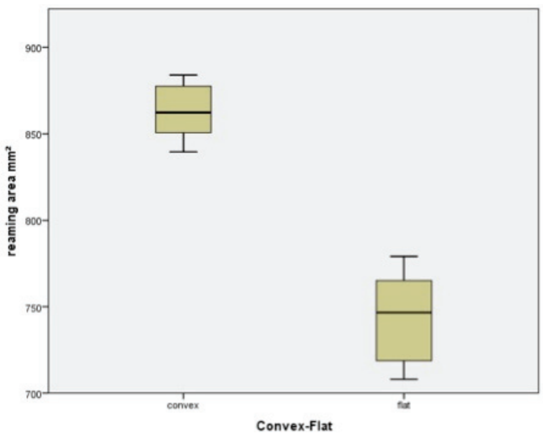

Figure 6. Surface area in A glenoids for convex and flat reamers.

Discussion

Glenoid component failure remains the most important indication for revision surgery of total shoulder arthroplasty [17], [18], [19]. Biomechanical studies have shown that placement of a glenoid component in more than 10° of retroversion causes eccentric loading of the prosthesis and this can lead to instability, rocking horse phenomenon and early loosening [7], [20-24]. Correction of the version helps to restore the glenohumeral relationship and rebalances the force couple of the rotator cuff. Downreaming of the anterior glenoid is an accepted method to correct the retroversion, but limited by the volume of the glenoid vault. Excessive reaming can result in loss of glenoid bone stock and medialisation of the joint line jeopardizing solid fixation and with the risk of peg perforation [25-27]. If the retroversion is less than 15 to 20 ° downreaming of the anterior glenoid is advised. However, there are no explicit guidelines regarding the amount of version that can be safely corrected by eccentric reaming without compromising the glenoid bone stock [28]. The amount of bone resected by the different types of reamers (nipple or K-wire guided, flat and convex), is unknown. To our knowledge this is the first study investigating the effect of reaming with different reamers on bone volume and surface area in two different shaped glenoids. This study shows that convex reamers cause more bone loss than flat reamers in uniconcave type A glenoids. This is partly due to the deeper reaming range as a result of the convexity. Corrective reaming of biconcave type B2 glenoids with convex reamers tends to cause slightly more bone loss than with flat reamers, but the difference is not significant. In A glenoids the reaming angle is as close to neutral as possible, so this does not interfere with bone loss. The depth of reaming does have a significant effect on bone loss and every mm of additional reaming depth accounts for an extra 215 mm^3 of bone loss. In B2 glenoids the angle of correction along the X-axis (representing the version angle correction) is an important factor in determining the bone loss; every additional degree of correction along the X-axis results in an extra 56 mm^3 of bone loss. Similarly the depth of reaming has an important effect on bone loss; every mm of additional reaming depth accounts for an extra 235 mm^3 of bone loss. Obviously it is the degree of retroversion and biconcavity, and the intended correction, which dictates the loss of bone volume after reaming in biconcave glenoids. If a surgeon decides to correct more by reaming this has a direct effect on the amount of bone loss. There is a significant difference between surgeons in the correction of version in the B2 glenoids in this study. This is probably due to the surgeons' intention and experience to correct as close as possible to the native version [15]. In recent publications Iannotti [29] and Karelse [14] came to a similar conclusion that in biconcave glenoids correction of version by reaming is not reproducible. Convex reamers create a larger surface area than flat reamers in both A and B2 glenoids, and this is not affected by the correction angle. This finding differs from the results from Youngpravat [15], where smaller version corrections increase the surface area. In biconcave glenoids the convex reamers are at slight disadvantage to flat reamers concerning bone loss, but they win back in a larger surface area of the glenoid after reaming. For uniconcave type A glenoids, which are considered non-pathological glenoids, reaming with convex reamers causes more bone loss than with flat reamers. The difference in surface area between the reamers is small given the fact that reaming depth must be minimal in these non-eroded glenoids. If however glenoids are centrally eroded to type A 1 and A 2 glenoids according to Walch, and excessive medialisation of the joint line should be avoided, minimal reaming with a more conforming reamer is the objective. A convex reamer with a radius of curvature mimicking the radius of the native articular surface can maximally preserve surface area and existing bone stock in centrally eroded glenoids [35]. Whereas flat reamers would reduce both surface area and bone stock. Another explanation for the reduced bone loss after flat reaming can be that the radius of flat reamers is chosen accordingly to the largest radius of the glenoid thereby reaming mainly the circumferential bone and not reaching the centrally eroded part.

The surface area of B2 glenoids is larger after reaming over K-wires than nipple guided using flat reamers. The difference may partly be explained by the difference in diameter of the K-wire and the nipple, 2 and 6 mm respectively.

We are aware of the limitations of this study. We performed reaming procedures on foam blocks in a surgical set up but without the intraoperative conditions that can be of great influence to a procedure. We created only two types of morphology; while we are aware of the large variation of the concavity of the glenoid. Nevertheless we believe this study offers valuable information that can be of help in future decisions on reaming strategy and possibly influence the choice and development of flat or curved backed glenoid prostheses for certain pathological glenoids [35-38].

Conclusion

This study shows that the characteristics of the reamer and the experience of the surgeon influence the amount of bone removal and the remaining surface area of the glenoid. These findings account for the two morphologic types studied: A and B2 glenoids. Convex reamers are due to their conforming shape better indicated in pathological A glenoids, but the convexity of the reamer should be optimally adapted to the pathological curvature [37]. In B-glenoids convex reamers are preferred because they remove a similar amount of bone as flat reamers but offer a larger surface area while maximizing the correction of the retroversion.

Competing interests

Each author certifies that he or she has no financial or non-financial associations that might pose a conflict of interest in connection with the submitted article.
No duplicate publications or similar reports have been published and no patents are withheld.

Author's contributions:

This basic research was performed at the University Hospital of Ghent and at the Department of Mechanical Engineering of the Catholic University of Leuven, Belgium.

Anne Karelse is the first author. Anne Karelse, Alexander Van Tongel and Lieven De Wilde are surgeons that performed the reaming procedure, and reviewed the article. Steven Leuridan produced and measured all the samples, and wrote the material and methods section. Kathleen Denis and Jos Vandersloten are mechanical engineers who developed the bone samples and the protokol for measurement and analysis of the reamed samples.

Acknowledgements

We are grateful for the financial funding received from the BVOT (Belgische Vereniging voor Orthopedie en Traumatologie). This enabled us to finance the production of the glenoid bone models.

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Chapter 5 Accuracy of reaming of the glenoid.

5.1 Introduction

Once you have decided on the amount of version you want to correct, how is it in practice? Is it in a surgical setting with the difficult exposure of a glenoid possible for a surgeon to accomplish this? Iannotti and coworkers showed that corrective reaming (to less than 5 degrees of the ideal position) by an experienced shoulder surgeon is not reproducible if the retroversion exceeds 10 degrees.[1] It is however possible when there is minimal posterior glenoid erosion. Obviously greater amounts of deformity result in greater difficulty to convert preoperative CT measurements and intentions of correction to intraoperative actions. The aim of the fourth study is to explore if reaming of the glenoid is a difficult exercise and if it is a reproducible action. To start reaming one has to decide on a reaming center, a reaming angle and the depth of reaming. The accuracy of these variables are investigated for three surgeons with different levels of experience, not in a surgical setting, but on a series of similar sized type A and B2 glenoids created from Sawbone, using different types of reamers nowadays available.

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5.2 Article 4. A Glenoid reaming study; How accurate are current reaming techniques?

J Shoulder Elbow Surg (2014) 23, 1120-1127

ELSEVIER

Journal of Shoulder and Elbow Surgery

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A glenoid reaming study: how accurate are current reaming techniques?

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Background: Correct reaming of a degenerative glenoid can be a difficult procedure. We investigated how the quality of the reamed surface is influenced by different reamers, by the surgeon's experience, and by glenoid erosion patterns.
Material and methods: Three shoulder surgeons performed reaming procedures with different types of reamers (flat, convex, K-wire guided, and nipple guided) on a series of similarly sized uniconcave and biconcave glenoids. The reproducibility of reaming and the effect of different reamers on different-shaped glenoids were measured and evaluated.
Results: The center and direction of reaming were constant for all surgeons in the case of type A glenoids. For type B2 glenoids, the center and direction of reaming differed significantly between surgeons. The congruity of the reamed surface was better after flat reaming than after convex reaming. Whether the reamers were guided by a central K-wire or by a nipple had no significant effect on the reamed surface. The experience of the surgeon had no effect on the congruity of reaming.
Conclusions: Reaming of a uniconcave glenoid is reproducible, but reaming of a biconcave glenoid seems much more difficult. Erosion and deformity of the glenoid influence the accuracy of reaming the most. Surgical experience plays a less important role. We conclude that there is a need for guidance in reaming of biconcave glenoids.
Level of evidence: Basic Science Study, Investigation of Surgical Technique.

Keywords: Glenoid; reaming; version; erosion; shoulder; prosthesis

Total shoulder replacement has proved to be superior to hemiarthroplasty in treatment of glenohumeral arthritis. Unfortunately, the glenoid component remains the weak link, and glenoid loosening is still the main complication and reason for revision. Correct placement of a glenoid component seems essential for longevity of the prosthesis and positively affects the functional outcome.[1,4,16,18,21,33,35,44] Correct positioning and fixation are difficult and depend on numerous factors. These are surgeon dependent, implant and accompanying instrumentation related, and patient related, depending on the anatomic variations of the glenoid.

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1058-2746/$ - see front matter © 2014 Journal of Shoulder and Elbow Surgery Board of Trustees.
http://dx.doi.org/10.1016/j.jse.2013.11.023

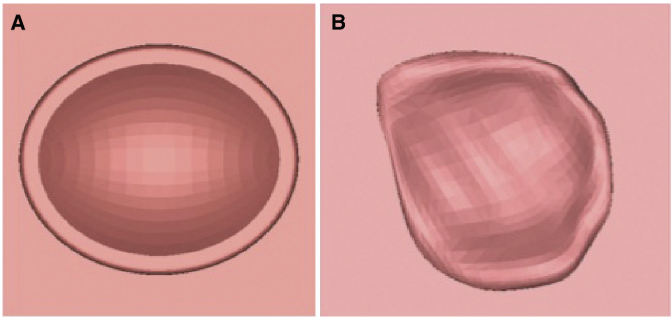

Figure 1 Computer-aided design of a uniconcave type A glenoid (**A**) and a biconcave type B2 glenoid (**B**).

Surgeon-dependent variables are acquired experience and skills helping in determining the surgical bone landmarks but also a natural sense of 3-dimensional (3D) orientation, enabling the surgeon to determine the amount of correction of the eroded glenoid.

Implants and instrumentation aim at an optimally seated glenoid component. The type of reamer and the technique of reaming play an important role in obtaining this.

The anatomy of the glenoid varies largely, and often posteroinferior erosion of the native glenoid, weakening of the subchondral bone, cysts, and osteoporosis are observed in arthritic shoulders. During surgery, it is important to find a balance between reaming to correct the orientation of the eroded glenoid and maintaining an optimal glenoid bone stock for adequate fixation of a glenoid component. This appears to be a difficult exercise even in experienced hands, and it explains the increasing interest in patient-specific instruments and navigation systems for guidance during this procedure.[15,23,28,34,38]

The goal of this study was to evaluate the accuracy of current glenoid reaming techniques and how the surgeon's experience, the type of reamer, and the orientation of the glenoid influence this.

Materials and methods

This is a basic science study investigating different reaming techniques performed on uniconcave and biconcave glenoid models.

Bone models

Ninety glenoid bone models were created from Sawbones solid rigid polyurethane foam (Sawbones, Malmö, Sweden) with material properties similar to glenoid subchondral bone.[7] The models were divided into 2 groups, 45 with a uniconcave shape and 45 with a biconcave shape, thereby mimicking type A and type B2 glenoids according to the Walch classification.[43]

The dimensions of an original female biconcave glenoid were used to create the B2 glenoid models with Mimics (Materialise, Haasrode, Belgium). The radius of the inferior circle of the native glenoid is 15 mm.[14] The retroversion measured according to Friedman[19] is 12°. The dimensions of the A model glenoids were chosen to be comparable in size to the B models, measuring 30 mm in width, 39 mm in length, and 5 mm in depth. The version was neutral, 0°. These A model glenoids were ovoid.[10,31] The Standard Tessellation Language (STL) surface was used to prepare computer-aided design drawings (Fig. 1) and to generate computer-aided manufacturing commands for the milling process in NX 7.5 (Siemens PLM, Plano, TX, USA). Both type A and type B2 glenoids were milled from the polyurethane blocks by use of a 3-axis milling machine (Haas, Oxnard, CA, USA) (Fig. 2).

Methodology

A setup was prepared with the bone blocks positioned vertically at surgical working height. Three surgeons (L.D.W., A.K., A.V.T.) performed the reaming, representing an experienced, intermediate, and inexperienced surgeon with, respectively, more than 50, more than 20, and less than 20 total shoulder arthroplasties performed per year.[22] The 3 surgeons each individually defined their preferred center on the glenoid for the reaming procedure. A flat semicircular guide (Zimmer, Warsaw, IN, USA) (Fig. 3) was used to orient and assist in finding this center. In doing this, the surgeons were guided by their personal preference: the center of the inferior circle guided by the anteroinferior glenoid rim,[40,41] the gravity center of the glenoid,[30] or the intersection point of superoinferior and widest anteroposterior line on the glenoid surface.[13]

The surgeons individually determined the direction of reaming to obtain the intended correction of version and inclination. For the A glenoids, the aim was to keep the version neutral; for the B2 glenoids, the aim was to correct the version as close to neutral as possible (retroversion between 10° and 0°).[10] Correction of the version can be obtained in 2 ways. The surgeon can be guided by the anteroinferior glenoid rim, which indicates the native glenoid plane and helps in reconstructing the native glenoid orientation.[14,40] Alternatively, one can focus entirely on the retroversion in the 2-dimensional (2D) orientation and correct to neutral.[10] The flat guide used by all surgeons assisted in aiming for the correct plane.

For the A glenoids, reaming was performed until the reamer was over its entire surface in contact with glenoid bone, creating

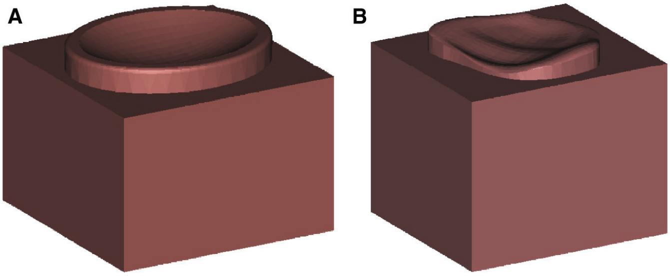

Figure 2 Bone models of A glenoid (**A**) and B2 glenoid (**B**).

Figure 3 Flat semicircular guide (Zimmer, Warsaw, IN, USA).

a smooth bone bed. For the B2 glenoids, reaming was performed similarly, taking into account a correction to a neutral version and inclination.

Four different reamers with a similar radius were used (Fig. 4):

- convex reamer guided by a K-wire (Global AP, diameter 33 mm; DePuy, Warsaw, IN, USA);
- convex reamer guided by a nipple (Global Advantage, diameter 33 mm, nipple 6 mm; DePuy, Warsaw, IN, USA);
- flat reamer guided by a K-wire (custom made, diameter 30 mm); and
- flat reamer guided by a nipple (diameter 30 mm, nipple 6 mm; Zimmer, Warsaw, IN, USA).

All reamers were used with the companies' instruments with a set arm length of 18 cm. Each surgeon reamed a series of 3 A and 3 B2 glenoids with the 4 different reamers. An additional 9 B2 glenoids were reamed with a convex reamer guided by a K-wire with a short arm length (9 cm). This resulted in 27 reaming procedures per surgeon. Of 90 samples, 9 were defectively over-reamed, and these were not used for the study. Eighty-one samples were reamed with success and included in the study.

Parameters and statistics

The reamed bone models were scanned with a 3D coordinate measuring machine (MC16; Coord3, Turin, Italy). The resulting point clouds were processed by GOM Inspect (Braunschweig, Germany), from which STLs were built in 3-Matic (Materialise, Haasrode, Belgium) for further analysis. All bone models were aligned in the software to the same identical coordinate system ("world coordinate system"), ensuring comparability between the parameters of different blocks. The following parameters were extracted from the A and B2 bone blocks: the center of reaming; the direction of reaming; the reaming depth; and the sphericity or flatness of the reamed surface for, respectively, convex and flat reamers used.

Sphericity describes the congruity of a convex surface, and flatness describes the congruity of a flat surface. Flatness (mm) and sphericity (mm) of the scanned reamed surfaces were determined in accordance with the methods used in geometrical dimensioning and tolerancing.[32]

The reaming center was expressed by its x, y, and z coordinates in the world coordinate system. The z-coordinate of the reaming center was used as a proxy for the reaming depth. The direction of reaming was determined as the normal to the surface for the flat reamer and as the direction of the line connecting the reaming center and the sphere center for bone blocks prepared with a convex reamer. These 3 direction angles were expressed with respect to the local anatomic x, y, and z axes ("anatomic coordinate system") of the A and B2 glenoids defined according to Verstraeten[41] (Fig. 5). Defining the angles with respect to this local anatomic coordinate system allowed a uniform and clinically relevant interpretation of the angles between A and B2 blocks. Repeatability of the parameter extraction procedure was verified for all parameters with 10 repetitions per parameter, resulting in a mean standard deviation of 0.23% on the parameter values.

Statistical analyses were performed with IBM SPSS Statistics, version 21 (SPSS Inc, Chicago, IL, USA). Hypothesis

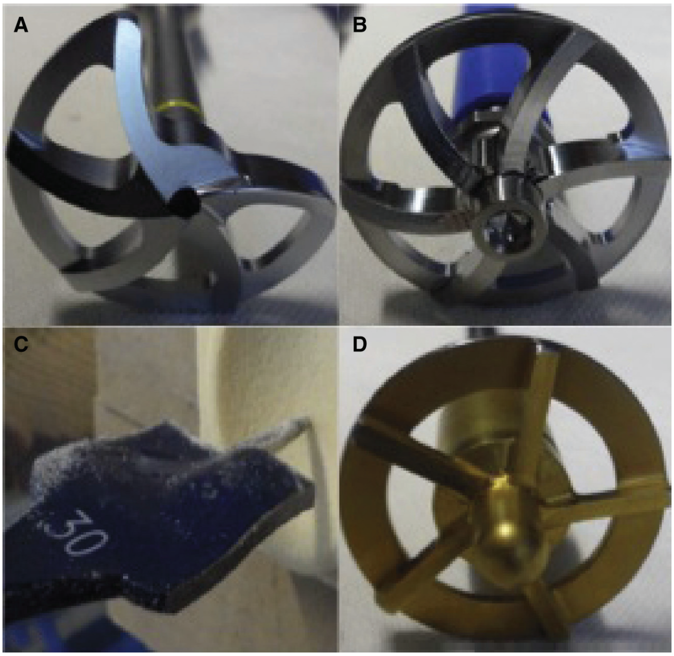

Figure 4 Different reamers used. (**A**) Convex reamer, K-wire guided. (**B**) Convex reamer, nipple guided. (**C**) Flat reamer, K-wire guided. (**D**) Flat reamer, nipple guided.

testing between the 2 groups was performed by a *t* test if both groups to be compared were normally distributed according to a Kolmogorov-Smirnov/Shapiro-Wilk normality test (depending on the subject size). Alternatively, a Mann-Whitney *U* test was used if one of the groups failed to pass the normality test. When more than 2 levels per factor were compared, an analysis of variance was carried out if the normality assumption was satisfied or a Kruskal-Wallis test if this assumption was not fulfilled. Significance was assessed at the 5% level.

Results

Center of reaming

The 3 surgeons chose a similar center of reaming for the A glenoids. For the x-axis (anteroposterior axis of the glenoid), we noted a significant difference ($P = .015$) between surgeon 1 and surgeon 3 (Table I). For the y-axis (craniocaudal axis of the glenoid) and the z-axis (depth), there was no difference.

There was a significant difference between surgeons for the chosen center of reaming for the B2 glenoids. There was a significant difference between 2 surgeons for the x-axis ($P = .020$) and between the 3 surgeons for the y-axis ($P = .043$, .024, and .001). There was no difference for the z-axis (Table I).

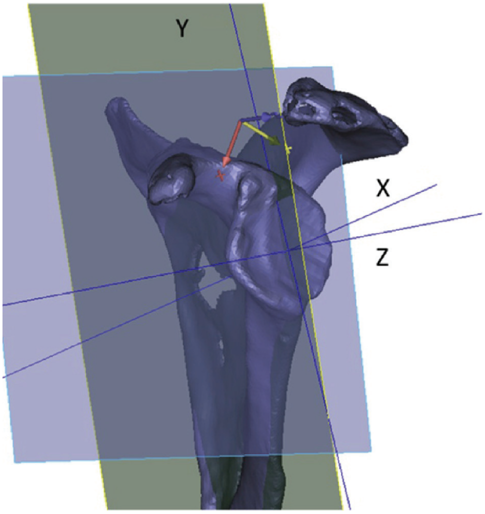

Figure 5 Anatomic coordinate system with the x-axis and y-axis in the plane of the glenoid and the z-axis perpendicular to this plane.

Concerning the reamers (convex and flat), there was no difference in center of reaming between K-wire–guided and nipple-guided reamers for all axes.

Table I Center of reaming, difference (mm) between surgeons

Difference between surgeons	Experienced vs medium experience		Experienced vs little experience		Medium vs little experience	
Glenoid type	A	B2	A	B2	A	B2
Axis						
z	0.4	0.4	0.4	0.5	0	0.3
y	0.3	**0.7***	0.1	**1.1***	0.2	**1.8***
x	0.6	**0.9***	**0.8***	**0.9***	0.2	0.2

* Significant differences.

Reaming depth was similar for K-wire–guided and nipple-guided reamers, and there was no significant difference between surgeons, both for A ($P = .815$) and B2 ($P = .499$) glenoids.

Direction of reaming

The direction of reaming was constant for all 3 surgeons for the A glenoids, except for a slight difference between surgeon 1 and surgeon 2 for the z-axis ($P = .005$) (Table II).

The direction of reaming differed between all 3 surgeons on all axes in B2 glenoids (x-axis, $P = .002$; y-axis, $P = .007$; z-axis, $P = .003$) (Table III).

We did not find a difference in direction of reaming between K-wire–guided and nipple-guided reamers for all axes in both types of glenoids.

There was a significant difference in direction of reaming between long and short reamers (x-axis, $P = .001$; y-axis, $P = .002$; z-axis, $P = .001$). Reaming with short reamers was more variable (Table IV).

Table II Difference in reaming angle between surgeons for A glenoids

	N	Minimum	Maximum	Mean	Standard deviation
Surgeon 1					
z-axis	12	1	5	3	1
y-axis	12	86	95	92	3
x-axis	12	87	91	89	1
Surgeon 2					
z-axis	12	1	3	2	1
y-axis	12	88	92	92	2
x-axis	12	89	91	90	1
Surgeon 3					
z-axis	12	1	6	3	1
y-axis	12	87	96	90	3
x-axis	12	88	92	90	1

Degrees relative to the local anatomic coordinate system.

Congruity of the surface

The sphericity of the surface after convex reaming was similar for K-wire–guided and nipple-guided reamers. The flatness of the surface after use of the flat reamers was similar for K-wire–guided and nipple-guided reamers. This applied for both A ($P = .542$) and B2 ($P = .134$) glenoids.

There was a difference in congruity between the sphericity and flatness after reaming. Flat reaming resulted in better flatness than convex reaming resulted in sphericity. The difference was significant ($P = .004$). A short reamer created better sphericity than a long reamer ($P = .029$).

Discussion

Loosening of the glenoid component remains a matter of concern in total shoulder arthroplasty. The occurrence of both tilting and subsidence of the prosthesis is associated with reaming of the glenoid.[45] Excessive reaming can result in weakening of the subchondral bone and loss of bone volume and surface area of the glenoid vault.[9] The lack of solid strong bone to support the prosthesis enhances the chances of loosening.[45] On the other hand, inaccurate reaming with failure to restore glenoid version also puts the prosthesis at risk for premature loosening.[30,37] To minimize failure, the surgeon should aim for a solid and durable fixation of a correctly oriented glenoid component.[25,37] Reaming is performed to create a congruent surface and to correct the orientation of the native glenoid. Multiple factors play a role in acquiring this.

To our knowledge, this is the first study to evaluate the surgical-, instrument-, and anatomy-related parameters affecting the reaming procedure of the glenoid. We were able to perform this study because 3D computed tomography (CT) scan reconstruction allowed us to create bone models of similarly sized A and B glenoids.[3]

This study showed that reaming of a uniconcave, type A glenoid is reproducible. The 3 surgeons chose similar centers of reaming and reaming direction for type A glenoids. The center and the direction of reaming were independent of the type of reamer used.

A biconcave, B2 glenoid causes more difficulties, as is evident from the significant difference between both parameters. The center of reaming differed between all 3 surgeons (Table I). The angle of reaming differed largely between surgeons and individually (Table III).

Table III Difference in reaming angle between surgeons for B2 glenoids

	N	Minimum	Maximum	Mean	Standard deviation
Surgeon 1					
z-axis	12	4	15	10	4
y-axis	12	93	103	98	3
x-axis	12	78	87	85	3
Surgeon 2					
z-axis	12	2	11	6	3
y-axis	12	89	99	94	3
x-axis	12	83	92	87	3
Surgeon 3					
z-axis	12	0	9	4	2
y-axis	12	90	99	94	2
x-axis	12	86	92	89	2

Degrees relative to the local anatomic coordinate system.

Table IV The direction of reaming differed significantly between long and short reamers

	x-axis	y-axis	z-axis
Standard deviation			
Short reamer	2.9	2.4	2.4
Long reamer	1.8	2.0	2.0

Reaming with short reamers showed more variation.

This implies that the orientation of the resultant reamed surface is variable. Correct reaming of a biconcave glenoid is in this setup obviously not reproducible. Iannotti[26] came to a similar conclusion in a study testing the ability of an experienced surgeon to correct retroversion with traditional surgical methods. Optimal glenoid component placement could be achieved only when there was minimal bone deformity and retroversion of less than 10°. Surgeons individually decide the center of the glenoid, and this depends on their personal preference and is influenced by the orthopaedic center at which they were trained. Determination of the center of the glenoid can be done in several ways. The center of gravity (centroid) is the center of a maximal equilateral triangle best fit on the rim of the glenoid.[40] This is easily applicable for nonpathologic or A1 glenoids (as in our A glenoid bone models) but creates difficulties in A2 and B pathologic processes with deformed glenoids and osteophytes. Lewis[30] showed how a computerized gravity point could be estimated by sphere fitting of the digitized glenoid. Another option is the center of the inferior glenoid plane. De Wilde[14] showed that this has the lowest variability and can approximate the native glenoid plane. Verstraeten[40] defined surgical reference points on the anteroinferior glenoid rim to reconstruct the native glenoid plane. This can be particularly useful in posterior erosion because the degenerative disease often does not affect the anteroinferior rim.

The reaming direction is determined by the glenoid plane the surgeon intends to reconstruct. It seems essential to correct the native glenoid plane, but this plane is not well defined. The inferior circular glenoid plane has the lowest variability to the coronal scapular plane and is therefore the most reliable plane in which to restore normal anatomy according to Verstraeten.[41] Preoperative measurement of glenoid version on 2D CT images is common practice but varies significantly with scapular rotation and is influenced by the amount of deformity and osteophytes.[6,19,36] The use of 3D reconstruction images to determine the native glenoid plane has been shown to be more precise and is independent of the position of the scapula.[5,6,29] A 3D CT reconstruction study by Beuckelaers[3] showed that the orientation of the erosion in a B1 glenoid is more inferior than in a B2 glenoid, a finding that would be underestimated on a 2D CT scan. With the knowledge of preoperative measurements, the surgeon can estimate the desired amount of reaming. It is desirable to approach normal version, which averages between 1° and 2° of retroversion for the majority of the population.[10] If retroversion exceeds 10°, correction is advised to avoid eccentric loading.[17,20,25,37] The possibilities are limited, though; if retroversion exceeds 15°, corrective reaming already risks violation of the glenoid vault, compromising placement of a glenoid prosthesis.[11,34] The 3D CT approach is difficult to translate into exact surgical acts. The surgeon's experience and ability to work with 3D configurations are advantages in accomplishing this.[22,27,42] Patient-specific preoperative planning and preoperative templating can be of help to decide on correction and component sizing.[24,46] This study shows the variability in center and direction of reaming for the B2 glenoids. Of the 3 surgeons performing the reaming, 2 junior surgeons were trained by the senior surgeon. Even 3 surgeons with the same working methods and reaming strategy did not manage to consistently ream a biconcave glenoid. This calls for guidance during reaming in the case of eroded glenoids.

Different implants come with different reamers, and we believed that the type of reamer might have an effect. The glenoid implant must match the size, shape, and congruity of the glenoid surface.[8] Curved back components have a biomechanical advantage over flat glenoids with a larger contact area and a better spreading of pressure.[2,39] A perfect fit between the congruity of implant and glenoid improves load transfer and reduces deformation and displacement of the implant.[9,12] Motorized reaming creates the best conformity of the glenoid surface with the undersurface of the implant and outperforms shaping with a curet or hand reaming.[12] This is to our knowledge the first study to investigate the quality of the resulting surface after reaming with various types of reamers. It shows that there is no difference in sphericity or flatness of the surface whether the reamers are guided by a central K-wire or by a nipple. There is a significant difference in congruity after convex and flat reaming. The flatness after reaming with a flat reamer is better than the sphericity after reaming with a convex reamer. The length of the reamer plays a significant role: with the short reamer, the congruence of the surface is better; and with the long reamer, there is less variation in direction of reaming. The longer reamer seems to create a more stable position to control the direction.

The experience of the surgeon seems to have no effect on the congruity of reaming.

We used reamers with small diameters (30 and 33 mm) because they fit into the cortical edge of the A and B2 glenoids with the dimensions of a female patient with a small glenoid. These reamers met the criteria (flat, convex, K-wire guided, and nipple guided) and were readily available for the study. The difference in diameter of the reamers had no effect on parameters of this study. It is obvious that severely eroded type B2 glenoids present difficulties for the surgeon. There is a lack of preoperative anatomic reference points available to the surgeon, and there is a lack of preoperative instrumentation and guidance. Computer-assisted surgical navigation might be the solution according to different surgeons.[15,28,32] Disadvantages of these techniques include the intraoperative tracking system, which is vulnerable to technical mistakes; failure of the tracking devices; and high costs. Patient-specific instrumentation can avoid the use of these tracking devices. Suero[38] used a custom-made jig for optimal implant positioning. With this instrument, accurate placement of a glenoid implant seems possible. Hendel[23] compared patient-specific instrumentation with the standard surgical technique and found significant improvement in accuracy of glenoid component placement in version, inclination, and medial offset, in particular in patients with more severe retroversion. Although this patient-specific instrumentation eliminates some of the technical difficulties faced with surgical navigation, manufacturing costs of these devices are expensive as well.

Conclusions

The current study demonstrates that there is a need for guidance in reaming of biconcave glenoids. Erosion and deformity of the glenoid seem to influence accuracy of reaming the most. The congruity of the reamed surface is better after flat reaming than after convex reaming. Surgical experience plays a less important role.

Acknowledgment

We are grateful for the financial funding received from the Belgian Association of Orthopedics and Traumatology. This enabled us to finance the production of the glenoid bone models.

Disclaimer

The authors, their immediate families, and any research foundation with which they are affiliated did not receive any financial payments or other benefits from any commercial entity related to the subject of this article.

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Chapter 6 The importance of inclination

6.1 Introduction

The majority of studies on glenoid component positioning focus on the restoration of, in particular, the version. There is however much less knowledge of the importance of inclination. The force couples of the rotator cuff and deltoid provide active centering of the humeral head in the glenoid, both in the transverse and in the coronal plane.[1, 2] Like the transverse force couple of the rotator cuff creates eccentric loading of the glenoid in case of increased retroversion, there must be an interaction between the force couple of the rotator cuff and the inclination of the glenoid.

The aim of this fifth study is to analyse the magnitude of the shear force (eccentric loading), as part of the total joint force, exerted by the transverse force couple of the rotator cuff on a virtual glenoid component with different angles of inclination.

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6.2 Article 5. The rocking horse phenomenon of the glenoid component: the importance of inclination.

J Shoulder Elbow Surg (2015) ■, 1-7

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Rocking-horse phenomenon of the glenoid component: the importance of inclination

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Background: Abnormal glenoid version positioning has been recognized as a cause of glenoid component failure caused by the rocking horse phenomenon. In contrast, the importance of the glenoid inclination has not been investigated.
Materials and methods: The computed tomography scans of 152 healthy shoulders were evaluated. A virtual glenoid component was positioned in 2 different planes: the maximum circular plane (MCP) and the inferior circle plane (ICP). The MCP was defined by the best fitting circle of the most superior point of the glenoid and 2 points at the lower glenoid rim. The ICP was defined by the best fitting circle on the rim of the inferior quadrants. The inclination of both planes was measured as the intersection with the scapular plane. We defined the force vector of the rotator force couple and calculated the magnitude of the shear force vector on a virtual glenoid component in both planes during glenohumeral abduction.
Results: The inclination of the component positioned in the MCP averaged 95° (range, 84°-108°) and for the ICP averaged 111° (range, 94°-126°). A significant reduction in shear forces was calculated for the glenoid component in the ICP vs the MCP: 98% reduction in 60° of abduction to 49% reduction in 90° of abduction.
Conclusion: Shear forces are significantly higher when the glenoid component is positioned in the MCP compared with the ICP, and this is more pronounced in early abduction. Positioning the glenoid component in the inferior circle might reduce the risk of a rocking horse phenomenon.
Level of evidence: Basic Science, Computer Modeling.

Keywords: Rotator cuff; force couple; glenoid plane; inclination; retroversion; rocking horse

The most frequent complication of total shoulder arthroplasty remains loosening of the glenoid component. Radiologic loosening is regarded as radiolucent lines progressing in size or as actual implant migration. This can progress to clinical loosening, which is associated with increased pain and decreased function of the shoulder, with revision surgery as the end point. According to literature, the occurrence of loosening is time dependent, with

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1058-2746/$ - see front matter © 2015 Journal of Shoulder and Elbow Surgery Board of Trustees.
http://dx.doi.org/10.1016/j.jse.2014.12.017

asymptomatic radiolucent lines seen at a rate of 7.3% per year after a primary shoulder replacement. Symptomatic glenoid loosening is seen at a rate of 1.2% per year, and surgical revision at 0.8% per year.[17] The risk ratio for revision of radiolucent lines amounts 0.27, with a higher risk for keeled than for pegged components.[23] Moreover, metal-backed prostheses have a higher rate of failure than all-polyethylene components.[16]

Besides the features of the prosthetic material, the positioning of the glenoid component also is a determining factor in the occurrence of loosening.[26] The position of the glenoid component relative to the scapular plane seems to be important in the transversal plane of the body (type B2 and C glenoids according to Walch) and in the scapular plane of the body (type A1 and A2).[7,17] This can partially be explained by the role of the rotator cuff muscles in compressing the humeral head into the glenoid socket.[18] An equal distribution of the rotator cuff forces in the transversal plane is required to obtain active centering, since a change in retroversion resulted in a posterior displacement of the humeral head and eccentric loading of the glenoid component causing glenoid loosening (rocking horse phenomenon). Surprisingly, this rocking horse phenomenon at the glenoid has not yet been studied for the inclination of the glenoid plane. The aim of this study was to analyze the magnitude of the eccentric loading (shear force), as part of the total joint force, exerted by the transversal force couple of the rotator cuff on a virtual glenoid component positioned in two differently orientated planes.

Materials and methods

This is a computed tomography (CT) scan simulation study determining forces on a virtual glenoid component in different positions.

Methodology

We measured 152 CT scans of healthy shoulders from patients who were scanned for pathology at the contralateral side. Since 2007, we have included in a radiologic database the Digital Imaging and Communications in Medicine (DICOM) information of both shoulders of all patients who have had a CT arthrogram in our shoulder unit for pathology of 1 shoulder. Because it is not possible to position only the diseased shoulder centrally in the CT gantry, both shoulders are scanned simultaneously; however, patients do not receive supplementary irradiation.

Exclusion of pathology of the shoulder to be studied was done by history taking, physical examination, and CT scan evaluation. The senior author (L.F.D.W.) inspected all CT scans for structural bony lesions (eg, cysts and visible bony deformations of the clavicle, scapula, and humerus, and the sternoclavicular, acromioclavicular, and glenohumeral joints) and soft tissue lesions (eg, integrity of the rotator cuff tendons, atrophy or muscular fatty degeneration of the rotator cuff or deltoid muscles, or both). If such lesions were present, the data were excluded.

The selected group of 152 patients had different pathologies from the contralateral shoulder, including rotator cuff tears in 35 (5 partial and 30 full-thickness tears), acromioclavicular-joint osteoarthritis in 33, instability lesions in 30, subacromial impingement in 17, calcifying tendinitis in 12, tendinitis of the long head of biceps brachii in 12, frozen shoulder in 8, and fractures of the proximal humerus in 5.

A standardized method was used to position all patients in the CT gantry, as detailed in a previous study.[5] The patient is placed in dorsal recumbence, with a cushion on the belly and a strap around the body and this cushion. The upper arms are positioned at the side of the body with the elbows flexed to 90° and the hands holding the cushion. This keeps both arms adducted in the coronal plane and the forearm flexed in the sagittal plane of the body.

A Somatom Volume Zoom–Siemens CT (Siemens, Erlangen, Germany) with a matrix set to 512 × 512, kV at 140/eff, and mAs at 350 was used with a field of view adapted to each patient. This resulted in a maximum of 500 mm for both shoulders and 180 mm for 1 shoulder with a pixel size of no more than 0.97 or 0.35 mm, respectively. The glenohumeral joint was scanned with maximum 1.5-mm interval slices. To create 3-dimensional images of the shoulder joint, the DICOM CT images are imported into medical imaging computer software (Mimics 14.0 for Intel X86 Platform V14.0.0.90 1992–2010; Materialise NV, Leuven, Belgium). This software permits virtual separation of both bones of the joint so that the determination of the bony reference points or best-fitting shapes for measurement purposes can be done digitally. Three investigators independently performed the measurements.

Determination of planes

A virtual glenoid component was positioned in 2 different planes: the maximum circular plane (MCP) and the inferior circular plane (ICP). We defined the MCP as the best fitting circle (maximum circle [MC]) constructed by the most superior point of the glenoid and 2 points at the lower third glenoid rim (Fig. 1, *A*). The MCP was chosen because it is the most commonly used plane in osteoarthritis.[20] The ICP was defined as the best fitting circle (inferior circle [IC]) of the rim of the inferior quadrants (Fig. 1, *B*). We chose the ICP because it is important for glenohumeral stability and has the least variability in orientation.[1,8,13,24,25] The radius (r) of the MC (rMC) and IC (rIC) was calculated.

To obtain a reproducible Cartesian coordinate system, we defined the scapular plane. This was constructed by the most medial point (Smed) and most inferior point (Sinf) of the scapula and the center of each circle. The center the MC (cMC) and center of the IC (cIC) was also the origin of a Cartesian coordinate system, with the x-axis positioned in parallel to the MCP or ICP, and the y-axis defined as the intersection of the scapular plane and the MCP (Fig. 2, *A*) or ICP (Fig. 2, *B*).

Parameters

The inclination of the glenoid component was measured as the angle between the perpendicular to the scapular plane (different related to different center of each circle) and the 2 different glenoid planes (Fig. 3, *A* shows this for the ICP). The version was measured as the angle between the perpendicular to the scapular plane and the x-axes of the two different glenoid planes (Fig. 3, *B* shows this for the ICP). The position of the center of rotation (cR)

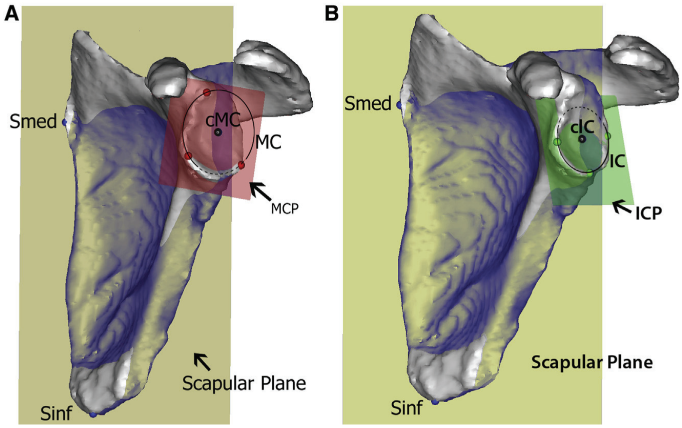

Figure 1 Determination of the maximum circular plane en of the inferior circular plane. (**A**) *MC*, maximum circle; *cMC*, center of maximum circle; *MCP*, maximum circular plane; *Sinf*, most inferior point of the scapula; *Smed*, most medial point of the scapula. (**B**) *IC*, inferior circle; *cIC*, center of inferior circle; *ICP*, inferior circular plane; *Sinf*, most inferior point of the scapula; *Smed*, most medial point of the scapula.

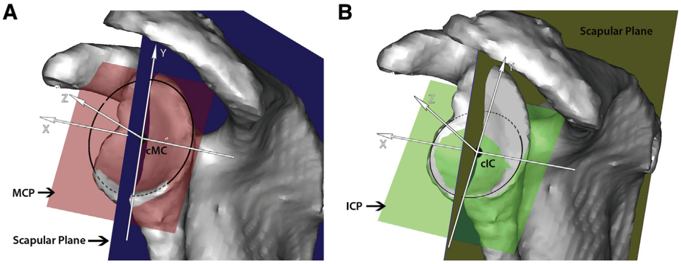

Figure 2 2: The glenoid planes and the scapular plane in a Cartesian coordinate system: (**A**) *cMC*, center of maximum circle; *MCP*, maximum circular plane. (**B**) *cIC*, center of inferior circle; *ICP*, inferior circular plane.

of the humeral head, defined as the midpoint of the best fitting sphere of the humeral head, was determined in the Cartesian coordinate system (Fig. 4). The force vector of the transversal force couple was defined with the origin of the vector at cR and the direction of the vector through the center of each circle (cMC or cIC; Fig. 5). The joint force vector can be split in a compression force vector and a shear force vector. We calculated the magnitude of the shear forces as a percentage of the total joint force (%) on the virtual glenoid component for both planes during glenohumeral abduction. When taking into account the difference in inclination and the different radii of both virtual glenoid components, it is possible to calculate the difference in joint force direction. This difference is defined as the θ angle. This θ angle can be calculated using the trigonometry relations in the 2 triangles.

Intermediate calculations that are performed:

$$\alpha\text{ICP} = \text{Arcsin}\left(\frac{\text{rICxsin}(111^{\circ})}{\text{L}}\right);\ \alpha\text{MCP} = \text{Arcsin}\left(\frac{\text{rMCxsin}(95^{\circ})}{\text{L}}\right)$$

$$\theta\text{ICP} = 180^{\circ} - 111^{\circ} - \alpha\text{ICP}\ ;\ \theta\text{MCP} = 180^{\circ} - 95^{\circ} - \alpha\text{MCP}$$

$$\text{L} = \sqrt{[16^2 + \text{SSAMCP}^2 - 2\times\ \text{rMC}\times\text{SSAMCP}\times\cos(95^{\circ})]}$$

$$\theta = \theta\text{MCP} - \theta\text{ICP} = (111^{\circ} - 95^{\circ}) + \text{Arcsin}\left(\frac{\text{rICxsin}(111^{\circ})}{\text{L}}\right) - \text{Arcsin}\left(\frac{\text{rMCxsin}(95^{\circ})}{\text{L}}\right)$$

The shear forces applied on the glenoid can be calculated in relation to the direction of the joint force (glenohumeral angulation of the joint force = GH). The joint force *F*, applied on the glenoid with an angulation *GH*, the shear force by using the MCP plane is: F × sin (GH); the shear force by using the ICP plane is: F × sin (GH-θ).

Statistics

An intraobserver and interobserver fault was assessed for all parameters by intraclass correlation coefficients (ICC). An ICC value below 0.40 indicates poor agreement, values between 0.40 and 0.75 indicate fair to good agreement, and values greater than 0.75 show excellent agreement.[6]

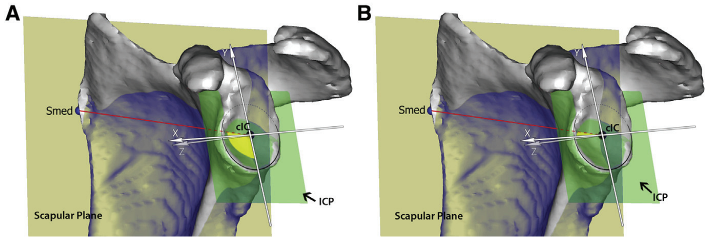

Figure 3 Measurement of (**A**) inclination and of (**B**) version in the inferior circular plane (*ICP*). *cIC*, center of inferior circle; *Smed*, most medial point of the scapula.

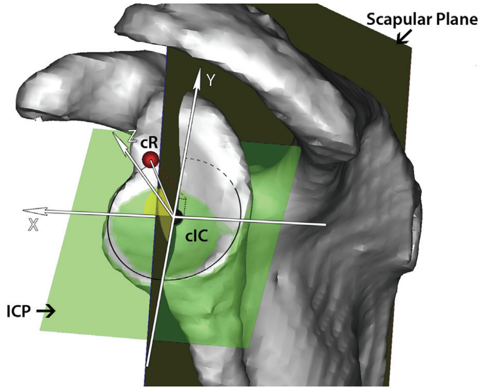

Figure 4 The position of the cR of the humeral head in the Cartesian coordinate system. *cIC*, center of inferior circle; *cR*, center of rotation; *ICP*, inferior circular plane.

Results

We studied 72 women and 80 men, with a mean age of 41.8 years (range, 18-80 years). Intraobserver and interobserver variability was excellent for all parameters. The ICC was 0.86 to 0.99 for the MCG and 0.89 to 0.99 for ICG.[24,25]

Descriptive statistics

The radius from the MC was 16 mm (range, 13-19 mm) and from the IC was 13 mm (range, 10-16 mm). The glenoid inclination of the component positioned in the MCP averaged 95° (range, 84°-108°), the glenoid retroversion measured 95° (range 81°-108°; *x*-axis). The inclination of the component positioned in the ICP averaged 111° (range, 94°-126°), and the retroversion was 93° (range 78°-104°; *x*-axis). The location of the cR was 92° (range, 79°-103°) on the *x*-axis and 91° (range, 81°-102°) on the *y*-axis for MCP. The location of the cR was 92° (range, 84°-99°) on the *x*-axis and 92° (range, 81°-103°) on the *y*-axis for ICP. By using the mean value of the anatomic measurements (SSAMCP = 108 mm; rMC = 16 mm; rIC = 13 mm), the mean calculated value of θ is 14°. This implies that the joint force direction applied on the glenoid is changed by 14°, if the MCP is compared with the ICP. The magnitude of the shear force (%) of the total joint force is shown in Fig. 6. The difference between the magnitudes of the shear forces (%) on both virtual glenoid components can be seen in Fig. 7.

Discussion

As recently stated in the first systematic review on glenoid component failure, it is evident that the problem of glenoid component failure continues unabated and that existing studies provide little evidence to guide future attempts to curb the rate of this complication.[17] The transversal force couple, composed of the subscapularis muscle anterior and the infraspinatus and teres minor muscle posterior, is an essential stabilizing factor intended to center the glenohumeral joint.[10,19] An equal distribution of the rotator cuff forces in the transversal plane is required to obtain active centering, because a change in retroversion was proven to result in a posterior displacement of the humeral head and posterior loading of the glenoid component. To our knowledge, this effect at the glenoid has not yet been studied for the inclination of the glenoid plane, even though every surgeon is confronted with the need of reaming a glenoid plane, taking into account version and inclination.

This study investigated 2 glenoid planes with a different inclination that can be used to reconstruct the native glenoid plane.[24] Our calculations showed that the shear force exerted at the glenoid is greater for the glenoid in the MCP than in the ICP, in particular during early abduction. This induces off-center loading that can result in a rocking horse phenomenon causing loosening of the glenoid component. The American Society for Testing and Materials (ASTM) uses a standard protocol for examining glenoid implant loosening based on the concept of the rocking horse effect.[11] In these testing protocols, rim displacement of the implant, influenced by the number of load cycles, is considered an indicator of loosening. The force load is either a horizontal load applied through the glenoid or a vertical load created by displacing the humeral head superiorly (vertically upwards) and back to the center of the

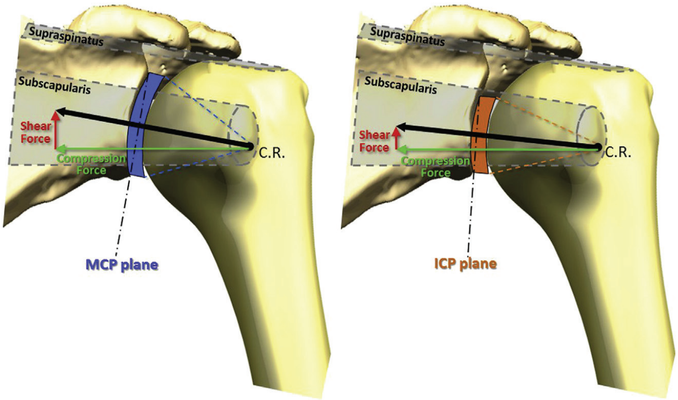

Figure 5 The force vector can be split into a compression force vector and a shear force vector. *CR*, center of rotation; *ICP*, inferior circular plane; *MCP*, maximum circular plane.

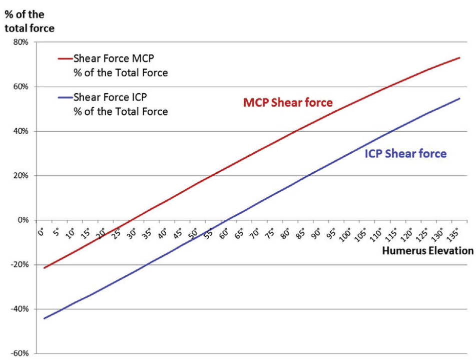

Figure 6 The magnitude of the shear force is shown as a percentage of the total joint force. *ICP*, inferior circular plane; *MCP*, maximum circular plane.

glenoid. This method is chosen because it resembles the loading mode observed clinically.[2,22] This protocol has proven its efficacy but not take into account the direction of the forces exerted by the transversal force couple of the rotator cuff.

Our study demonstrated that there is a distinct difference between the MCP and the ICP of 6° (−1° minimum to 22° maximum). We calculated that the magnitude of the shear force exerted at the superior pole is greater in abduction of the shoulder. However, the relative difference of shear force at the superior glenoid prosthesis is most important for early abduction (91% at 15° of abduction to 11% at 70° of abduction; Table I). We believe that the different inclination between the 2 planes, even though clinically this might appear minimal to negligible, can partially explain why loosening lines can occur around the glenoid component/cement interface.[9,12,14,22,27] The compressive forces on the glenoid prosthesis approximate a magnitude of 440 N.[3] This means the shear force exerted at the glenoid in the frontal plane (the rocking horse phenomenon) in the MPC can approach 375 N during glenohumeral abduction. In the extreme position, the magnitude of the shear force on the glenoid component in the ICP is larger than on the MCP. But in patients with shoulder arthroplasty, the correlation between the scapulohumeral and the glenohumeral rhythm changes, such that there is less glenohumeral abduction compared with a normal shoulder joint and thus minimizing its clinical importance.[4] The difference in inclination of the glenoid planes does not alter the position of the glenohumeral center of rotation (92° on the *x*-axis for MCP and ICP; 91° and 92° on the *y*-axis for MCP and ICP, respectively). We believe this can be explained by the fact that a circular section of a sphere will always have the same relationship to the center (center of rotation vs midpoint of the circular section), regardless of where this section is made at the sphere. This contrasts with the change of position of the center of rotation of the humeral head if the retroversion is not restored anatomically.[15]

For the mean prosthetic configuration, a change of 10° of version induces a displacement of approximately 5 mm of the center of rotation. Obviously, the difference in inclination of the glenoid component does alter the compression and shear forces applied by the rotator cuff. In our opinion, this change in line of action adds to the explanation of the fact that oval (or ovoid) glenoids, irrespective of the particular fixation design, fail at the implant-cement interface and that failure is initiated at the inferior part of the fixation in the study of Sarah et al.[21] This might also explain the finding that a significantly increased upward rotation is seen in patients with a total shoulder prosthesis compared with normal shoulders. With this upward rotation, the thoracoscapular entity probably tries to compensate for the increased vertical forces exerted at the superior glenoid.[4]

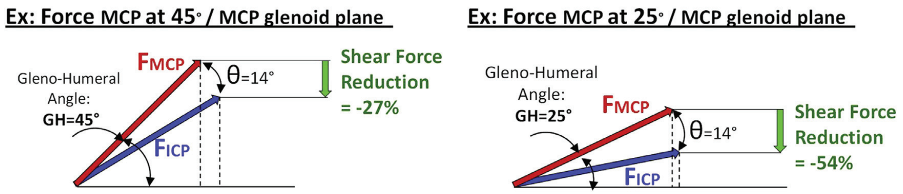

Figure 7 The difference between the magnitudes of the shear forces (%) (*F*) on both virtual glenoid components. *ICP*, inferior circular plane; *MCP*, maximum circular plane.

Table I Shear forces in different planes

GH angulation of the joint force/ glenoid plane (MGC)	Shear force (% of the total force)		Shear force reduction
	MCP	ICP	(%)
0°	0	−24	NA
5°	9	−15	NA
10°	17	−7	NA
15°	26	2	91.7
20°	34	11	68.3
25°	42	19	53.9
30°	50	28	44.1
35°	57	36	36.9
40°	64	44	31.3
45°	71	52	26.7
50°	77	59	22.9
55°	82	66	19.5
60°	87	72	16.6
65°	91	78	14.0
70°	94	83	11.5
75°	97	88	9.3
80°	98	92	7.1
85°	100	95	5.0
90°	100	97	2.9

GH, glenohumeral; *ICP*, inferior circular plane; *MCP*, maximum circular plane; *NA*, not applicable.

We are aware of the weaknesses of this study. We performed an anatomical computer simulation study, measured angular differences between glenoid planes, and then calculated the effect of these differences on the forces applied to a virtual glenoid prosthesis. Nevertheless, we believe that this theoretical approach can be valuable for future considerations of prosthetic design.

Conclusion

This is the first study investigating the biomechanical consequences of the inclination of the glenoid prosthesis. The shear forces exerted on the glenoid by the rotator cuff (the transversal force couple) are significantly different for the inclination of 2 different planes (MCP and ICP). However the center of rotation of the glenohumeral joint appears to be 3-dimensionally situated in the same position for both glenoid planes. The creation of a shear force vector is more important for MCP than ICP, and this difference is more pronounced during the first 90° of glenohumeral abduction. This can imply that the risk for a rocking horse phenomenon is higher if the glenoid component is implanted in the MCP compared with the ICP.

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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Chapter 7 Severe bone defects of the glenoid.

7.1 Introduction

Prosthetic surgery in case of severe glenoid bone loss can be a challenging problem for a surgeon. Most current glenoid implants rely entirely on the bone in the glenoid vault for fixation with pegs, keels or screws, but the bone loss can be so severe that adequate fixation is not possible.

Causes of severe glenoid bone defects are diverse. In primary osteoarthritis there is often posterior bone loss due to asymmetric wear. A retroversion exceeding 15 to 20 degrees cannot be corrected by downreaming without compromising bone stock for correct implantation.[1,2]
Rheumatoid arthritis creates mainly central erosion and these patients may have cyst formation and osteopenia compromising fixation.[3] In rotator cuff tear arthropathy the erosion can be typically eccentric and superior.[4] Dysplastic glenoids classified as type C by Walch are retroverted 25 degrees or more, but with the head centered in the retroverted glenoid.[5] There is no consensus whether or not to implant a prosthesis in the native glenoid orientation of the dysplastic glenoid (in this case accept the retroversion) or to perform a limited correction. Complete correction of the version is thought to put too much tension on the posterior soft tissues (tendon and muscle fibers of the infraspinatus & teres minor muscle). In severe dysplasia the amount of bone available may be inadequate for fixation of a glenoid even without correction of the version.[6, 7, 8]
Chronic instability and dislocation can cause large anterior and posterior bone defects.

Glenoid bone deficiencies are most frequently encountered in revision surgery. Antuna and coworkers classified bone defects after glenoid component removal in central, peripheral or combined lesions, implicating contained & non-contained defects, as being either mild, moderate or severe.[9] (Figure 1a and 1b)

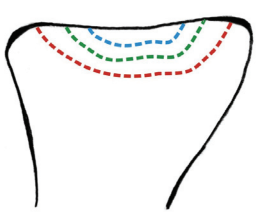

Figure 1a: Central defects of the glenoid fossa. Blue: mild, green: moderate, red: severe.

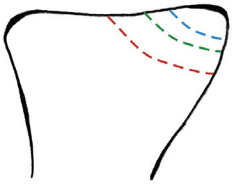

Figure 1b: Peripheral defects of the glenoid fossa. Blue: mild, green: moderate, red: severe.

How do we proceed when the amount of bone is inadequate for solid fixation? (Figure 2)

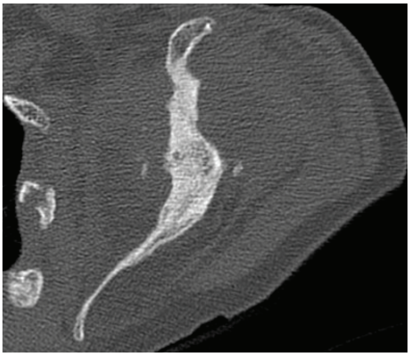

Figure 2: Severe glenoid bone loss.

There are several surgical options:
Reconstruction of large defects by a bone graft offers the advantage of restoration of the bone volume and the version. Bone grafting for eccentric wear is done with a large segmental graft (from the humeral head or iliac crest) fixed with screws before the prosthetic glenoid is positioned. In case of central or combined bone deficiency (peripheral defects are rare), as are seen after failed arthroplasty, the defect can be filled with cancellous auto- or allografts and implantation of a new anatomic glenoid component can be done at first stage. If this is not possible a structural autograft can be fixed with screws and a glenoid implantation can then be performed at second stage after adequate ingrowth of the graft.
But bone-grafting techniques are technically difficult, with varying results and a high complication rate due to loss of glenoid fixation or failure of graft incorporation. [10 - 18] To be successful the graft requires immediate solid fixation, preferentially to a bleeding surface, and eventually incorporation in the underlying bone. The lack of sufficient native viable bone undermines this.

Another option is the posteriorly augmented glenoid prosthesis, which is designed to assist in correction of the version of the glenoid with the aim to preserve a maximum of native bone. Early results are promising, long-term results are awaited.[19 - 23] Besides, a posterior stepped prosthesis also needs a ground for fixation, and its placement is only possible if sufficient glenoid bone is left.

Custom-made glenoid implants adjusted to glenoid deformity are under development.[24 - 26]
This option is recently becoming more popular in Belgium, because one of the major manufacturers (Materialise) is a compatriot. [24 -26]

Recently it has been shown that the reversed total shoulder arthroplasty (RSA) is a reliable option in case of primary severe bony deficits or for revision of a TSA with a failed glenoid component. [27, 28]
This seems to work better due to the inherent medialisation of the center of rotation of the shoulder joint which decreases significantly the lever arm of the shoulder muscles resulting in decrease of the rocking horse phenomenon. This system allows a reconstruction of the glenoid whereby the bone graft is not only fixed with the baseplate by the long central peg but also by locking screws which can be divergent and aim to the native scapular bone. This construction is proven to enhance the primary stability.[29] (Figure 3)

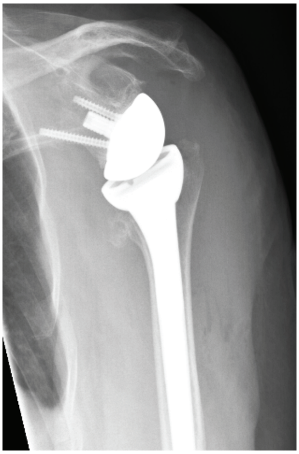

Figure 3: Reversed total shoulder arthroplasty.

The fixation of a bone graft and/or a glenoid component can be highly problematic due to lack of sufficient bone of the vault. In these cases we need bone for fixation beyond the glenoid vault. An anatomy study in 1996 from Anetzberger and Putz described the presence of radiological denser cortical bone areas in the spine of the scapula and near the lateral margin.[30] The sixth study of this thesis is a cadaveric study with the aim to identify strong bone areas in the scapula, which are reproducible, surgically accessible and can serve as a point of fixation for screws. These anatomic findings may expand the surgical possibilities for total shoulder revisions, and may be used to improve current screw fixation designs. (Figure 4)

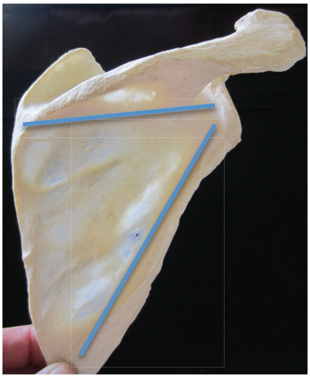

Figure 4: Areas of strong bone in the scapula.

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7.2 Article 6. The Pillars of the Scapula

Clinical Anatomy 20:392–399 (2007)

ORIGINAL COMMUNICATION

The Pillars of the Scapula

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Total shoulder replacement has been shown to provide predictable pain relief and functional improvement in patients with glenohumeral arthritis. Loosening of the glenoid component remains the most frequent indication for revision surgery at long-term follow-up. The component most widely used is an all-polyethylene keeled or pegged design cemented to the glenoid cavity of the scapula. The glenoid is small and its cup-shaped morphology allows only a restricted site for limited fixation devices. This is particularly so in revision surgery where there are often large bony defects of the glenoid. In an anatomical study, we investigated the scapula in order to identify substantial bony pillars for better component fixation. Forty cadaveric shoulders (mean age 86, range 67–101) were dissected, the glenoids were denuded from cartilage, and the subchondral and cancellous bone was removed. Two bony pillars approaching the glenoid were consistently identified in all scapulae investigated. These pillars were outlined by three cortices and orientated to the circle formed by the rim of the inferior quadrants of the glenoid. One pillar is directed inferiorly near the margo lateralis and the other pillar is directed superiorly into the spine of the scapula. We defined these pillars in length and direction, and three-dimensionally located them in relation to the joint surface. This study demonstrated two bony pillars as important anatomical landmarks in the scapula. They were constant in presence, surgically accessible, and have not been described before. These results can be used as a guideline in the development of prosthetic designs to improve the fixation of glenoid components. Clin. Anat. 20: 392–399, 2007.

Key words: scapula; anatomy; prosthesis; glenoid

INTRODUCTION

Total shoulder arthroplasty (TSA) has proven to provide predictable improvement in pain and function in patients with a degenerative shoulder joint and an intact rotator cuff (Von Schroeder et al., 2001).

Compared to patients with a hemiarthroplasty (humeral head replacement), the patients with a TSA have been reported to have a better stability, less pain, and increased mobility in cases of sufficient glenoid bone stock and a functional rotator cuff (Sperling et al., 1998; Gartsman et al., 2000; Kelly and Norris, 2003; Bishop and Flatow, 2005). If the rotator cuff is deficient a reversed prosthesis can be a valuable alternative in selected patients (Sirveaux et al., 2004).

Loosening of the glenoid component remains the most frequent indication for revision surgery of anatomical and reversed total shoulder prostheses at long-term follow-up (Godeneche et al., 2002; Sirveaux et al., 2004). Many alterations in component design, surgical techniques, and cementing techniques have provided already significant improvements. Today's gold standard for primary glenoid replacement is a cemented all-polyethylene component. There is still controversy over whether this should be a curved or pegged, or a conforming or non conforming component (Stone et al., 1999; Lazarus et al., 2002; Bicknell et al., 2003; Nyffeler et al., 2003; Mileti et al., 2004; Gartsman et al., 2005). In revision glenoid replacement, and glenoid and cuff deficient arthrosis, cemented anatomical glenoid replacement is not always possible

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Received 11 December 2005; Revised 18 April 2006; Accepted 30 July 2006

Published online 27 October 2006 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ca.20420

nor indicated. This is due to lack of sufficient bone stock, enhanced by osteolysis and residual holes left behind by pegs, keels or screws (Sperling and Cofield, 1998; Steinmann and Cofield, 2000; Antuna et al., 2001; Sirveaux et al., 2004).

An anatomical study by Anetzberger and Putz (1996) described the consistent presence of radiological denser cortical bone areas in the spina scapulae and near the lateral margin of the scapula. These areas appear to represent a structural adaptation of bone to mechanical loading. We assumed that they could offer a possibility for improved stable fixation of a prosthetic glenoid component. This can be valuable since the alternative fixation in the acromion and the coracoid processus (Coughlin et al., 1979) is not optimal, either because of the extreme variability of the superior glenoid (Prescher and Klumpen, 1997) and the acromion (Von Schroeder et al., 2001), or because of the bony erosion of the acromion in cuff tear arthropathy (Hamada et al., 1990).

The purpose of this study was to investigate the scapula in order to discover and define anatomical landmarks as certain 'strong bony pillars', which could offer an anatomical and solid base for glenoid component fixation in primary and in revision cases.

We attempt to define:

1. the anatomical characteristics of the inferior bony glenoid circle; diameter, version, inclination, and its relation to anatomical landmarks as coracoid process, acromion, and supraglenoid tubercle,
2. the presence of bony pillars in the scapula. Can length and direction be defined?
3. the relation between these pillars and the glenoid circle,
4. the surgical benefit of these pillars: are they surgically accessible? Are the pillars susceptible for screw placement?

MATERIALS AND METHODS

Specimen Preparation

Forty fresh-frozen human shoulders (20 left and 20 right shoulders; paired) were harvested from 14 female and 6 male cadavers. These specimen ranged in age from 67 to 101 years (mean: 86 years). They were stored at −20°C and thawed before dissection. Each shoulder was dissected to expose the shoulder joint. The deltoid muscle was removed and the integrity of the rotator cuff muscles, tendons, and long head of biceps were noted. The glenohumeral joints were disarticulated and the cartilage of the humeral head and glenoid were evaluated for degenerative changes, and classified according to Outerbridge (1961). No obvious posttraumatic findings or bony abnormalities of the glenoid were found, so all forty specimen could be included in this study. The humeral head and rotator cuff were removed. The glenoid was denuded from all cartilage and the remaining soft tissues were removed from the glenoid neck, coracoid process, and the acromion.

Of the 40 shoulders, 18 (45%) had mild (grade 1–2) degenerative chondropathy, and 22 (55%) had moderate to severe (grade 3–4) arthritic deformities.

An intact rotator cuff was seen in 55%. In 45%, a rotator cuff tear of which three massive tears, 13 supraspinatus and infraspinatus tears and two subscapularis tears was found. The long head of biceps was ruptured in eight cases. No clinical information was available of these specimens.

Morphologic Measurements

From each of the scapulae different morphologic measurements were obtained (Fig. 1): (1) superoinferior glenoid diameter, (2) anteroposterior glenoid diameter, (3) diameter of the best fitting circle on the inferior quadrants of the glenoid, (4) depth of the glenoid, (5) distance from the centre of the inferior circle to the supraglenoid tubercle (insertion of the long head of biceps), (6) distance of the articular surface to the base of coracoid, (7) distance of the articular surface to the base of acromion, (8) glenoid inclination, and (9) glenoid version.

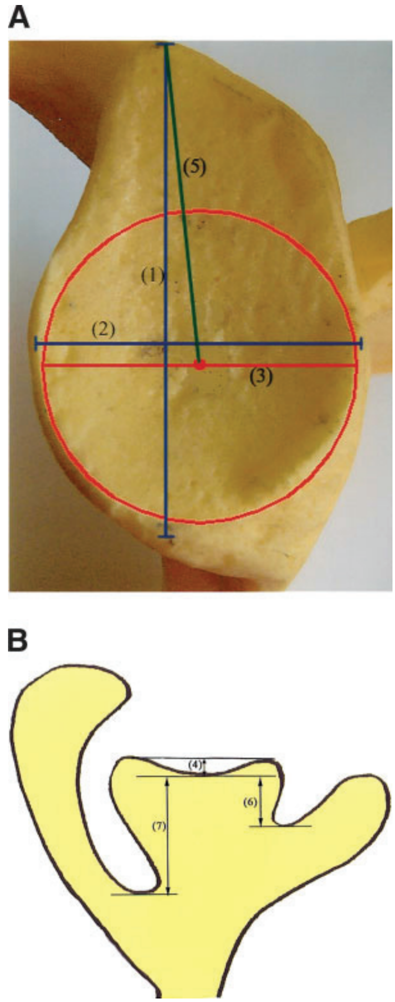

Fig. 1. Diagram showing morphologic measurements. (1) Superoinferior glenoid diameter, (2) anteroposterior glenoid diameter, (3) diameter of the best fitting circle on the inferior quadrants of the glenoid, (4) depth of the glenoid, (5) distance from the centre of the inferior circle to the supraglenoid tubercle, (6) distance of the articular surface to the base of coracoid, (7) distance of the articular surface to the base of acromion. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

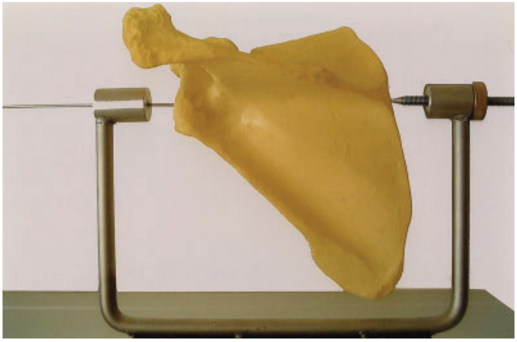

Fig. 2. Scapula holder used to measure the glenoid version and inclination according to the method of Churchill et al. (2001). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

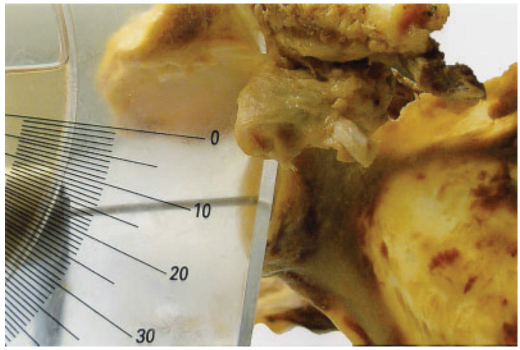

Fig. 3. Version and inclination were measured with a spirit-level goniometer. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Measurements of the superoinferior and the (widest) anteroposterior diameter of the bony glenoid were done with sliding calipers, precise up to 0.1 mm.

With an architect's device, the best fitting circle was defined on the denuded inferior glenoid rim and the diameter was determined, as described by De Wilde et al. (2004). The centre of this circle was marked with a marker pen. At this point the depth of the glenoid was measured. This implied the distance between the surrounding glenoid rim and the subchondral bone at the centre of the inferior circle.

At the centre, a 2.2 mm drill-bit was drilled to a depth of approximately 1 cm and left in place together with the architect's circle device. The most prominent tip of the supraglenoid tubercle was marked. The distance of this tip to the centre of the circle was measured. The distance from the base of the coracoid to the surface of the circle was measured, and the same was done from the base of the acromion. The depth of the glenoid was deducted from the latter measurements. So calculated values of the linear distance from the subchondral bone to the base of the coracoid and acromion were obtained.

Each scapula was placed in a custom-made holder (Fig. 2) and the inclination and version of the glenoid were measured according to the method described by Churchill et al. (2001) and Kwon et al. (2005).

A pin was placed in the previously drilled centre of the inferior circle. Another pin was positioned at the junction of the scapular spine and the medial scapular border. The scapula was rotated until the inferior angle was either parallel or perpendicular to the horizontal and respectively the version and the inclination were measured with a spirit-level goniometer (Fig. 3). Retroversion was defined positive and anteversion negative; a positive inclination was marked superiorly.

Preparation and Measurement of the ''Pillars''

After taking all measurements of anatomical parameters and landmarks, the glenoid was emptied centrally in the defined inferior circle with a large hollow drill with a radius of 19 mm, and a curette. The spongious bone was removed until the surrounding cortex was reached and three different tunnels bordered by cortex were visualized; in the coracoid base, in the spina scapulae, and close to the margo lateralis. These tunnels were cleaned with small rongeurs, curettes, and a decalcifying substance, as deep as possible (Figs. 4a and 4b). The tunnels, all bordered by strong cortical bone, seem to represent ''bony pillars'' radiating from the level of the glenoid into the scapula.

A designed copper circle with a diameter of 21 mm was fixed onto the remaining edges of the inferior glenoid with small Kirschner-wires (k-wires). From within this circle 2 mm k-wires were placed centrally into the pillars and drilled until they perforate a distant cortex. It was immediately clear that placing a k-wire in the center of the pillar to the coracoid process would be too steep to be surgically accessible. Therefore in the further study two k-wires were used; one was placed in the spina scapulae and one in the lateral pillar. The designed copper circle was divided in quadrants by an accessory device (Fig. 5). This allowed orientation of the k-wires in the different quadrants. The length of the k-wires in the scapula was measured from the level of the circle to the location of perforation of the distant cortex (Fig. 6). The angles between the k-wires and the level of the circle were measured in two planes (Fig. 7). The length measurements were made with the sliding calipers. For the angular measurements the spirit-level goniometer was used.

Statistical Analysis

Statistical analysis was performed to detect any significant differences in the length measurements and the angular measurements of the k-wires among sides, sexes, age, inclination, and version of the glenoid.

In particular, an analysis of variance (ANOVA) was conducted, in which the first order coefficient of a linear regression was investigated by means of a t-statistic (note that this resembles performing a Student-t test on the populations of shoulders differing in one of the aspects mentioned above). A confidence level of 95% was used to identify any possible significant differences.

RESULTS

Morphological Measurements

The measured glenoid orientation was $3.3^\circ \pm 2.7^\circ$ (mean and one standard deviation) of retroversion (range, 11° of ret-

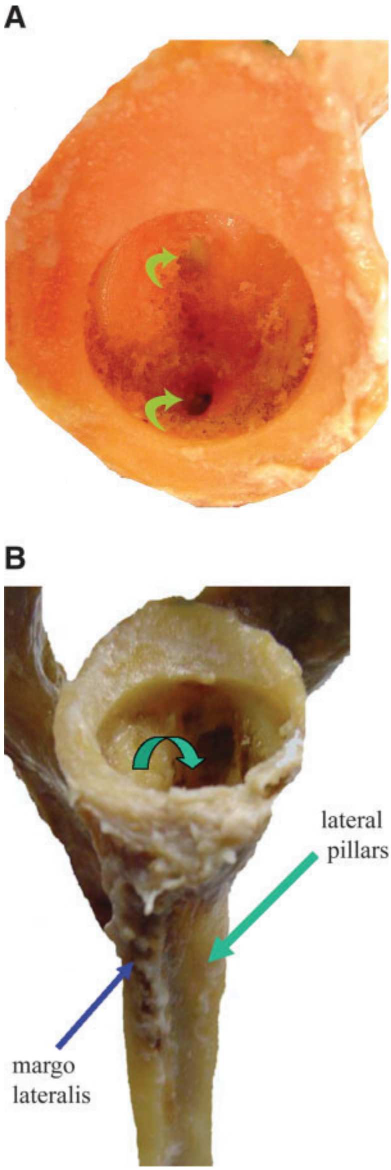

Fig. 4. Specimen of an emptied glenoid (**A**) showing entrance to spina and lateral tunnels (or ''pillars''). **B:** Note that the lateral pillar projects anterior and medial from the margo lateralis. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

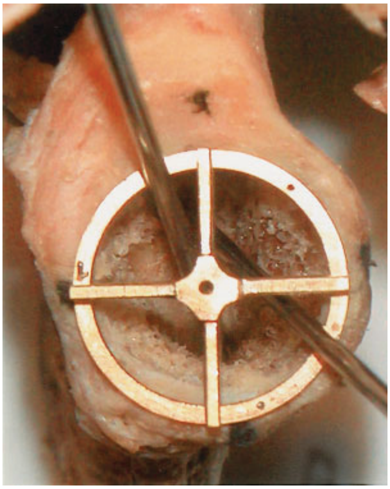

Fig. 5. Orientation of k-wires in quadrants of inferior circle. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

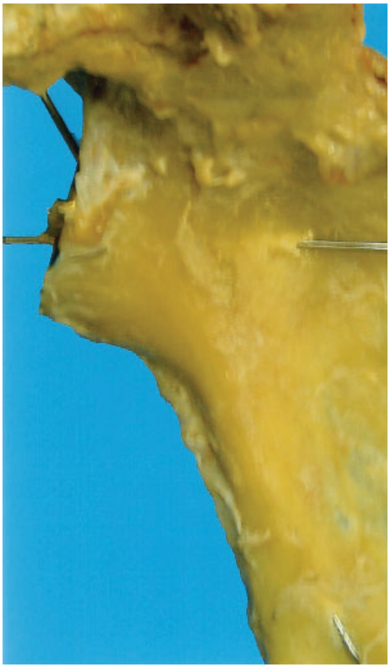

Fig. 6. Length measurements; from the level of the circle to the place of exit through distant cortex. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

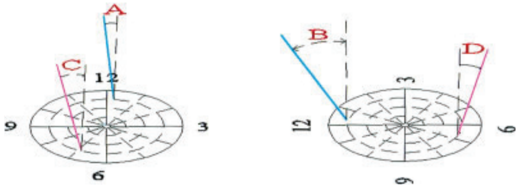

Fig. 7. Diagram showing angular measurements of the two different k-wires. Angles A and B represent the angles in the transversal and frontal plane for the lateral pillar, respectively; Angles C and D represent the angles in the transversal and frontal plane for the spina pillar, respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

roversion to 6° of anteversion), and an inclination of 7.1° ± 3.5° (range 1°–16°).

The average dimensions of the glenoid in the superoinferior and anteroposterior directions were 35.9 ± 3.6 mm (range 30–44 mm) and 27.2 ± 3.0 mm (range 23–33 mm), respectively. No significant differences in version or inclination were found between ages, sexes, or sides. There were no significant differences in version and inclination between groups with mild or moderate (grade 1–2) to severe (grade 3–4) arthritic deformities, or between shoulders with or without rotator cuff tears.

The mean diameter of the best fitting inferior circle measured 26.5 ± 3.7 mm (range 23–34 mm). The mean depth of the glenoid was 3.4 ± 1.2 mm (range 0.5–5.5 mm).

The mean distance of the articular surface to the base of the coracoid process was −3.9 ± 1.7 mm (range −0.75 to −7.5 mm). This means that the deepest area of the subchondral bone of the glenoid was situated medially compared to the base of the coracoid in all scapulae.

The mean distance of the articular surface to the base of acromion was 15.0 ± 2.3 mm (range 10−20.5 mm). The mean distance between the centre of the inferior circle and the supraglenoid tubercle was 22.1 ± 2.8 mm (range 17–28 mm).

No significant differences in depth of the glenoid or distances to coracoid base, acromion base, or supraglenoid tubercle were found between ages, sexes, sides, version, or inclination.

Length and Orientation of the Pillars

The length measurements show considerable ranges for both pillars (Fig. 10). The mean length of the spine pillar was 46 ± 10.7 mm (range 31–79 mm). The lateral pillar measured 97 ± 28.4 mm (range 35–160 mm).

The orientation of the pillars in relation to the articular surface of the inferior glenoid is clearly depicted. They approach the glenoid in constant locations as shown in Figure 8. The spine pillar intersects at the anteroinferior quadrant; the lateral pillar intersects at the posterosuperior quadrant.

The direction of the pillars in relation to the articular surface of the glenoid was measured in two planes. Figure 8 shows the angular measurements of the two different k-wires. Angles A and B represent the angles respectively in the transversal and frontal plane for the lateral pillar; Angles C and D for the spina pillar respectively in the transversal and frontal plane. The direction of the spine pillar starting from the articular surface is 15° ± 7.8° (range 1–31) to posterior in the transversal plane and 24° ± 5.8° (range 12–36) to superior in the frontal plane.

The direction of the lateral pillar is 0° ± 5.0° (range −11 to 17) in the transversal plane and 34° ± 6.2° (range 24–47) to inferior in the frontal plane. The magnitude of the angles is shown in Figures 9a–10d.

No statistically significant differences in the length of the pillars and their angles of coordination among sides, sexes, age, inclination, and version of the glenoids were detected.

DISCUSSION

Restoration of the glenoid anatomy seems to be important in primary and revision prosthetic shoulder surgery to obtain a functional improvement (Levine et al., 1997; Gartsman et al., 2000; Antuna et al., 2001). Symptomatic glenoid component loosening is the most common reason for revision surgery leading often to severe glenoid bony deficiencies (Stone et al.,

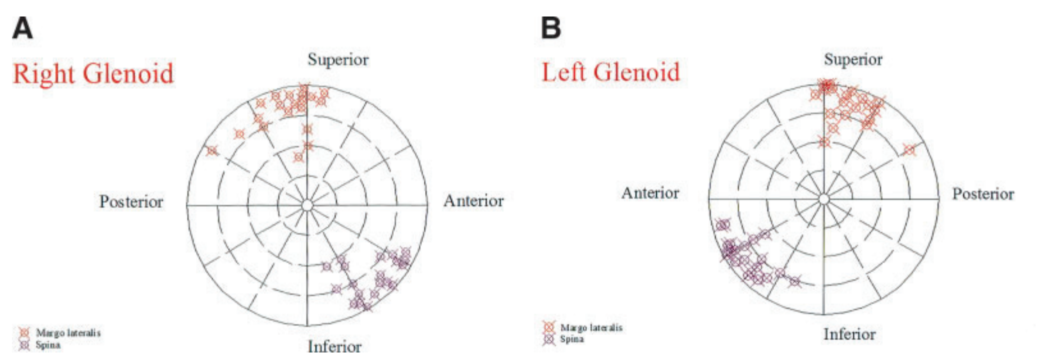

Fig. 8. Diagram of right (**A**) and left (**B**) glenoid. The location of the two pillars intersecting the articular surface of the inferior glenoid was registered. It is clearly shown that the lateral pillar extends at the superoposterior quadrant, and the spina pillar at the anteroinferior quadrant. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

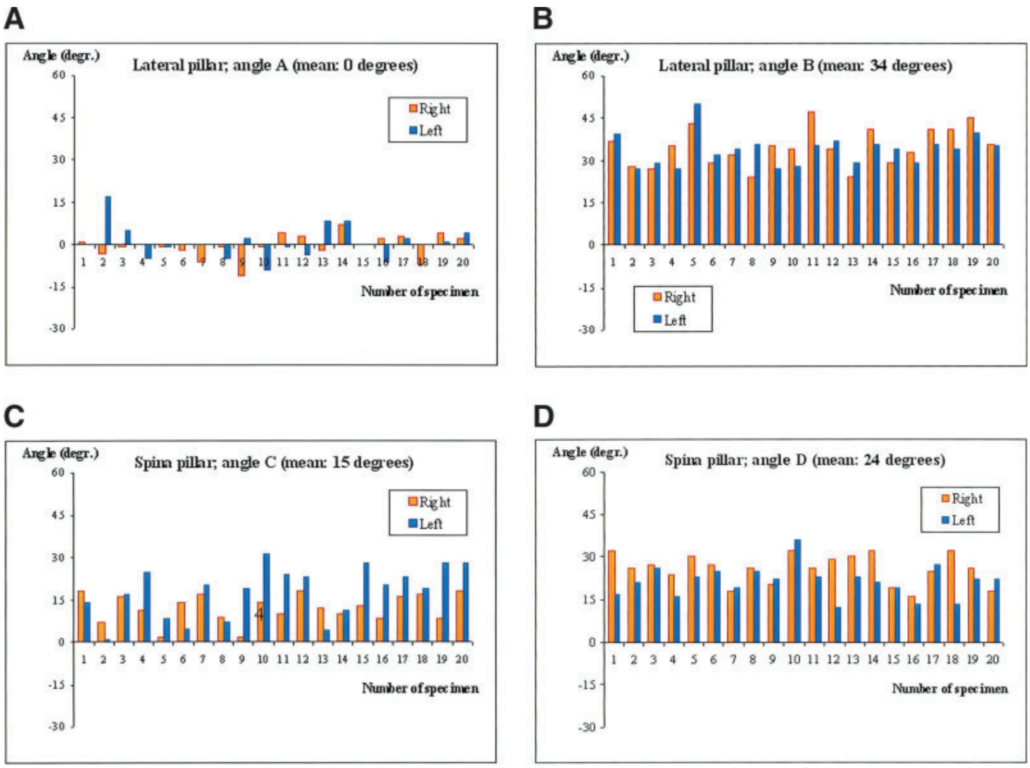

Fig. 9. Angulation of the lateral pillar (**A, B**) and spina pillar (**C, D**). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

1999; Antuna et al., 2001; Norris and Ianotti, 2002). This can be caused by unequal stress distribution as occurs in instability or absence of the rotator cuff or other causes like infection, inadequate primary bone stock, and poor initial fixation (Ibarra et al., 1998; Stone et al., 1999; Gartsman et al., 2000; Antuna et al., 2001; Wirth et al., 2001; Boileau et al., 2002; Godeneche et al., 2002; Lazarus et al., 2002; Bicknell et al., 2003; Nyffeler et al., 2003; Mileti et al., 2004; Gartsman et al., 2005). To improve this initial fixation precise knowledge of the glenoid geometry is essential. Numerous studies have characterized the macro- and microscopic anatomy of the glenoid. The size, shape, surface area, thickness of articular cartilage, inclination and version of the glenoid articular surface, and bone density distribution have all been extensively described in normal and osteoarthritic shoulders (Randelli and Gambrioli, 1986; Friedman et al., 1992; Iannotti et al., 1992; Lintner et al., 1992; Soslowsky et al., 1992; Anetzberger and Putz, 1996; Prescher and Klumpen, 1997; Walch et al., 1999; Churchill et al., 2001; Couteau et al., 2001; Von Schroeder et al., 2001; Checroun et al., 2002; Lehtinen et al., 2004). There is no consensus on the design of the glenoid plate (oval, egg-shaped, flat or curved backing) or on the anchoring system (pegs, keels, screws, cement, all- polyethylene or metal-backed) to be used (Anetzberger and Putz, 1996; Prescher and Klumpen, 1997; Ibarra et al., 1998; Anglin et al., 2000; Steinmann and Cofield, 2000; Boileau et al., 2002; Checroun et al., 2002; Lazarus et al., 2002; Bicknell et al., 2003; Nyffeler et al., 2003; Churchill et al., 2004; Mileti et al., 2004; Gartsman et al., 2005).

These issues are extremely important if it comes to fixation of a component in a glenoid with sufficient bone stock. In revision surgery, the loss of bone stock is often so severe due to osteolysis and residual holes left behind by pegs, keels or screws, that reimplantation of a new component is not possible and bone grafting of the deficient glenoid becomes inevitable.

In certain cases anatomical restoration of the glenohumeral unit is not feasible and an inversed total shoulder arthroplasty is indicated, for which a strong initial fixation of the glenoid component seems to be particularly important (Harman et al., 2005).

A study by Anetzberger and Putz (1996) described two supporting pillars of the scapula (the lateral border and the spina scapulae), which appear to represent a structural adaptation of bone to mechanical loading. These areas of stronger bone can be of great surgical interest for the design of the anchoring system of prosthetic glenoid components. The present study could confirm the presence of two firm pillars approaching the glenoid cavity and articular surface.

The 40 cadaver shoulders examined seemed to represent an average population since the values of morphologic mea-

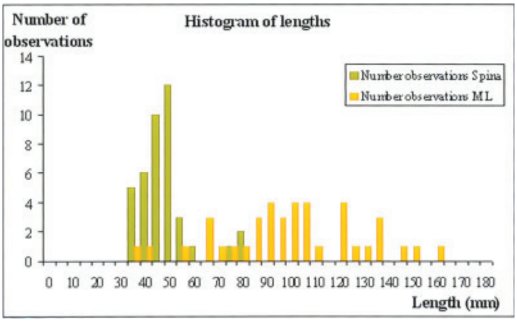

Fig. 10. Histogram of lengths of both pillars. Note that the shortest length measurement is still over 30 mm. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

surements as size, version, inclination, and diameter of the inferior circle of the glenoid are comparable to other reports found in the literature (Randelli and Gambrioli, 1986; Friedman et al., 1992; Iannotti et al. 1992, Soslowsky et al., 1992; Anetzberger and Putz, 1996; Prescher and Klumpen, 1997; Walch et al., 1999; Churchill et al., 2001; Couteau et al., 2001; Von Schroeder et al., 2001; Checroun et al., 2002; De Wilde et al., 2004), despite the fact that we worked with specimens with a high mean age (86 years).

In the present study it was shown that the glenoid subchondral bone was, in all cases, located medial to the base of the coracoid process (-3.9 ± 1.7 mm) and lateral to the base of the acromion (15.0 ± 2.3 mm). In an anatomical study of 140 shoulders (96 cadaver shoulders and 44 MRI images of living patients) by Iannotti et al. (1992), the distance between the base of the coracoid process and the deepest point of the glenoid articular surface was 1.3 ± 2.4 mm. So the joint surface is merely located lateral to the base of the coracoid. No signs of arthritis were found in Ianotti's series and the mean age was 75 years. This may explain the difference with our measurements since our population had a higher mean age (86 years) with more extensive degenerative erosion (55% grade 3–4 degenerative changes) with subsequent medialisation of the articular surface. Besides that the cartilage was removed to the subchondral bone in our study before measurement. Another possible cause of error can be the fact that the transverse scapular axis defined by Churchill et al. (2001) differs slightly from the axis defined by Friedman et al. (1992) in which the pin was placed in the center of the glenoid. We assumed that there is no difference in measuring the version to this axis since Churchill et al. (2001) did not find a significant difference in version if he changed the scapular rotation in his study.

In primary glenohumeral arthritis the erosion is predominantly central or posterior (Walch et al., 1999) without superior migration of the humeral head, and so there is preservation of the supraglenoid tubercle (insertion site of the long head of biceps). This tubercle was preserved in all scapulae in this study and is a reference point to define the centre of the inferior circle (mean distance 22.1 ± 2.8 mm).

De Wilde et al. (2004) suggest in their study that the inferior glenoid cavity is the ''polar cap'' and the superior part of the glenoid is an oversized tubercle much more variable in shape. The center of the inferior cavity is situated in the strongest part of the glenoid bone and considered important in glenoid component fixation.

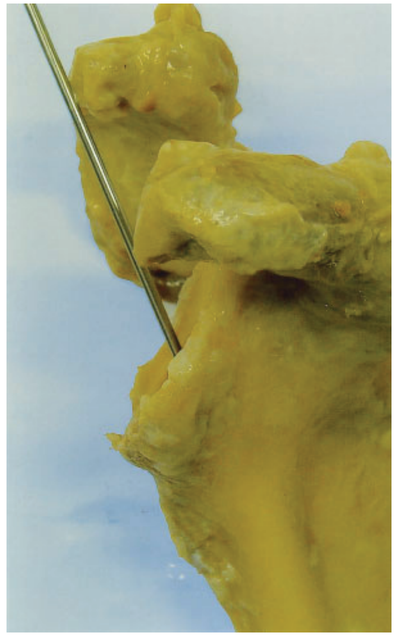

Fig. 11. The lateral pillar is accessible from superior, and always lateral to the acromion. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Landmarks as the coracoid process, acromion, and supraglenoid tubercle are, in particular in case of severe bone loss, of great value to localize the correct position of the joint line and to build up the glenoid to the right level. Preoperative computed tomography is of major importance in determining the three dimensional (3D) characteristics of the bony glenoid circle, of the pillars described, and of their relative position (Randelli and Gambrioli, 1986). If it would be possible to determine the direction and length of the pillars preoperatively with 3D images, these pillars can be used for accurate screw placement. The fixation of a glenoid component with two divergent screws in two bony pillars can have major advantages: (1) the screws are placed in physiologically strong bone; (2) the screws can be integrated in a locking-compression plate system; (3) the considerable length of the pillars allows long screws, possibly perforating a distant cortex; (4) if revision is necessary, bone loss of the glenoid will be minimal since no bone substance for accommodation of pegs or keels has been removed.

The third pillar found was located in the coracoid base. Due to its steep superior direction starting from the inferior glenoid circle, it was considered surgically inaccessible through conventional deltopectoral approach.

In both the spine and lateral margin pillar, the k-wire could be placed without interference in its approach by the acromion as shown in Figure 11. We believe that both these pillars are surgically accessible through a deltopectoral approach.

CONCLUSIONS

The present study could determine the existence of three osseous pillars in the scapula which are surrounded by cortex and approach the glenoid cavity. Two of these pillars are surgically accessible and their existence can have important implications in the development of prosthetic glenoids and of computer assisted surgery. A glenoid implant base plate with a screw fixation system can be designed for the use in anatomical and in inversed shoulder prostheses, and for revision cases with severe bone deficiency. Further study is warranted to optimize the knowledge of this surgical anatomy.

ACKNOWLEDGMENT

The authors thank Marc Pot for developing and producing the scapula holder and the quadrant measuring device.

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Chapter 8 Interpositioning arthroplasty

8.1 Introduction

The glenoid prosthesis remains the weak link in the success story of the total shoulder prosthesis, and this is particularly so in the younger patient holding the risk of accelerated loosening of the glenoid component.[1,2,3] An alternative to the young patient with symptomatic glenohumeral arthritis is an isolated humeral hemiarthroplasty. However, in several large series, hemiarthroplasty has inferior results compared to total shoulder arthroplasty with regard to pain relief, range of motion, strength, and functional outcome. The progression of glenoid arthritis and medialisation of the joint line results in pain and stiffness requiring revision to a TSA.[4]

Matsen introduced concentric reaming of the glenoid fossa to a spherical concavity (the radius of curvature of the reamer is 2 millimeters larger than that of the prosthetic humeral head) without placement of a glenoid component. This so-called "ream and run" procedure induces remodelling of the glenoid to a concentric smooth surface covered with a fibrocartilagenous layer. This can offer significant functional improvement, similar to total shoulder arthroplasty, although the time to recover may take longer.[5,6] Even in cases of glenoid biconcavity, retroversion, and posterior subluxation of the humeral head, the ream and run procedure can correct humeral centering on the glenoid, and improve comfort and function without the risk of glenoid component failure.[7]

The combination of a humeral head arthroplasty and biologic resurfacing of the glenoid is an alternative technique to avoid complications associated with the conventional glenoid component. An interposition soft tissue graft is thought to protect the glenoid from erosion, at least temporary. In the past different kinds of grafts have been used; synthetic grafts (silicone, nylon), autografts (anterior capsule, fascia lata, periosteum) and allografts (humane: dura mater, achillestendon, skin, menisci; bovine; porcine), in different joints (carpometacarpal joint of the thumb, hip, elbow, temporomandibular joint).[8] In the shoulder the use of achilles tendon allografts, meniscal allografts and dermal allografts is described.
Results are varying, but overall there is limited improvement in patient outcomes and a relatively high revision rate at medium-term follow-up. The progressive decrease in glenohumeral joint space noted radiographically raises concern for both the functional benefits and the durability of the glenoid bone-sparing effect; therefore biologic resurfacing of the glenoid with humeral head prothesiology should be used with caution.[9-15]

The use of soft tissue interposition arthroplasty, without humeral head replacement, as a treatment of glenohumeral arthritis is an attractive alternative to avoid or delay traditional hemi or total shoulder arthroplasty, particularly in young active patients who might otherwise require revision of an implant placed at an early age.

Currently this can be performed arthroscopically and this offers the major advantage of sparing the subscapularis tendon.[16, 17] To date, few studies have specifically examined soft tissue interpositioning without hemiarthroplasty of the shoulder.[18, 19] The aim of the 7th and final study of this thesis is to evaluate the results of a clinical study of biological resurfacing of the glenoid with either a meniscal allograft (Figure 1) or a Graft Jacket (Figure 2) (Graftjacket, Regenerative Tissue Matrix, Wright Medical Technology, Inc., Arlington, TN).

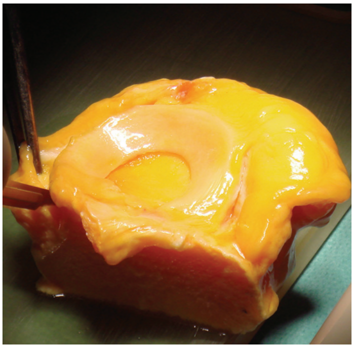

Figure 1: Lateral meniscal allograft.

Figure 2: Graft jacket: Human skin allograft.

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8.2 Article 7. Arthroscopic treatment of the young degenerative shoulder joint; is there a role for interpositioning arthroplasty?

This article is accepted for publication in Acta Orthopaedica Belgica (March 17, 2015).

Arthroscopic treatment of the young degenerative shoulder joint; is there a role for interpositioning arthroplasty?

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Arthroscopic treatment of the young degenerative shoulder joint; is there a role for interpositioning arthroplasty?

Abstract

Purpose: We evaluate our experience with arthroscopic interpositioning arthroplasty as a treatment of the young degenerative shoulder joint.

Material and Methods: Between 2007 and 2009 ten patients were treated with either a dermal allograft or a meniscal allograft.

Results: In seven patients the graft failed and within 13 months these were revised to a total shoulder arthroplasty. Three patients are still satisfied after 7 to 8 years follow-up.

Conclusions: Biologic resurfacing of the glenoid may have a role in the management of glenohumeral arthritis in the young and active patient, but the optimal graft and pathology still need to be defined.

Introduction

A painful arthritic shoulder in a young and active patient can have a diverse etiology. Most frequent causes are post-traumatic (fracture or instability) or postsurgical (persistent instability, capsulorrhaphy arthropathy, hardware problems), but causes as avascular necrosis, glenoid dysplasia or a localized degeneration do occur. Chondrolysis has also been associated with the use of intraarticular local anesthetic pain pumps and with the use of thermal energy probes *(13).* The treatment of this pathology is challenging and once conservative treatment fails there are two surgical options, either arthroscopic debridement of the glenohumeral joint or prosthetic surgery. The latter needs to be postponed as long as possible because of the expected need for a revision of the shoulder prosthesis during his or her lifetime. Bartelt and Sperling studied outcomes of hemi arthroplasty and total shoulder arthroplasty (TSA) in patients less than 50 to 55 years old and within a follow-up of 5 years they found an unacceptable rate of symptomatic glenoid erosion and glenoid loosening *(3,20).* A study by Dillon showed that patients younger than 59 have a two times higher risk of revision at early follow-up than older patients *(9).* Clinical studies show successful short to mid-term results of arthroscopic debridement of the cartilage with microfracture and capsular release *(17, 21, 24).* If this fails biological resurfacing of the glenoid can be an alternative to prosthetic surgery in a young and active patient *(1, 5, 6).* This procedure preserves the glenoid bone stock and it can be performed as a minimal invasive arthroscopic procedure thereby sparing the subscapularis tendon. In this article we evaluate our experience with a prospective randomized controlled trial investigating clinical and radiographic outcomes of arthroscopic soft tissue interpositioning arthroplasty with either a meniscal allograft or a dermal allograft as a treatment for severe osteoarthritis of the glenohumeral joint after failed conservative treatment.

Material and Methods

This is a prospective randomized controlled clinical trial investigating clinical and radiographic outcomes of interpositioning arthroplasty.

Material

Young and active patients with painful non-inflammatory osteoarthritis of the shoulder, a spherical humeral head and not responding to conservative treatment for at least 3 months were included in the study. Only patients motivated to sustain a long rehabilitation were selected. Exclusion criteria were inflammatory arthropathy, avascular necrosis, rotator cuff lesions, previous arthroplasty, persistent glenohumeral instability and infection.
Patients were randomized for treatment with either a meniscal allograft or a dermal allograft.

The grafts we used were lateral meniscal allografts from the tissue bank from the University hospital of Ghent, Belgium, or processed human dermal allografts (Graftjacket, Regenerative Tissue Matrix, Wright Medical Technology, Inc., Arlington, TN).

Methods

Preoperatively clinical evaluation included a Constant Murley score and a VAS score *(7).* The grade of osteoarthritis was classified on anteroposterior and lateral X-rays according to the Kellgren and Lawrence grading system (Grade 0: no radiographic features of osteoarthritis are present; Grade 1: doubtful joint space narrowing and possible osteophytic lipping; Grade 2: definite osteophytes, unimpaired joint space; Grade 3: multiple osteophytes, moderate diminution of joint space; Grade 4: large osteophytes, marked joint space narrowing, severe sclerosis and definitely bony deformity) *(11).* Preoperative CT images were used to define glenoid morphology according to Walch *(23).*The retroversion was measured as described by Friedman *(10).* An examination under anesthesia was performed to measure the passive range of motion of the shoulder. Peroperatively the cartilage lesions were graded 1 to 4 according to Outerbridge *(15).* (Figure 1 and 2) Postoperatively clinical evaluation including scores was done after 1, 6, and 12 months, and at final follow up at 2 years. X-rays were taken immediately postoperative, and at clinical follow-up data. At one year a MRI scan with Gadolinium administered intravenously was planned to evaluate positioning and ingrowth of the graft. If a patient had continuous severe pain and no noticeable functional improvement after 4 to 6 months they were withdrawn from the study and treated with a TSA. Patients who had a conversion to a TSA within 2 years after placement of the graft jacket were considered as failures of the arthroscopic treatment. All patients consented prior to being included in the study. Approval of the local ethical committee was received.

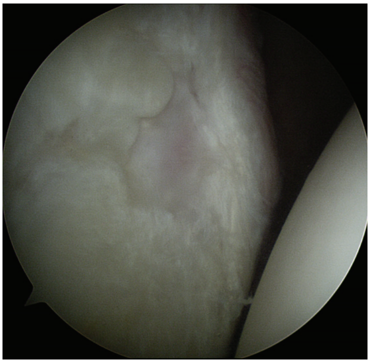

Figure 1: Unipolar lesion on the glenoid. Outerbridge Grade 4.

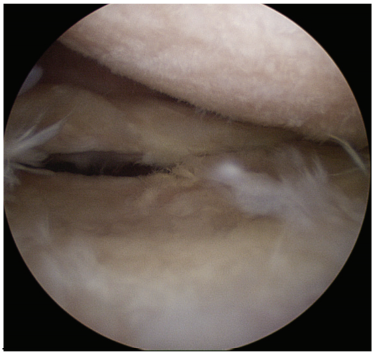

Figure 2: Bipolar lesion of glenoid and humeral head. Outerbridge Grade 3 to 4.

Surgical Procedure

Surgery was performed under general anesthesia in a lateral decubitus position with longitudinal and lateral traction. All patients received cefazoline according to protocol pre- and postoperatively for 24 hours. Standard arthroscopic portals were used: posterior, anterosuperior and anteroinferior. A thorough debridement of the cartilage, removal of loose bodies and a release of the rotator cuff interval were performed using a shaver and a VAPR electrode (DePuy Synthes Mitek Sports Medicine). If the passive range of motion was limited due to a capsular contracture then a synovectomy and a circumferential capsular release were performed. The entire glenoid surface was denuded from cartilage and with a burr microfracture of the subchondral bone was done. (Figure 3) In case of a biconcave glenoid we planned to remove the intraarticular rim in an attempt to correct the glenoid version. The labrum, if still present, was kept unattached since it can be used for fixation of the graft. Next the size of the glenoid was estimated with a calibrated probe. Preparation of the graft was done outside the joint. If a graft jacket was used it was cut to the right size and a circumferential running suture was placed to reinforce the edge. If a lateral meniscus was used the horns were sutured together and overlapped depending on the size. (Figure 4) Either graft was armed with six sutures, three anteriorly and three posteriorly. The three posterior sutures were also used as traction sutures to introduce the graft through the anterior portal into the joint, as described by Bhatia *(4).* Graft alignment was done under arthroscopic control until the entire surface was covered. Next the graft was sutured to the labrum or to the capsule. Loosening the traction on the arm stabilizes the graft by the pressure of the humeral head into the glenoid. (Figure 5 and 6) The postoperative protocol existed of 3 weeks of immobilization in a sling after which gentle auto active movement can start.

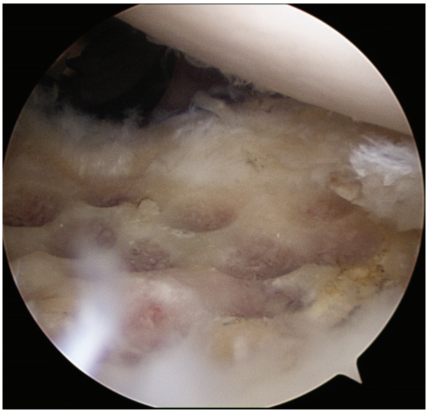

Figure 3: Chondroplasty of the glenoid surface

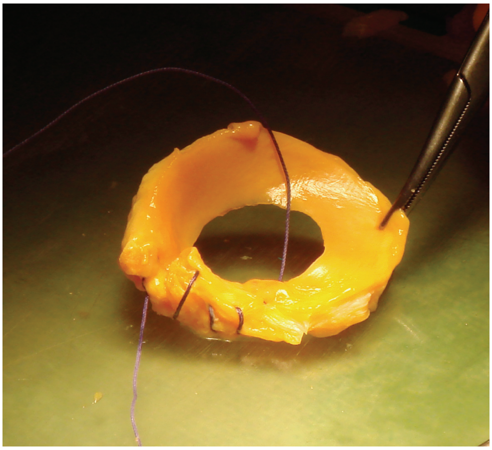

Figure 4: Lateral meniscal allograft

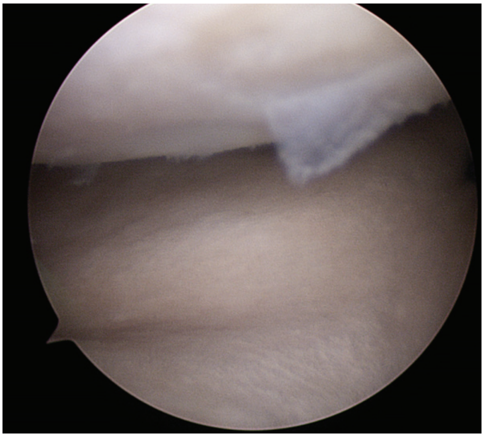

Figure 5: Graft jacket in place

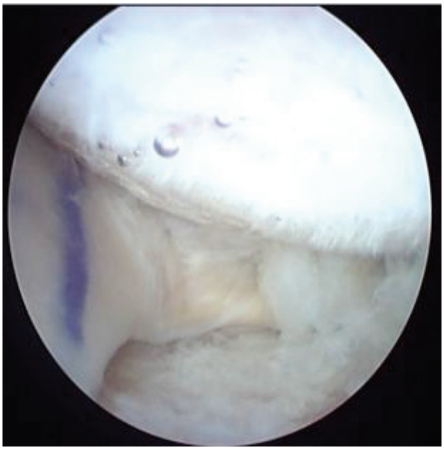

Figure 6: Meniscal graft in place

Results

Between 2007 and 2009 ten patients were included in the study, 6 males and 4 females, with an average age of 44 (19 to 57). Four lateral meniscal allografts and 6 graft jackets were implanted, but due to a lack of meniscal allografts the study was aborted early. Seven patients had previous instability surgery (4 patients had open capsular shifts, 1 patient had an arthroscopic stabilization, and 1 patient had an arthroscopic stabilization and a Latarjet procedure), 3 patients had no surgery on the shoulder before. Preoperatively all shoulders had limited passive range of motion due to a capsular contracture and the average Constant score was 34 (15 to 46), the VAS 29 (28 to 33). Seven patients were classified with osteoarthritis grade 3, 2 patients with grade 2, and 1 patient with grade 4. The CT images showed 5 type A1 glenoids, 4 type B1 glenoids and 1 type C glenoid. The retroversion averaged 14 degrees (2 to 55).

Peroperatively all patients had severe glenoid cartilage damage graded 3 to 4 according to Outerbridge. The humeral head was in 3 patients graded as 1 to 2, and in 7 patients 3 to 4.

Within 13 months after the interpositioning procedure 7 patients underwent a revision to a TSA. All of them had severe damage to the humeral head. One patient (with previous stabilisation and Latarjet) had an infection after the arthroscopic procedure and was treated with arthroscopic debridement and a TSA at a second stage. Three patients are still satisfied at the latest follow-up, although on X-ray OA is deteriorating with diminishing of joint space and enlarging of osteophytes. Of these 1 patient has a dysplastic glenoid and was 19 years old at the time of surgery. He is now a social worker and able to do his job. The Constant score at 8 years follow up is 52. The second patient had severe postraumatic cartilage lesions after a skiing accident and he was 44 at the time of surgery. He is in an administrative job and still reasonably satisfied at 8 years follow up with a Constant score of 67. The third patient was 34 at the time of surgery, and treated with a lateral meniscal graft. (Figure 7 and 8) He was able to return to his job in a factory doing light manual work. The constant score at 2 years of follow-up was 56, and deteriorating, to 44 at 4 years of follow-up. At 1 year of follow-up an MRI scan with Gadolinium of 2 of the shoulders with graft was performed (1 patient refused). This showed small vascular channels in de edge of the meniscal graft. In the shoulder with the graft jacket a fibrocartilaginous layer was identified over the glenoid. Post-arthroplasty the mean Constant Score was 64 (from 61 to 68) at an average follow-up of 3,4 years.

Figure 7: Meniscal allograft; Preoperative X-ray.

Figure 8: Meniscal allograft; Postoperative X-ray.

Discussion

Clinical studies show successful short to mid-term results of arthroscopic debridement of the cartilage with microfracture and capsular release in patients with a residual joint space of more than 2 mm and an absence of large osteophytes. On average these patients have decreased pain and increased function from 9 months to nearly 3 years in approximately 80 to 90 % of cases *(17, 21, 24).* The results are less satisfying if the joint space is less than 2 mm and osteophytes are large *(12, 21, 24).* Millett combines debridement of the joint, capsular release, subacromial decompression and biceps tenodesis with removal of the inferior osteophyte in order to decompress the axillary nerve *(14).* The results are good in 85 % after 2 years. Despite the limited period of success and the high frequency of failures at the medium and long term of arthroscopic debridement, it seems that this type of treatment can be indicated in a younger active patient with concentric wear of the glenohumeral joint, a residual joint space of more than 2 mm, mild loss of range of motion, and after a failed conservative treatment for at least 3 to 6 months. The procedure is performed arthroscopically and consists of lavage of the glenohumeral joint, debridement of the cartilage and labral tears, removal of loose bodies, and a capsular release of 360 degrees. In case of cartilage lesions grade 3 or 4 stable margins should be created with a curette and microfracture of the defects is performed with a curved awl. It is not clear if it helps to remove the inferior osteophyte or to correct the biconcavity of the glenoid surface. Immediate exercises postoperatively are critical to avoid stiffness however strengthening exercises are avoided for 6 weeks.

If the degeneration is more severe with a joint space of less than 2 mm and if the cartilage defect is situated predominantly on the glenoid side a biological resurfacing of the glenoid as an interposition arthroplasty has been proposed as an alternative to prosthetic surgery. Savoie used the Restore patch (DePuy) in 20 patients with OA with a mean age of 32. A follow-up of

3 to 6 years resulted in 15 patients satisfied (75%) and 5 patients with a TSA (25%) after failure of the patch *(19).* De Beer used a Graftjacket on 32 patients with osteoarthritis with a mean age of 54. A mean follow-up of 4 years resulted in 23 patients satisfied (72%) and 9 failures (28%) of which 5 patients received a TSA *(8).* Both authors concluded that arthroscopic debridement and resurfacing of the glenoid is a minimally invasive option for treatment of glenohumeral osteoarthritis in the young and active patient with a potential for midterm success. It is considered a time buying procedure to postpone prosthetic surgery. Currently many commercialized processed grafts are available and of these the Restore patch (porcine small intestine submucosa) and the Graft Jacket show superior tissue remodeling *(6).* A Graft Jacket is decellularised human skin with minimal antigenicity, and the extracellular matrix in which the vascular channels are preserved for rapid repopulation and tissue ingrowth. It is a thicker structure than the Restore patch, with a large tensile strength optimising suture retention. Pennington performed arthroscopic resurfacing of the glenoid with a lateral meniscal allograft. He showed that this is technically possible and results are good on the short-term *(16).* Meniscal allografts have proved their beneficial effect in the knee and remodelling of the meniscus by synovial cells has been shown *(2, 18, 22).* Vascular ingrowth was also found on the MRI of the meniscal allograft in this study. A lateral meniscus is particularly suited to fit the glenohumeral joint because of the profile of a wedge and the circular shape if the horns are sutured together. Our results, 7 failures and 3 satisfied patients for more than five years, are less satisfying than the reports in literature. We had to convert 7 patients to a shoulder replacement within 13 months; all of them had severe damage of the humeral head, together with chondropathy of the glenoid cartilage preoperatively. Seven of the patients in our study had instability surgery in the past, including 2 patients with a positive outcome after the resurfacing procedure. The patient with type C dysplastic glenoid and retroversion of 55 degrees is one of the 3 satisfied patients, and both other patients had grade

2 cartilage lesions on the humeral head. A difference with the populations of De Beer and Savoie is that these study groups consisted mainly of patients with primary osteoarthritis without previous surgery. The amount of subluxation and width of the joint line seem not to interfere with the outcome, maybe because the most important therapeutical aim for those patients is pain relief and to a lesser degree improvement of motion. All 'successful' patients in our series showed significant shoulder stiffness. We are aware of the shortcomings of this study; the series of 10 patients is too small to draw explicit conclusions from the results. We aimed to find out which patient and pathology would be best indicated for this type of surgery; the possible influence of glenoid version and biconcavity; the influence of humeral head damage; adherence, ingrowth and remodelling of a graft; durability; long term effect on the glenoid and if there is indeed lesser wear of the glenoid with preservation of the bone stock. Surgery was performed by a single surgeon (AK), and failures can be surgeon dependent. Nevertheless we believe our results suggest that biologic resurfacing of the glenoid may have a minimal and as yet undefined role in the management of glenohumeral arthritis in the young active patient over more traditional methods of hemiarthroplasty or TSA. This minimally invasive arthroscopic procedure permits to postpone prosthetic surgery in selected indications. Contraindications are large bipolar lesions and a deformed caput humerus for which other treatments like hemi arthroplasty or TSA have superior results.

To conclude: If conservative treatment fails arthroscopic debridement is a reasonable approach for treating early glenohumeral osteoarthritis in which the humeral head and glenoid remain concentric, and where there is still a visible joint space on an axillary radiograph. If this is not succesfull and the lesions are severe and predominantly on the glenoid side biologic resurfacing can be an option in selected patients. Further investigation is necessary to determine the optimal graft, the durability and the long-term effect on the glenoid bone.

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Chapter 9 Future considerations

An important theme of this thesis is the lack of orientation in the surgical approach of the glenoid. The orientation of the native glenoid plane related to the scapular plane was investigated, as were the consequences and accuracy of corrective reaming of an eroded glenoid. Reaming procedures seem not to be reliable and reproducible, partly because there is no accurate guiding, and partly because there is no agreement on how to determine the center, the direction and the quantity of reaming. And if the damaged glenoid is beyond reaming and a build up with grafts is needed, what points of fixation do we have and how can these be localised?

There is a lack of peroperative reference points guiding the surgeon in reconstruction of the native glenoid plane. Computer-assisted surgery was developed to optimize positioning of the glenoid, and it proved to be advantageous in accuracy and reproducibility.[1-4] However, disadvantages as added operation time and costs caused intraoperative navigation to become unpopular.

The 3 D reconstruction techniques have improved adequate measurement of bone loss and preoperative planning.[5,6] In addition it offers the possibility to develop patient specific instrumentation (PSI) based on 3 D models printed of the patient's anatomy. The PSI guides the positioning of a K-wire at the glenoid plane and this has been shown to improve accuracy of glenoid component positioning.[7-10] Obstacles to the accuracy of these 3 D prints are that these are bone models and do not take into account the soft tissue, labrum, cartilage and removed or fractured osteophytes, and the presence of soft tissue contractures, retractors and a humeral head interfering with the approach in real time surgery. Not every surgeon has access to this expensive technology, which is patient specific and therefore single use, adding even more costs to the procedure.

Augmented glenoids are developed to conserve more of the anterior glenoid bone and create less muscle shortening than with eccentric reaming. 3 D technology can guide in the design and printing of custom-made components allowing optimal glenoid reconstruction and screw fixation. The amount of reaming is minimised and the maximum amount of bone stock is preserved. This technique can have its use in reconstruction of severely damaged glenoids. [11]
Mobile bearing glenoids are under development to improve constraint and stability and at the same time preserve the sliding movement at the glenohumeral joint surface. Further clinical studies are necessary to validate these concepts.

Verstraeten and coworkers suggested extracorporeal guiding to assist in the reconstruction of the native glenoid plane.[12] This group developed an aiming device connecting the center of the inferior glenoid circle and the most medial scapular point. Three surgeons used this for central positioning of the K-wire on cadaveric scapulae and the results were compared with a virtual 3 D scan positioning on the same specimen. Outcomes were positive and with this device they succeeded in highly accurate positioning of the central K-wire on the glenoid, not influenced by the experience of the surgeon. The device was used in surgical practice to evaluate its usefulness. It requires more extensive sterile draping of the shoulder to reach the medial scapular border and a small extra incision at that point, but once it is placed it helped in manipulating the scapula so that better visualization of the glenoid was possible. If further development of an extracorporeal guide is undertaken this could lead to a device that is reusable in daily practice lowering the costs, and it can be used by less experienced surgeons with little additional surgical actions to master.

This extracorporeal aiming device utilizes 2 reference points on the scapula; the center of the best fitting inferior circle and the most medial scapular point. In eroded glenoids it may be problematic to recognize the inferior circular glenoid, however, the anterior glenoid is often preserved in primary osteoarthritis, and Verstraeten showed that three points situated at the native anterior glenoid rim can help in reconstruction of the inferior glenoid plane.[13] Additional reference points would improve the reliability of such a device and if we could add the most inferior scapular point this would improve the accuracy of reconstruction of the native glenoid plane. (Three points, on the most medial and the most inferior scapular point and the center of the glenoid circle, define the plane of the scapula.)

In a recent cadaver study we measured and evaluated the accuracy of various reference points of the scapula that are surgically accessible for clinical use. Measurements were done on 24 cadaveric shoulders with an intact cuff and intact glenohumeral joint. After removal of the humeral head and rotator cuff the glenoid was denuded from cartilage and the remaining soft tissues were removed from the glenoid neck, coracoid process and base, and the acromion. Each scapula was fixated in a custom-made holder held on 3 points defining the scapular plane; the center of the best fitting inferior circle, the most medial scapular point, and the most inferior scapular point.[14] (Figure 1)

Figure 1: Cadaveric scapula in a custom-made holder. *Acknowledgements to Marc Pot for the development of the custom-made scapula holder and measurement tools.*

A custom-made device allowed us to measure distance and angle from the center of the inferior circle to different points on the scapula; the tuberculum superius, the coracoid base, the lateral tip of the coracoid, the base of the acromion accessible straight next to the posterior glenoid rim, and the lateral tip of the acromion. We selected these as possible reference points because they are surgically accessible. The distance was measured in a plane parallel and a plane perpendicular to the coronal scapular plane. All measurements were taken with the scapula fixed in the coronal scapular plane, and angles were measured to this plane. From each of the scapulae parameters as diameter, version and inclination were measured. All cadaveric scapulae were scanned and the same measurements were done and compared to the manual measurements on the cadavers. The results are being examined and shortly send for publication. With this study we intend to contribute to the design of an external guide for reconstruction of the glenoid. (Figure 2)

Figure 1: Prototype of an extracorporeal guide: 1 = the center of the best fitting inferior circle, 2= the most medial scapular point, 3= the most inferior scapular point

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Chapter 10 Summary and Conclusions

The continuous adaptations and improvements of design, material and fixation modes of shoulder prostheses are mainly the work and merit of the biomechanical engineer in highly specialized labs. Surgeons can contribute to this process of continuous improvement by careful outcome measurement and data registration of the procedure, prosthesis, patient and pathology. This information offers confirmation if whether or not certain adaptations lead to better placement and a reduction of clinical loosening. To be able to do so it is necessary to map all variables and potential reasons for failure of prostheses. An extensive literature study of anatomic total shoulder prostheses learns that the main reason for failure is the loosening of the glenoid component, and this is the focus of this thesis.

One of the problems encountered when studying the variables that lead to loosening is the labyrinth of information with a lack of organisation. There is no structured literature approach to the description of potential risk factors, the patient population involved, radiographic measurement of fixation and loosening, study design and analysis. Above that there appears to be a lack of agreement on definitions of loosening and failure. In the first article **' Parameters of glenoid loosening'** clear definitions of glenoid loosening are proposed, and potential risk factors are categorized as implant related, patient related or surgeon related, in order to structure present and future study and investigation.

As mentioned, the implant related parameters belong to the field of the engineer. We cannot influence the patient related factors as they are inherent to our patient, but with all available means we can try to optimize knowledge, measurement and recognition of the pathology. The responsibility of the surgeon lies in the selection and the execution of the right operation for the right patient and pathology.

Codman emphasized already in 1934 the importance of the orientation of the glenoid surface and how a change of its orientation immediately changes the center of rotation and position of the humeral head. We know that small alterations in anatomy result in altered glenohumeral kinematics (every 10 degrees of glenoid angulation will displace the center of rotation of the humeral head by 5 mm). In anatomic total shoulder prostheses this can result in the so-called rocking horse phenomenon whereby the repetitive eccentric loading of the humeral head on the glenoid component causes tensile stresses at the bone-implant or bone-cement-implant interface initiating failure of fixation of the glenoid. It is obvious that in prosthetic surgery we must aim to reconstruct the normal geometry to restore the center of rotation and the soft tissue tension, but this is only feasible with the knowledge of the original configuration.

There is a large variation in anatomic parameters as version and inclination, influenced by the technique of measurement and the position of the patient. 3 D techniques can avoid this, and planes instead of lines are measured.
Several methods are described to define the native glenoid plane. Some advocate using the glenoid plane (defined by 3 points on the glenoid rim: superior, anteroinferior and posteroinferior) compared to the scapular plane. Others describe a 3 D glenoid vault model that mimics the contralateral shoulder to assist in predicting the native glenoid plane. The center of each plane defines the surgical center; consequently different centers result in different positions of the prosthesis. Nowadays the orthopaedic surgeon still tends to use the surface of which the center is defined as the crossing line between the most superior and inferior point of the glenoid (Saller's line) and the largest antero-posterior distance.
We believe that the plane of the glenoid with the least variability would be the most suitable plane to restore normal anatomy. In the second article **' Reliability of the glenoid plane'** a three-dimensional CT reconstruction study is described in which the normal 3 D relationship of different glenoid planes with the scapular plane is investigated. This study shows that the inferior plane of the glenoid formed by the most anterior, posterior, and inferior points of the rim of the glenoid has a constant degree of retroversion. This finding supports the use of this plane as the 'true surgical plane', all the more because easily surgically accessible bony landmarks define this plane.

Glenohumeral osteoarthritis is often associated with glenoid bone erosion, either concentric (type A), in approximately 60 %, or eccentric (type B), in over 30%. In total shoulder arthroplasty the increased retroversion and erosion of the glenoid are associated with a higher rate of loosening of the glenoid component. The surgeon should aim to correct the retroversion, and, if this does not exceed 15 to 20 degrees, it is common practice to ream down the anterior high side of the glenoid, but the glenoid bone volume limits the amount of reaming. The exact amount of correction has not been clearly defined and it is agreed to correct the retroversion to as close to the native version as possible (to within 10 degrees). Yet it is unknown how much bone is removed by reaming with different types of reamers, or how this reaming affects the glenoid supporting area with respect to the pathology of the glenoid. This is investigated and described in the third article **'Consequences of reaming with flat and convex reamers for bone volume and surface area of the glenoid'**. The aim is to quantify bone loss and contact surface area of uniconcave (type A) and biconcave (type B2) glenoids after reaming with different types of reamers by different surgeons. The results show that 1. Convex reamers cause more bone loss than flat reamers, but the difference is only significant for uniconcave glenoids, 2. In biconcave glenoids the amount of bone loss depends largely on (and increases with) the amount of version correction, and 3. Convex reamers create a larger surface area than flat reamers in both uni- and biconcave glenoids. Because of the conforming shape convex reamers seem to be better indicated in pathological A glenoids, and this can be optimized if the convexity of the reamer is adapted to the pathological curvature. In B glenoids convex reamers are preferred because they remove a similar amount of bone as flat reamers, but offer a larger surface area while maximizing the correction of the retroversion. To our knowledge this is the first study quantifying loss of bone volume and the surface area after reaming of the glenoid.

Three- dimensional planning provides the possibility to precisely determine the amount of reaming needed to obtain the desired correction. But is the reaming procedure itself a reproducible action? And is it a difficult surgical exercise? Is it feasible in a surgical setting where exposure of the glenoid surface is a difficult exercise itself? In the fourth article **'A glenoid reaming study: how accurate are current reaming techniques?'** we explore the influence of the experience of the surgeon, the type of reamer and the pattern of erosion of the glenoid on the accuracy of reaming.
It appears to be the type of glenoid that is determinant; the surgical experience and the type of reamer play a role of secondary importance. Reaming is reproducible for concentric eroded type A glenoids but not for eccentric posterior eroded type B glenoids and the grade of erosion seems to determine the inaccuracy of the procedure. This is similar to other results reported in literature and confirms the presumption that there is a necessity for guidance in reaming of biconcave glenoids.

The consequences of deviation of version on the glenohumeral kinematics and on the longevity of the glenoid prosthesis are extensively studied. However much less is known about the effect of the inclination. In the fifth article **'Rocking-horse phenomenon of the glenoid component: the importance of inclination'** the biomechanical consequences of the inclination of a glenoid component are analysed. To our knowledge no similar study has been published before. The magnitude of the eccentric loading (shear force), as part of the total joint force, exerted by the transversal force couple of the rotator cuff on a virtual glenoid component positioned in two differently orientated planes is measured. This demonstrates that shear forces are significantly less when the glenoid component is positioned in the inferior circle compared to the plane of the maximum glenoid circle that has a lesser inclination. Positioning of the glenoid component in the plane of the inferior circle might therefore reduce the risk of a rocking horse phenomenon, decreasing the problem of loosening.

The inferior circle is situated in the strongest part of the glenoid bone and considered important for a solid component fixation. In situations with extensive bony defects of the glenoid, as often encountered in revision surgery, there is a need for fixation beyond the glenoid vault. Radiological studies have revealed denser bone areas near the lateral margin and the spine of the scapula.
In the sixth article **'The pillars of the scapula'** two strong bone areas (one near the margo lateralis and one in the spine of the scapula) are identified in cadaveric scapulae, which are consistently present, surgically accessible and can serve as a point of fixation for screws. These pillars are outlined by three cortices and orientated to the inferior circle. These findings may expand the surgical possibilities for revision surgery with severe bone deficiency, and may be used to improve current screw fixation designs in anatomic and reversed systems. If the 3 D characteristics of the inferior circle, and the pillars, and of their relative position can be determined preoperatively this information can be used for accurate screw placement.

In the final article **'Arthroscopic treatment of the young degenerative shoulder joint; is there a role for interpositioning arthroplasty?'** we aim to find the optimal graft (dermal allograft or meniscal allograft) for resurfacing of the glenoid as an alternative to prosthetic treatment in selected young and active patients with early degenerative arthritis. The rationale for this being that if this procedure is successful it can postpone prosthetic placement avoiding the risk for early revision surgery. Because it is performed minimally invasive (arthroscopically) the subcapularis tendon is spared, an advantage if open surgery is necessary in the future. The clinical results in our study are not convincing, but 33 % (3 out of 10) of patient's do experience less pain and better function for several years. Patients who had an early revision to a prosthesis, all had severe cartilage damage of the humeral head, possibly the deformation interferes with preservation of the graft, and these bipolar (humeral and glenoid side) lesions are probably not indicated for this type of surgery.
Arthroscopic biologic resurfacing of cartilage defects of the humeral head is technically possible, but this technique is not administered frequently and results are unknown.
Does the type of erosion affect the result of resurfacing of the glenoid? In case of severe retroversion one would expect shear forces delaying ingrowth and causing early wear of the graft. However 2 of our satisfied patients had severely retroverted glenoids (type B1 and C) in this small series.
To conclude there may be a role for biologic resurfacing of the glenoid, but the optimal graft and pathology still need to be determined. Future studies should aim at defining the correct indication for biologic resurfacing of the glenoid, and at investigation of options for partial defects of the glenoid cartilage. In these cases localised coverage with a graft sutured in the defect or localised resurfacing with a polyethylene component are options to take into account, in particular since these can be performed minimally invasive.

Custom made polyethylene resurfacings for partial defects, but also for extensive asymmetrically eroded glenoids could minimise the necessity of reaming avoiding loss of bone stock. These techniques are within reach through the expansion of 3 D technology.

The red line of this thesis is the lack of orientation in the surgical approach of the glenoid
This thesis did build up as a process based on anatomical and radiological studies in order to improve the placement of the glenoid component in shoulder prosthesis. The role of version and inclination of the glenoid was studied in depth, as well as the need for adequate placement and fixation of the glenoid during surgery. These findings need however to be practically implemented during the act of surgery. In order to do so one uses 3 D navigation and 3 D printing to design patient specific instrumentation, but expenses are high. That is why we choose to start developing an external guide that can transfer out anatomical findings in a reproducible way to the daily practice when performing shoulder arthroplasty. If this leads to an accurate and reliable surgical device that is reusable in daily practice it will lower the costs of prosthetic surgery. One of the current subjects of future research in our department is the development of this external guide.

Samenvatting en Conclusies

Symptomatische artrose van de schouder kan behandeld worden met een schouderprothese waarbij de bol (humerus) en kom (glenoid) gereconstrueerd worden. Bij de meeste patiënten geeft dit een aanzienlijke verbetering van de pijnklachten en de functie. Uit de literatuur blijkt dat loslating van de glenoidale component de meest frequente oorzaak is voor het falen van een anatomische schouderprothese. Dit is het hoofdonderwerp van deze thesis.

Een uitgebreide literatuurstudie toont ten eerste het grote gebrek aan omschrijving en organisatie van variabelen zoals potentiële risicofactoren, patiënten populaties, radiologische metingen van fixatie en loslating, studie aanpak en analyse. Ten tweede blijkt er geen heldere definiëring te zijn van radiografische en klinische loslating. In het eerste artikel **' Parameters of glenoid loosening'** wordt een duidelijke definiëring van loslating van een glenoidale component voorgesteld, en de potentiële risicofactoren worden onderverdeeld als prothese gerelateerd, patiënt gerelateerd of chirurg gerelateerd.

Heden probeert de chirurg zo goed mogelijk de normale anatomie van het gewricht te herstellen. Om dit te kunnen bereiken is het van belang om de kennis van de normale anatomie, het herkennen van afwijkingen, en meetmethoden van deze afwijkingen te optimaliseren en te uniformiseren.

Om de metingen te vereenvoudigen wordt in de literatuur het kommetje beschreven als een vlak (glenoidale vlak).
Reeds in 1934 benadrukte Codman het belang van de oriëntatie van het glenoidale vlak. Hij beschreef hoe een verandering van oriëntatie het centrum van rotatie beïnvloedt en daardoor ook de positie van de humeruskop. Biomechanische studies hebben aangetoond dat 10 graden afwijking in het glenoidale vlak een verschuiving van het centrum van rotatie van 5 millimeter geeft. In anatomische schouderprothesen kan dit leiden tot het 'hobbelpaard' fenomeen, waarbij door de asymmetrische belasting van de humeruskop op het glenoid trekkrachten ontstaan op het raakvlak van prothese, bot en eventueel cement, die eventueel loslating kunnen veroorzaken. Het is duidelijk dat in prothesechirurgie de reconstructie van de normale anatomische afmetingen en oriëntatie cruciaal zijn om het centrum van rotatie van het glenohumeraal gewricht te herstellen. Maar dit is alleen mogelijk indien de originele afmetingen gekend zijn.
Om de oriëntatie van het vlak in de ruimte te beschrijven gebruikt men de termen inclinatie en versie waarbij inclinatie die hoek is die het vlak vormt in het coronale vlak, en versie de hoek in het transversale vlak.

Echter deze metingen van inclinatie en versie van het glenoid op twee dimensionele (2 D) CT beelden tonen een grote variabiliteit en de uitkomst van deze metingen wordt beïnvloed door de meetmethoden en de positie van de patiënt. Door middel van drie dimensionele (3 D) reconstructies kunnen meetfouten ten gevolge van positionering worden uitgeschakeld. Daarnaast bestaat er discussie wat nu juist het glenoidale vlak is. Dit komt door het feit dat een vlak bepaald wordt door 3 punten, maar dat het vlak dus sterk kan verschillen afhankelijk van de 3 gekozen punten.
In het tweede artikel '**Reliability of the glenoid plane**' worden met behulp van 3 D CT reconstructies verschillende glenoidale vlakken gedefinieerd en gemeten ten opzichte van het scapulaire vlak. Hieruit blijkt dat het inferieure vlak, gevormd door punten op de anterieure, posterieure en inferieure rand van het glenoid, de meest constante versie vertoont. We stellen dat het glenoidale vlak met de kleinste variabiliteit in versie het meest geschikte vlak is om de originele anatomie te reconstrueren en derhalve het aangewezen vlak is om te gebruiken in prothese chirurgie. Zeker aangezien dit vlak kan gedefinieerd worden met oriëntatie punten welke chirurgisch benaderbaar zijn.

Artrose van het glenohumeraal gewricht kenmerkt zich door erosie van het glenoid, dit kan concentrisch zijn (type A), in ongeveer 60 %, of excentrisch (type B), in meer dan 30%.
In de prothesiologie van de schouder worden toegenomen retroversie en erosie van het glenoid geassocieerd aan toegenomen frequentie van loslating en falen van de glenoidale component.
Indien de versie niet meer dan 15 tot 20 graden bedraagt kan de chirurg proberen te corrigeren door de anterieure rand weg te nemen met riemers. Echter de hoeveelheid die gecorrigeerd kan worden is beperkt door het volume van het glenoid.

Het is niet duidelijk hoeveel bot juist geriemd moet worden om de juiste correctie te verkrijgen. De consensus is om te corrigeren tot minder dan 10 graden afwijking van het originele vlak. Het is eveneens niet duidelijk hoeveel bot juist verwijderd wordt tijdens het riemen en het effect ervan op het resulterende oppervlak. In het derde artikel **'Consequences of reaming with flat and convex reamers for bone volume and surface area of the glenoid'** wordt het botverlies en het resulterende contact oppervlak gekwantificeerd. Daarnaast wordt het effect van verschillende soorten riemers en het type glenoidale erosie onderzocht. De resultaten tonen aan dat convexe riemers een groter contact oppervlak creëren dan vlakke riemers in zowel uni als biconcave glenoiden. Daarnaast veroorzaken convexe riemers meer botverlies dan vlakke riemers, maar dit is alleen significant voor een uniconcaaf glenoid. In een biconcaaf glenoid blijkt het botverlies vooral afhankelijk te zijn van de ernst van de erosie en dus de grootte van de correctie. In een biconcaaf glenoid prefereren we een convexe riemer omdat deze een groter oppervlak creëert zonder meer botverlies te veroorzaken.

Vanwege de convexiteit lijken convexe riemers ook beter aangewezen voor een concentrisch geërodeerd glenoid. Aanpassen van de riemers aan de convexiteit van het pathologisch glenoid zou het botverlies ten gevolge van riemen minimaliseren. Dit is de eerste studie die het botverlies en contact oppervlak na riemen kwantificeert.

Preoperatieve planning met 3 D technologie kan precies berekenen hoeveel er geriemd moet worden om de gewenste correctie te verkrijgen. Maar is het riemen zelf wel een betrouwbare en reproduceerbare chirurgische handeling ? Is het een moeilijke chirurgische handeling, en is nauwkeurig riemen mogelijk tijdens een procedure waarbij het vrijprepareren en in beeld brengen van het glenoid op zich al een moeizame opdracht kan zijn ? In het vierde artikel **'A glenoid reaming study: how accurate are current reaming techniques?'** onderzoeken we het effect van de ervaring van de chirurg, het type riemer en de graad van erosie van het glenoid op de kwaliteit en accuraatheid van het riemen. Het type van het glenoid blijkt bepalend te zijn, de ervaring van de chirurg en het type riemer blijken veel minder belangrijk. Voor een concentrisch geërodeerd glenoid is riemen een reproduceerbare actie, maar voor een type B glenoid blijkt dit niet het geval. Hier bepaalt de graad van erosie de accuraatheid. Dit komt overeen met de bestaande literatuur en het bevestigt de veronderstelling dat ondersteuning door richters peroperatief hoognodig is in geval van ernstige erosie.

Het effect van de retroversie op de glenohumerale kinematica en op de duurzaamheid van de glenoidale component is uitvoerig bestudeerd. Er is veel minder gekend over het effect van de inclinatie. In het vijfde artikel **'Rocking-horse phenomenon of the glenoid component: the importance of inclination'** worden de biomechanische consequenties van de inclinatie van een glenoidale component bestudeerd in een CT simulatie studie. Vergelijkbare studies zijn bij ons weten niet gepubliceerd. Twee virtuele glenoidale componenten worden geplaatst in twee verschillend georiënteerde vlakken; het inferieure circulaire vlak en het maximale circulaire vlak.
Het transversale krachtenkoppel van de rotaroren cuff oefent een bepaalde kracht uit via de humeruskop op het glenoid. Van de totale kracht is een deel wrijvingskracht , dit is de vector die parallel loopt met het gewrichtsvlak. Deze blijkt het kleinst te zijn voor het glenoid geplaatst in het inferieure circulaire vlak. Theoretisch betekent dit dat wanneer een glenoidale component geplaatst wordt in het inferieure vlak dit minder wrijvingskracht veroorzaakt dus minder snel tot het 'hobbelpaard' fenomeen zal leiden, en dus minder loslating veroorzaakt.

Ter hoogte van de inferieure cirkel bevindt zich het sterkste deel van het glenoid en dit is van belang voor stevige fixatie van een prothese. Wanneer het botverlies relatief groot is, zoals vaak het geval in revisiechirurgie, is er nood aan fixatiepunten achter het niveau van het glenoid. Radiologie studies tonen zones met grotere botdensiteit in de spina van de scapula en tegenaan de laterale rand. In het zesde artikel **'The pillars of the scapula'** hebben we deze twee sterke beenderige pijlers geïdentificeerd in kadaverspecimen. Deze pijlers waren steeds aanwezig en goed chirurgisch benaderbaar vanuit de inferieure cirkel. Ze worden steeds afgelijnd door 3 cortices en kunnen daardoor voldoende stevigheid bieden voor corticale schroeven. Wanneer deze pijlers met 3 D technieken gelokaliseerd kunnen worden in de scapula, en in relatie tot de inferieure cirkel, zouden deze gebruikt kunnen worden voor de opbouw van het glenoid in revisiechirugie, maar ook ter verbetering van de huidige anatomische en omgekeerde prothesen welke gebruik maken van schroeven om het glenoid te fixeren.

Het laatste artikel **'Arthroscopic treatment of the young degenerative shoulder joint; is there a role for interpositioning arthroplasty?'** beschrijft een klinische studie waarbij een allogreffe (huid of laterale meniscus) gebruikt wordt als biologische bedekking van het glenoid in een serie jonge patiënten met vroegtijdige artrose van de schouder. Deze procedure zou prothesechirurgie op jonge leeftijd kunnen voorkomen of toch tenminste uitstellen. Indien dit arthroscopisch kan gebeuren wordt de subscapularispees gespaard hetgeen gunstig zou zijn voor eventuele toekomstige protheschirurgie.
De resultaten van deze studie zijn niet overtuigend positief; slechts 3 van de 10 patiënten is na een follow-up van 7 jaar nog tevreden. De andere 7 patiënten kregen binnen 13 maanden een revisie naar een totale schouderprothese. Deze patiënten hadden ernstige kraakbeendefecten ter hoogte van de humeruskop, misschien zal uit toekomstig onderzoek blijken dat deze groep patiënten met bipolaire letsels (glenoid en humeruskop) niet geschikt is voor een interpositie arthroplastie.
Concluderend lijkt er een rol te zijn voor interpositie arthroplastie, maar de optimale greffe, patiënt en pathologie moeten beter bepaald worden. Of er een indicatie is voor bedekking van gedeeltelijke kraakbeenletsels met een greffe of een op maat gemaakte polyethyleen component, bij voorkeur minimaal invasief, kan onderwerp zijn van verder onderzoek.

De rode draad van dit proefschrift is het gebrek aan oriëntatie bij de chirurgische benadering van het glenoid. Anatomisch en radiologische studies analyseren de rol van inclinatie en versie op de optimale plaatsing van de glenoidale component.
Deze bevindingen dienen echter geëxtrapoleerd te worden naar het chirurgische veld. Peroperatieve computer navigatie of patiënt specifieke instrumenten blijken dure hulpmiddelen met beperkte efficiëntie. Er is nood aan peroperatieve referentiepunten en richtapparatuur en misschien kan een externe richter welke uitgaat van het scapulaire vlak om het glenoid te reconstrueren uitkomst

bieden. Wij hopen in de nabije toekomst een dergelijk richtapparaat te ontwikkelen en aangezien dit herbruikbaar is zou het de kosten van prothesechirurgie kunnen reduceren.

Dankwoord

Mijn moeder en mijn vader

Mijn lieve mama die er steeds voor ieder van ons is en altijd de rust bewaard thuis. Ik hoop dat ik net zo een geweldige moeder als jij zal zijn voor mijn kinderen.

Mijn lieve bijzondere vader. Behalve dat je Jaap en mij altijd hebt geholpen op de momenten dat het telde, heb je ons vooral ook altijd vrij gelaten om te doen wat we wilden. Hard werken, eerlijk zijn en in jezelf geloven zijn waarden die we van jullie meekregen en elke dag van pas komen.

Mijn broer Jaap

Kan me altijd laten lachen, behalve wanneer het over statistiek gaat. Bedankt voor je hulp bij de studietjes.

Professor Verdonk

Toen ik na veel omzwervingen de moed bij elkaar had geraapt om me kandidaat te stellen voor de opleiding orthopedie kreeg ik van u mijn kans. Dankzij u heb ik nu het mooiste beroep van de wereld.

Professor De Wilde

Beste Lieven, zonder jou had ik dit boekje niet geschreven. Je bent een fantastische promotor geweest voor mij. En je bent een enorm inspirerende en gedreven opleider, denker, uitvinder en chirurg. Ik kan alleen maar hopen dat ik ooit zo goed kan opereren als jij.

Alexander Van Tongel

Jij bent de best georganiseerde van ons drieën. Bedankt voor je hulp bij elk deel van deze thesis. Of het nu op een zaterdag een hele dag botblokjes riemen is, of opzoeken, of nalezen, het is je nooit teveel.

Bart Berghs, Tom Van Isacker

Met Lieven en Alexander slagen we er al sinds jaren in om met ‘ Terbruggen’ een mooie schouderunit te realiseren waar ruimte is voor studies, ideeën , opleiding, overleg en gezellige avonden, die ik enorm koester.

Professor Victor

Dank voor het vertrouwen en de steun bij het finaliseren van deze thesis.

Marc

Lieve Marc, jij heb de gave mensen te laten zijn wie ze zijn en ze hun dromen te laten najagen. Ook zonder jou was dit boekje er niet geweest.

Jules en Stef

Jullie zijn het beste in mijn leven. Het aller aller leukste aan het eind van een werkdag is naar huis gaan, naar jullie.

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This article is accepted for publication in Acta Orthopaedica Belgica (March 17, 2015).