



SHOULDER

Biomechanical considerations of the normal and rotator cuff deficient shoulders and the reverse shoulder prosthesis

F. Lam^{a,*}, D.N. Bhatia^a, S.B. Mostofi^b, K. van Rooyen^a, J.F. de Beer^a

^aCape Shoulder Institute, Medgroup Anlin House, Platteklouf, Panorma, Cape Town, South Africa

^bMassachusetts General Hospital, Boston, USA

KEYWORDS

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Summary

The treatment of combined glenohumeral arthritis and massive rotator cuff deficiency remains a unique challenge. Prosthetic reconstruction is aimed at restoring the normal kinematics of the glenohumeral joint. The reverse shoulder prosthesis medialises the centre of rotation of the glenohumeral joint, thereby lengthening the deltoid lever arm. The centre of rotation is also fixed at the glenoid bone prosthesis interface and this has the effect of reducing the torque on the glenoid component and lessens the risk of glenoid loosening. To further enhance the function of deltoid, the humerus is lowered relative to the glenoid, thereby increasing the deltoid tension. Although the preliminary results have been encouraging, there are still some unresolved issues such as prosthetic joint instability, scapular notching, wear of the polyethylene cup, fixation of the humeral stem and the lack of external rotation following surgery.

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Introduction

The design of a successful shoulder arthroplasty relies on the restoration of the normal anatomical relationship between the humeral head and glenoid so that the normal kinematics of the shoulder joint can be recreated.¹ The biomechanical considerations of the normal shoulder joint that are important in prosthetic design will be considered.

Anatomy of the humeral head

The mean humeral head radius is 24 mm (range 19–28) and the mean humeral head thickness is 19 mm (range 15–24).^{2,3} Both these variables correlate with the humeral head offset, which is the distance between the centre of the humeral head and the longitudinal axis of the humeral shaft. In the coronal plane, the humeral head offset is 7–9 mm medial to the central axis of the humeral shaft. In the axial plane, the humeral head offset is 2–4 mm posterior to the central axis of the humeral shaft. The ratio of the humeral head thickness to humeral head radius is reliably consistent at 0.7–0.9.^{2,3} This ratio is directly proportional to the amount

*Corresponding author.

E-mail address: mrflam@hotmail.com (F. Lam).

of humeral head which articulates with the glenoid, irrespective of other variables such as length of the humeral shaft or the size of the patient.³

Anatomy of the glenoid cavity

The normal glenoid has a pear shaped appearance with a shorter anteroposterior dimension in the superior half (mean 23 mm) than in the inferior half (mean 29 mm).² The glenoid offset is the distance between the base of the coracoid and the deepest portion of the glenoid articular surface.² This measurement determines the location of the glenohumeral joint line and again is not related to the size of the patient. The lateral glenohumeral offset is the distance between the base of the coracoid and the most lateral aspect of the greater tuberosity. This measurement is important as it determines the resting tension of the rotator cuff and the moment arm of the deltoid.

Humeral neck shaft angle

The humeral neck shaft angle is defined as the angle between the central intramedullary axis of the humeral shaft and the anatomical neck of the humerus. The mean neck shaft angle is 40° but significant variation does occur between individuals, ranging from 30° to 55° .⁴

Articular geometry of the glenohumeral joint

The articular surface of the humeral head has an upwards tilt of 45° and is retroverted 35° with respect to the epicondylar axis of the distal humerus (Fig. 1). The articular surface of the glenoid has a slight upwards tilt of 5° with respect to the medial border of the scapula and retroversion of 7° with respect to the plane of the scapula. The articular surface of the humeral head covers an arc of 155° but the articular surface of the glenoid covers an arc of only 76° . The implication of this difference is that the glenohumeral joint can only allow 79° of true elevation in the scapular plane. Combined with 41° of scapulothoracic motion, the arm can elevate 120° beyond which an 'obligatory' external rotation occurs to achieve maximal elevation.⁵ This means that the humerus must externally rotate to clear the greater tuberosity from the coracoacromial arch.

Articular congruity of the glenohumeral joint

The glenohumeral congruence (conformity) is the relationship between the radius of curvature of the humeral head and the glenoid.⁶ If the radii of curvature of the humeral head and glenoid are the same, i.e. congruency ratio of 1, then there is maximum contact between the two surfaces. This arrangement occurs in only 9% of individuals.⁵ The most common configuration (90%) is a smaller radius of curvature for the humeral head relative to the glenoid, such that the congruency ratio is less than 1. This has important biomechanical advantages in terms of increased range of movement but at the expense of decreased stability.

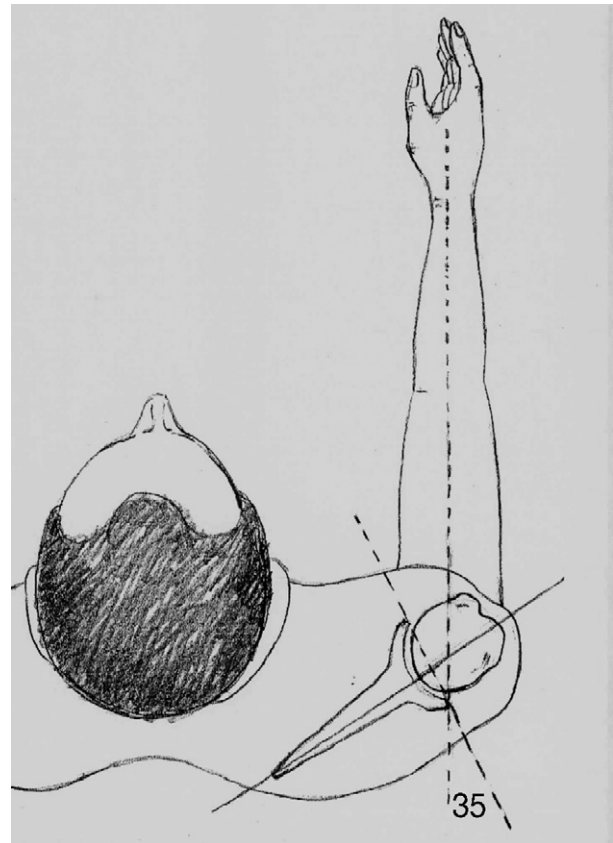


Figure 1 Transverse view of the glenohumeral joint showing the 35° retroversion of the glenoid.

Glenohumeral index

This is defined as the maximum transverse diameter of the glenoid divided by the maximum transverse diameter of the humeral head. This ratio is approximately 0.75 in the sagittal plane and 0.6 in the transverse plane.⁷ A low glenohumeral index is associated with recurrent anterior instability.⁸

Glenohumeral articular constraint

Constraint is the amount of humeral head which is in direct articulation with the glenoid cavity.⁶ It is related to the depth of the glenoid but is independent of articular congruence. The normal glenoid has a depth of 9 mm in the superoinferior direction and 5 mm in the anteroposterior direction. As a result, the glenoid is more constrained in the superoinferior direction than anteroposterior direction, accounting for the more frequently observed anteroposterior dislocation.

Stability of the glenohumeral joint

Unlike the hip joint, the glenohumeral joint is minimally constrained, with little inherent bony stability. The stability of the joint is maintained by an interconnecting network of static and dynamic restraints (Table 1). The static restraints

Table 1 Static and dynamic stabilizers of the glenohumeral joint.

Static

Capsuloligamentous

1. Capsule
2. Labrum
3. Glenohumeral ligaments
4. Coracohumeral ligament

Articular

1. Humeral head retroversion
2. Scapular inclination
3. Joint conformity
4. Negative intraarticular pressure

Dynamic

Scapulohumeral

1. Supraspinatus
2. Infraspinatus
3. Subscapularis
4. Teres major
5. Teres minor
6. Long head of biceps
7. Deltoid

Axioscapular

1. Trapezius
2. Rhomboids
3. Serratus anterior
4. Levator scapulae

Axiohumeral

1. Latissimus dorsi
2. Pectoralis major

may be further divided into soft tissue and articular stabilisers. An important soft tissue restraint is the glenohumeral joint capsule, which originates from the labrum and margin of the glenoid fossa. It is attached laterally to the anatomical neck of the humerus. It forms a continuous fibrous joint lining, except in the biceps groove where the tendon exits the joint. It maintains the negative intraarticular pressure, contributing to the stability of the glenohumeral joint. Cadaveric studies have shown that a simple puncture of the joint capsule can result in 2 cm of distraction of the joint surfaces resulting in significant glenohumeral instability.⁹ The glenohumeral ligaments are thickenings of the joint capsule and consist of superior, middle and inferior portions. The superior glenohumeral ligament originates from the base of the coracoid process and labrum and inserts into the humerus just above the lesser tuberosity. It functions as the primary restraint to inferior translation of the humeral head. The middle glenohumeral ligament is the most variable and is said to limit external rotation and anterior subluxation of the humeral head when the arm is in mid-abduction. The inferior glenohumeral ligament is the most important ligament in maintaining joint stability.¹⁰ It originates from the anterior, inferior and posterior margins of the glenoid labrum and inserts into the neck of the humerus. It consists of an anterior band, axillary pouch and posterior band. The anterior band is maximally taut when the arm is in abduction

and external rotation. Conversely, the posterior band is maximally taut when the arm is in abduction and internal rotation.

The coracohumeral ligament originates from the lateral aspect of the base of the coracoid process and runs downwards and laterally to attach to the greater and lesser tuberosities. It acts as the primary restraint to inferior translation of the adducted arm and also functions to limit external rotation of the adducted humerus. The labrum has several important functions. Firstly, it deepens the glenoid by 5 mm in the anteroposterior direction and 9 mm in the superoinferior direction.¹¹ This increases the depth of the glenoid by 50%. Secondly, it provides a site of attachment for the glenohumeral ligaments. Thirdly, it works synergistically with the rotator cuff to compress the humeral head against the glenoid cavity. Finally, it acts as a wedge, preventing translation of the humeral head. It is estimated that removal of the labrum results in a 20% reduction in the translatory force required to dislocate the humeral head over the glenoid rim.¹²

The articular factors are also important. The mean retroversion of the humeral head is 17.9°.¹³ There is evidence that insufficient humeral retroversion predisposes to anterior instability and Saha⁷ suggested a corrective humeral osteotomy if the retroversion angle is less than 20°. On the glenoid side the version is usually zero, although up to 10° of anteversion or retroversion can be regarded as normal. There is conflicting evidence as to whether hyper-anteversion of the glenoid may be associated with recurrent instability.

The dynamic restraints stabilise the joint by several mechanisms:

1. By a passive muscle tensioning effect.
2. By dynamic contraction thereby causing compression of the humeral head into the glenoid and glenoid labrum, sometimes referred to as concavity-compression.¹⁴
3. By causing a secondary tightening effect on the static constraints. For example, supraspinatus can simultaneously elevate and externally rotate the arm. The external rotation movement causes tightening of the inferior glenohumeral ligament, limiting upward elevation.
4. By exerting a direct barrier effect. For example, subscapularis acts as a direct anterior stabiliser preventing antero-inferior humeral instability.

Forces acting on the glenohumeral joint^{5,15}

The forces acting on the glenohumeral joint include:

- Weight of the arm.
- Abductor force by deltoid and supraspinatus.
- Downward pull of arm by subscapularis, infraspinatus and teres minor.
- Compressive force on the glenohumeral joint.
- Shear force of humeral head on glenoid.
- External forces such as weight held in the hand.

The deltoid is the most powerful muscle around the shoulder and can generate a force of up to 6 times the weight of the arm. It has the largest moment arm around

the glenohumeral joint and is the most effective muscle in arm elevation, acting superiorly at 63° when the arm is resting at the side of the body (Fig. 2). In the normal shoulder, the deltoid can alone provide 70% of the torque at 30° of abduction and 85% at 90°.16 The supraspinatus can generate a force of 2.5 times the weight of the arm and acts 15–20° superiorly. The infraspinatus acts 40–45° inferiorly and the force of the teres minor is also directed inferiorly at 55°. Together, the infraspinatus and teres minor can generate a force of 5 times the weight of the arm.17,18 When abduction of the arm is initiated, the shear force on the glenohumeral joint generated by the deltoid is counteracted by the compressive force produced by the rotator cuff. Generally speaking, the compressive force contributes towards joint stability while the shear force induces upward displacement of the humeral head. The combination of shear and compressive forces allows efficient abduction by stabilising the humeral head within the glenoid fossa. The magnitude and direction of the resultant joint reaction force is dependent on the position of the arm. At 90° of abduction, the joint reaction force is at its maximum and equates approximately the weight of the body. Fig. 3 represents a free body diagram of the forces acting on the glenohumeral joint when the arm is abducted 90°.

Cuff tear arthropathy

The concept of “cuff-tear arthropathy” was first introduced by Neer in 1977 to describe findings of arthritis associated

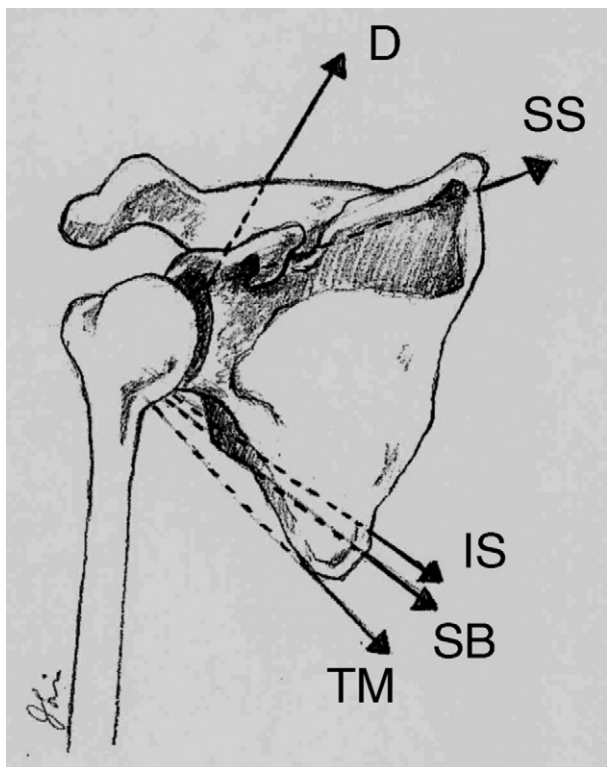


Figure 2 The direction of the rotator cuff muscle forces when the arm is resting at the side of the body (D—Deltoid, SS—Supraspinatus, IS—Infraspinatus, SB—Subscapularis, TM—Teres Minor).

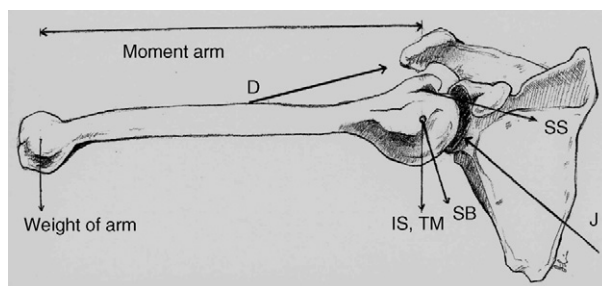


Figure 3 Free body diagram of the forces acting on the glenohumeral joint when the arm is abducted 90° (D—Deltoid, SS—Supraspinatus, SB—Subscapularis, IS—Infraspinatus, TM—Teres minor, J—Joint reaction force).



Figure 4 Cuff tear arthropathy with superior migration of the humeral head.

with massive rotator cuff deficiency.19 He postulated that without the superior stabilising effect of the rotator cuff, the humeral head migrates superiorly, leading to abrasion of the humeral head against the undersurface of the acromion and superior glenoid. Furthermore, as a result of inactivity, there is impaired nutrition of the articular cartilage, leading to osteoporosis and segmental collapse of the humeral head. In 1981, McCarthy et al.20 described similar findings, which they called ‘Milwaukee shoulder’ and postulated that it was a degenerative process caused by hydroxyapatite crystals, neutral proteases and active collagen.

The superior migration of the humeral head seen in massive rotator cuff deficiency (Fig. 4) is caused by muscle force imbalance. Normally, the rotator cuff stabilises the humeral head in the glenoid cavity during abduction and the head translates superiorly by 3 mm during the first 30° of motion.21 In massive rotator cuff deficiency, the shear force produced by the intact deltoid is no longer opposed by the

joint compressive force which is normally produced by the rotator cuff. This results in a superiorly directed resultant vector that occurs with initiation of abduction. Furthermore, the long head of biceps is usually torn in association with large rotator cuff tears, further losing its important role as a humeral head depressor. In advanced cases, as the deltoid contracts the humeral head articulates with the undersurface of the acromion, causing further articular destruction (Fig. 4).

The treatment of cuff tear arthropathy remains a difficult challenge. Options vary from hemiarthroplasty, bipolar hemiarthroplasty, massive head hemiarthroplasty, constrained total shoulder replacement, semi-constrained total shoulder replacement and shoulder arthrodesis.²²

The use of an unconstrained total shoulder replacement in the treatment of cuff tear arthropathy is now almost obsolete due to the high incidence of glenoid loosening. This is due to the high shear force which loads the superior part of the glenoid eccentrically, a phenomenon described by Matsen²³ as the 'rocking horse phenomenon'.

Hemiarthroplasty was also tried. Although it provided good pain relief for some patients, the range of active movement afterwards was still poor.²⁴ There is concern that results deteriorate with time due to erosion of the glenoid and coracrocromial arch. Bipolar hemiarthroplasty was also introduced to add further stability but the functional outcome was no better than hemiarthroplasty.²⁵

Development of the reverse shoulder prosthesis

The concept of a constrained total shoulder arthroplasty was first introduced by Scales in 1960 with the Stanmore constrained prosthesis. The rationale for this was to provide a fixed centre of rotation thereby converting the upwardly directed shear force produced by the deltoid into a rotatory movement. In 1972, Kolbel introduced the first reverse ball and socket prosthesis. Since then a number of similar designs have been introduced, including Fenlin, Neer, Liverpool, Gerard and Kessel. Unfortunately, all of these designs had the shortcomings of a lateralized offset of the humeral component, resulting in excessive torque and shear forces at the glenoid prosthetic bone interface, leading to glenoid loosening. Finally, in 1985, Professor Paul Grammont from Dijon, France, developed a semiconstrained reverse ball and socket prosthesis.²⁶ He made a number of key refinements in its design:

- The glenoid component consists of a large hemisphere with no neck. Compared to a small head, the larger head allows greater excursion of movement yet without compromising stability. The absence of a neck means that the lateral offset will be minimised.
- The centre of rotation is fixed at the glenoid bone prosthesis interface. This significantly decreases the torsional forces on the component-bone fixation, and thus lessens the risk of glenoid loosening.²⁷
- The centre of rotation is also medialised. This has important biomechanical advantages. Firstly, the lever arm of the deltoid is lengthened (Fig. 6), leading to a corresponding increase in the moment force. Grammont

found that if the centre of the glenoid hemisphere is medialised by 10mm, the abduction moment of the deltoid will be increased by 20% when the arm is abducted 60°. ^{26,28} Secondly, medialising the centre of rotation helps to recruit more deltoid fibres to act as abductors. Normally, only the middle fibres and part of the anterior fibres of the deltoid act as abductors. When the axis of elevation is medialised, more of the anterior and some of the posterior fibres of the deltoid are additionally recruited for abduction.

- The humeral neck angle is non-anatomical and has a horizontal inclination of 155°. This lowers the humerus relative to the glenoid and helps to restore deltoid tension. If the centre of the glenoid hemisphere is lowered by 10 mm, the abduction moment of the deltoid will be increased by 30% when the arm is abducted 60°. ^{26,28}
- The humeral component consists of a small cup covering less than half of the glenosphere. This allows a greater range of movement without causing prosthesis bone impingement.
- The articular geometry of the humeral and the glenoid components are well matched and the deeper socket has increased the articular conformity. Both have contributed to the increased joint stability.

Based on Grammont's original design, the two most popularly used reverse prostheses are the Delta III (Depuy, Warsaw, Indiana, USA) and the Aequalis Reverse prostheses (Tornier Inc., Houston, TX, USA). The Delta has been in use in Europe since 1992 and the Tornier (Fig. 5) since 1998. When the tension is correct after implantation, pulling the arm downwards should result in only 5mm of articular

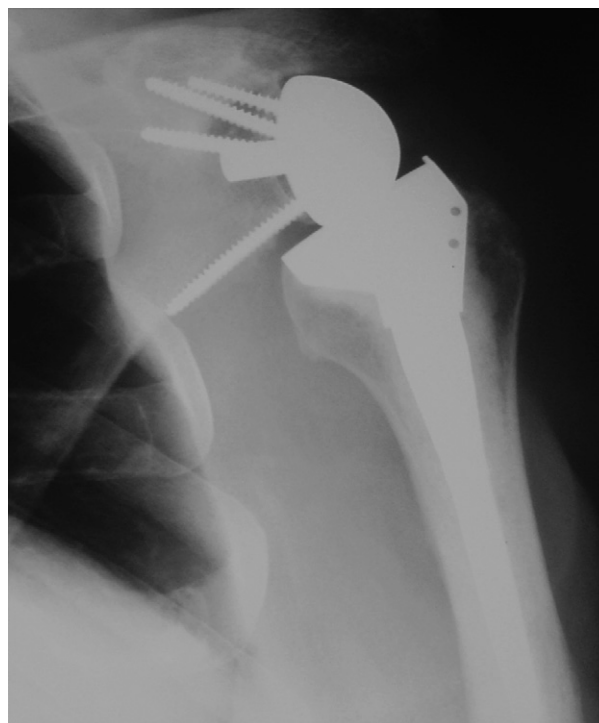


Figure 5 Radiograph of the reverse shoulder prosthesis.

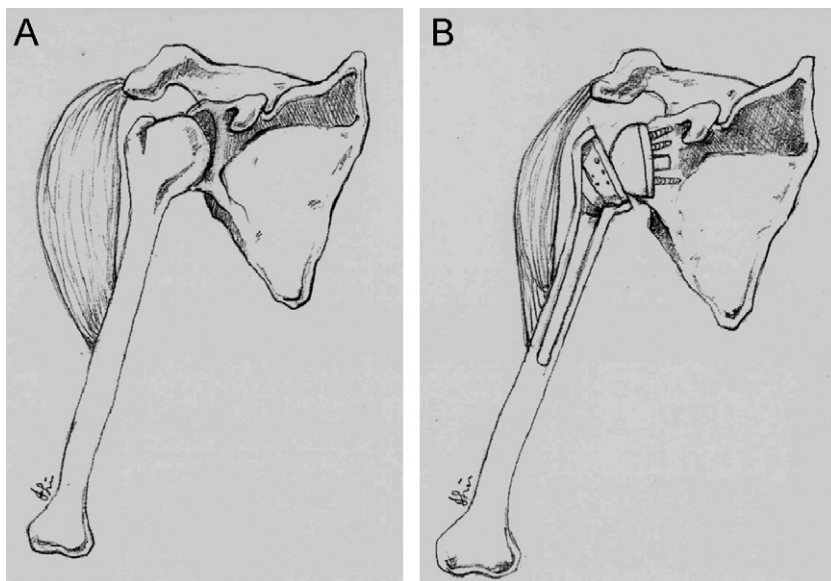


Figure 6 (A) The normal resting tension of the deltoid. (B) The reverse prosthesis in situ with a medialised centre of rotation and lowering of the humerus, thereby lengthening the deltoid.

surface separation and the joint should remain stable when the arm is adducted.²⁹

The most common indication for the reverse shoulder prosthesis is massive, irreparable cuff tear associated with glenohumeral arthritis. Other indications include revision of a failed hemiarthroplasty or total shoulder arthroplasty associated with irreparable rotator cuff damage, displaced comminuted fracture of the proximal humerus in the elderly, massive irreparable rotator cuff tear without arthritis, failed rotator cuff repair, rheumatoid arthritis and tumour reconstruction. The common denominator in all of these situations is the loss of a stable biomechanical fulcrum for arm elevation (Fig. 6).

Current status of the reverse shoulder prosthesis

Several studies have reported favourable results with the reverse shoulder prosthesis in the short to medium term.^{30,31} In a series of 60 patients with a minimum follow up of 2 years, Frankle et al.³⁰ reported an excellent or good outcome in 41 patients with significant improvement in all parameters of pain and function. There were 13 complications (17%) in 10 patients, 7 of whom required revision surgery to either hemiarthroplasty or another reverse shoulder prosthesis. The most recent published data come from Nice by Boileau et al.³¹ who reported the results on a consecutive series of 45 patients with a mean follow up of 40 months. There were significant improvements in active elevation (from 55° preoperatively to 121° postoperatively) and Constant score (from 17 to 58). Fourteen complications in 11 patients were encountered including 3 dislocations, 3 deep infections, 2 periprosthetic humeral fractures, 1 aseptic loosening of the humeral component, 1 intraoperative glenoid fracture, 2 late acromial fractures, 1 wound haematoma and 1 axillary nerve palsy. They found that the

complication rate of the reverse prosthesis carried out for revision surgery was significantly higher than for cuff tear arthropathy (47% and 5% respectively). This experience is shared by Schneeberger and Gerber who reported a similarly high complication rate of 50% in revision cases.³²

The long term survival of 80 reverse prostheses was evaluated by a multicentre study with a minimum follow up of 5 years.³³ Using replacement of the prosthesis as the end point, the survival rate was 91%. Using glenoid loosening as the end point, the survival rate was 84%. Using an absolute Constant score of less than 30 as the end point, the survival rate was 58% at 120 months. There were two breaks noted in the survival curves. The first break occurred at around 3 years as a result of early loosening of the prosthesis. The second break occurred at around 6 years as a result of progressive functional deterioration of the prosthesis.

Clearly, there are still many complicated issues of the Reverse prosthesis that need to be addressed. Firstly, the maintenance of joint stability remains a problem. Instability can be attributed to a variety of factors including insufficient deltoid tension, medial impingement caused by medialisation of the humerus and atrophy of the anterior deltoid. Grammont described the concept of “global decoaptation” which is shown radiographically by a radiolucent gap between the articular surfaces.³⁴ This is thought to be caused by insufficient deltoid tension. Over tensioning of the deltoid, however, can result in fracture of the acromion and can even cause damage to the axillary nerve.²⁹

Scapular notching remains a common complication and was seen in 68% of Boileau’s subjects.³¹ Its occurrence is a result of impingement of the humeral cup on the scapular neck during shoulder adduction. Concern remains that scapular notching might lead to secondary wear of the polyethylene cup with the potential for inducing osteolysis. Gerber found that by placing the glenosphere 2–4 mm more distally, this significantly improves the abduction and adduction angles thus reducing the risk of inferior glenoid notching.³⁵

The issue of subsidence and loosening of the humeral stem remains a challenge. Boileau²⁹ recommends that the humeral stem should be cemented, as the round cross section of the humeral stem offers little torsional stability. Furthermore, as the host bone in revision cases is often insufficient, a long stem implant should be used. The procedure should be performed in two stages if there is any suspicion of infection.

Finally, many patients following successful reverse shoulder arthroplasty still have little or no external rotation. This can be attributed to many factors including lack of compensation of the external rotators by the posterior deltoid, secondary to the medialisation of the centre of rotation, as well as fatty atrophy of the rotator cuff.²⁹

In conclusion, although the short to medium term results of the reverse shoulder prosthesis have been encouraging, the overall complication rate remains high when compared to anatomic implants. Until the long term results are known, the reverse prosthesis should be reserved for the treatment of severely disabling cuff tear arthropathy in patients over 70 years old with low functional demands.

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