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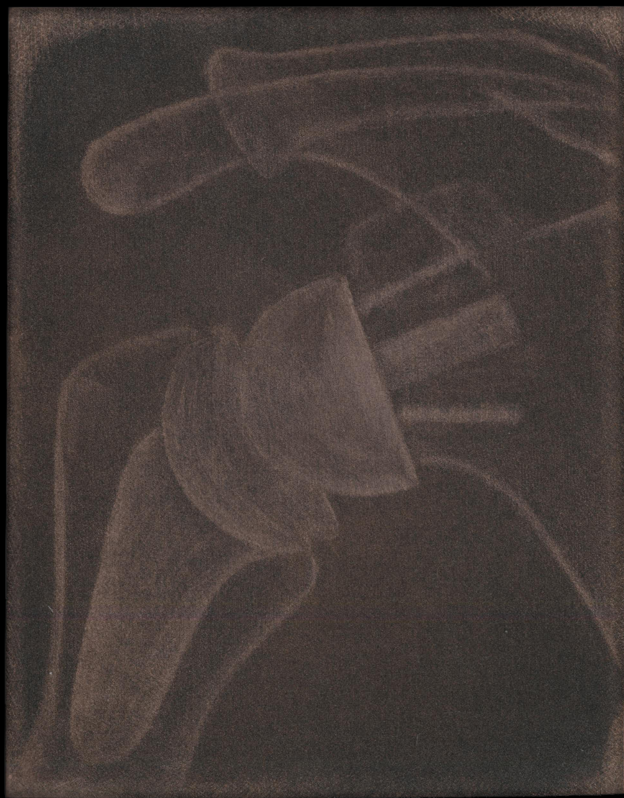

REVERSE SHOULDER ARTHROPLASTY

Factors affecting clinical results and risk of revision

Kaisa Lehtimäki

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
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In a world of full of dicks be a Canth

(Minna Canth 1844–1897,
Finnish writer and social activist)

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ABSTRACT

Reverse shoulder arthroplasty (RSA) is increasingly used to treat painful cuff tear arthropathy (CTA), shoulder osteoarthritis (OA), and proximal humeral fractures (PHF). This non-anatomical procedure, featuring a convex glenoid and concave humeral component, has shown promising short (1–2 years) - to mid-term (2–5 years) clinical results. However, RSA, like any major surgery, carries significant risks, including infection and instability, which may lead to revisions. The demand for RSA is expected to rise with the aging population, particularly for CTA/OA and PHF cases. This study aims to analyze factors influencing the clinical outcomes of RSA and the post-surgical risk of revision.

Numbers of RSA surgeries were found to have increased in Scandinavia shoulder registry for the treatment of glenohumeral OA and CTA. The overall mid-term risk of revision was low (5%), and the main reason for early revision was infection. Men had significantly increased risk of revision compared to women 3.8 times higher. In patients with RSA performed for acute proximal humerus fracture, the short-term risk of revision was low (2%), and the main reason for revision was instability. Patients treated with RSA at Turku University Hospital between 2007 and 2019 were analysed retrospectively. No direct correlation was found between radiological parameters and clinical results. Glenoid bone grafting in conjuction with RSA is a safe and reliable option to restore the glenoid bone stock and secure the construct in short term follow-up. There was no significant difference in component survival between auto- and allograft bone grafting techniques.

These studies are important for clinical practice as they provide valuable insights that can guide surgical decisions, improve patient selection, and inform patients with the potential risks and also realistic expectations related to the procedure. By understanding the factors influencing RSA outcomes, clinicians can enhance patient care, optimize surgical planning, and reduce revision rates, ultimately leading to better long-term (5–10 years) results.

KEYWORDS: reverse shoulder arthroplasty, cuff tear arthropathy, proximal humerus fracture, revision, range of motion, complications, glenoid bone graft

TURUN YLIOPISTO
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TIIVISTELMÄ

Olkapään käänteistä tekoniveltä (RSA) käytetään lisääntyvissä määrin hoidoksi kipeään ja kuluneeseen olkapäähän, jossa kiertäjäkalvosin on vaurioitunut (cuff-artropatia) sekä olkanivelen nivelrikon hoitoon ja olkaluun yläosan murtumissa. RSA on ei-anatominen proteesi, jossa lapaluun puoli on kupera ja olkaluupuoli kovera. Olkapään käänteisestä tekonivelestä on saatu lupaavia lyhyen (1–2 vuoden) ja keskipitkän (2–5 vuoden) kliinisen seurannan tuloksia. Toimenpiteeseen voi liittyä vakavia komplikaatioita, kuten infektiot ja tekonivelen sijoiltaanmeno, jotka voivat johtaa uusintaleikkaukseen. Väestön ikääntyessä on odotettavissa, että tarve olkapään käänteisen tekonivelen leikkauksille kasvaa, etenkin cuff-artropatia/nivelrikon ja murtuma tapauksien hoidossa. Tämän tutkimuksen tarkoituksena oli analysoida kliiniseen lopputulokseen vaikuttavia tekijöitä ja uusintaleikkaukseen johtavia riskejä ja riskitekijöitä.

Pohjoismaisen tekonivelrekisterin perusteella RSA:n leikkausmäärät lisääntyivät selvästi seuranta-aikana. RSA-leikkaukseen cuff-artropatiapotilailla liittyi 5 % revisioriski keskipitkän seurannassa. Yleisin syy alkuvaiheen revisioon oli infektio ja mies sukupuoli oli merkittävä riskitekijä, 3.8 -kertainen naisiin verrattuna. Murtumien hoidossa käänteisen tekonivelen lyhyen seurantavälin (1–2 vuoden) revisioriski oli pieni (2 %). Tekonivelen sijoiltaanmeno oli murtumapotilaiden uusintaleikkauksen yleisin syy. Tutkimuksessa seurattiin myös retrospektiivisesti TYKSissä vuosina 2007 ja 2019 välillä käänteisellä tekonivelellä leikattuja potilaita. Tässä analyysissä röntgenkuvasta mitatuilla parametreillä ei pystytty luottavasti ennustamaan kliinistä lopputulosta. Lapaluun luunsiirre RSA:n käytön yhteydessä on turvallinen ja luotettava vaihtoehto lapaluun luupuutoksen korjaamiseen ja takaa luotettavan rakenteen lyhyen seurannassa. Tutkimuksessa ei todettu merkittäviä eroja komponenttinen seurannassa auto- ja allografti ryhmien välillä.

Nämä tutkimukset tarjoavat arvokasta tietoa kliiniseen työhön, jotka ohjaavat kirurgista päätöksentekoa, potilasvalintaa ja informoi potilaita toimenpiteeseen liittyvistä riskeistä sekä antaa realistisen kuvan odotettavissa olevista tuloksista. Ymmärtämällä paremmin RSA:n tuloksiin vaikuttavia tekijöitä, kliinikot voivat parantaa potilashoitoa, optimoida leikkaussuunnittelua ja vähentää uusintaleikkausten määrää, mikä tavoite on saavuttaa paremmat pitkän aikavälin (5–10 vuoden) tulokset.

AVAINSANAT: käänteinen tekonivel, cuff-artropatia, olkaluun yläosan murtuma, uusintaleikkaus, liikeala, komplikaatiot, lapaluun luusiirre

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Abbreviations

AHI	Acromiohumeral interval
AOANJRR	Australian Orthopaedic Association National Joint Replacement Registry
ATg	Glenoid autograft bone
ALg	Glenoid allograft bone
BIO-RSA	Bony increased-offset reverse shoulder arthroplasty
BMI	Body mass index
CI	Confidence interval
COR	Centre of rotation
CRP	C-reactive protein
CS	Constant score
CSA	Critical shoulder angle
CT	Computer tomography
CTA	Cuff tear arthropathy
DAIR	Debridement, antibiotics and implant retention
DSA	Distalization shoulder angle
GIO	Glenoid inferior offset
HA	Hemiarthroplasty
HR	Hazard ratio
K-L	Kellgren-Lawrence
MRI	Magnetic resonance imaging
NARA	Nordic Arthroplasty Register Association
NJR	National Joint Registry
LSA	Lateralization shoulder angle
OA	Osteoarthrosis
OR	Odds ratio
PHF	Proximal humerus fracture
PJI	Periprosthetic shoulder infection
PROM	Patient reported outcome measure
RA	Rheumatoid arthritis
ROM	Range of motion
RR	Risk ratio
RSA	Reverse shoulder arthroplasty
SD	Standard deviation

SNL	Scapular neck length
VAS	Visual Analogue Scale
WOOS	Western Ontario Osteoarthritis of the Shoulder Index

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Lehtimäki K, Rasmussen JV, Mokka J, Salomonsson B, Hole R, Jensen SL, Äärimaa V. Risk and risk factors after primary reverse shoulder arthroplasty for cuff tear arthropathy and osteoarthritis: a Nordic Arthroplasty Register Association Study. *J Shoulder Elbow Surg*. 2018 Sept; 27(9):1596–1601.

II Lehtimäki K, Rasmussen JV, Kukkonen J, Salomonsson B, Arverud ED, Fenstadt AM, Brorson S, Jensen SL, Äärimaa V. Low risk of revision after reverse shoulder arthroplasty for acute proximal humeral fractures. *JSES Int*. 2020 Jan 2; 4(1):151–155.

III Lehtimäki K, Harjula J, Uurinmäki J, Kukkonen J, Löyttyniemi E, Mokka J, Tiusanen H, Äärimaa V. Radiographic geometry and clinical glenohumeral range of motion after reverse shoulder arthroplasty, a retrospective cohort study. *J Orthop*. 2021 May 24;25:283–287.

IV Lehtimäki K, Holstila M, Mäkelä K, Kukkonen J, Tirkkonen K, Harjula J, Kauko T, Äärimaa V. Structural auto- and allogenous glenoid bone grafting in reverse shoulder arthroplasty – retrospective radiological and component survial analysis. *J Orthop Reports.* 2025 Dec Volume 4, Issue 4.

1 Introduction

Reverse shoulder arthroplasty (RSA) was originally designed to treat pseudoparalytic and painful shoulders with cuff tear arthropathy (CTA). Promising early reports on improved functional outcomes and pain relief have been followed by a significant increase in the number of primary RSA operations worldwide (Kim et al. 2011; Dillon et al. 2017; Harjula et al. 2018; Mayfield et al. 2023). Encouraging results have expanded the indications for surgery to other complex shoulder problems including glenohumeral osteoarthrosis (OA) with severe glenoid bone loss, acute proximal humeral fracture (PHF), fracture sequelae, and revision surgery. RSA involves a semi-constrained prosthesis that improves shoulder stability and active elevation in the absence of a functional rotator cuff. The prosthesis design is based on four key elements:

1) The centre of rotation is medialized and distalized.
2) The deltoid muscle is the stabilizer of the joint and the motor of movement.
3) Lowering the humerus relative to the glenoid increases muscle tension in the deltoid.
4) There is a more constrained convexity of the glenoid component, with complementing concavity of the humeral component.

Despite promising clinical results of RSA, complications have been a concern. The most common complications include infection, dislocation, scapular notching, periprosthetic fracture, acromion fracture, and baseplate loosening (Zumstein et al. 2011; Richards et al. 2014; Morris et al. 2015; Villacis et al. 2016; Kang et al. 2019; Moeini et al. 2019; Belay et al. 2020; Kunutsor et al. 2020). The clinical outcome of RSA is sometimes unpredictable, with loss of active internal and external rotational movement of the arm. Scapular notching has been a major concern in the literature, as it can depreciate long-term clinical outcomes. Factors affecting clinical outcomes after RSA can be divided into patient, surgical, and implant-related. Patient-related factors include preoperative diagnosis, scapular anatomy, glenoid/humeral bone loss, and soft-tissue conditions around the joint. Surgical factors include both technical issues (e.g. glenosphere positioning and tilt, humeral and glenosphere version) and implant-related factors (e.g. glenosphere size and offset, humeral offset/valgus and polyethylene spacer eccentricity, constraint and thickness). The aim of this thesis was to investigate the risk and risk factors leading to revision after RSA in the Nordic register of CTA, OA, and PHF patients. Another goal was to investigate retrospectively patients who had undergone RSA at Turku University Hospital between 2007 and 2019 and the potential correlation between radiographic parameters and clinical outcomes. Additionally, the study aimed to assess the survival of bone auto- and allografts under the glenosphere in cases of significant glenoid bone loss.

2 Review of the Literature

2.1 Anatomy and function of the shoulder

The shoulder joint is often referred to as the glenohumeral joint, from the Greek *glene* (eyeball) and -*oid* (form of) and the Latin *humerus* (shoulder). The shoulder girdle has three joints: the sternoclavicular joint, which is the only joint articulating between the upper limb and the torso; the acromioclavicular joint between the lateral end of the clavicle and acromial process of the scapula; and the glenohumeral joint, defined as an enarthrodial or freely moving joint in which a sphere on the head of one bone fits into a rounded cavity in the other. The scapulothoracic joint makes up the “fourth” joint of the shoulder girdle and is a muscular suspension that stabilises the scapula during arm elevation. The scapulohumeral rhythm is the kinematic interaction between the scapula and the humerus (Codman 1934).

The deltoid is a triangular shaped muscle originating from the lateral and anterior scapula, the acromion, and the scapular spine. (Figure 1). The distal insertion is a wide insertion on the proximal, lateral humeral shaft. The deltoid muscle has three parts: the anterior (clavicular), lateral (acromion), and posterior (spinal) segments. It is a large, powerful muscle acting as an effective abductor and external and internal rotator. (Netter 1998).

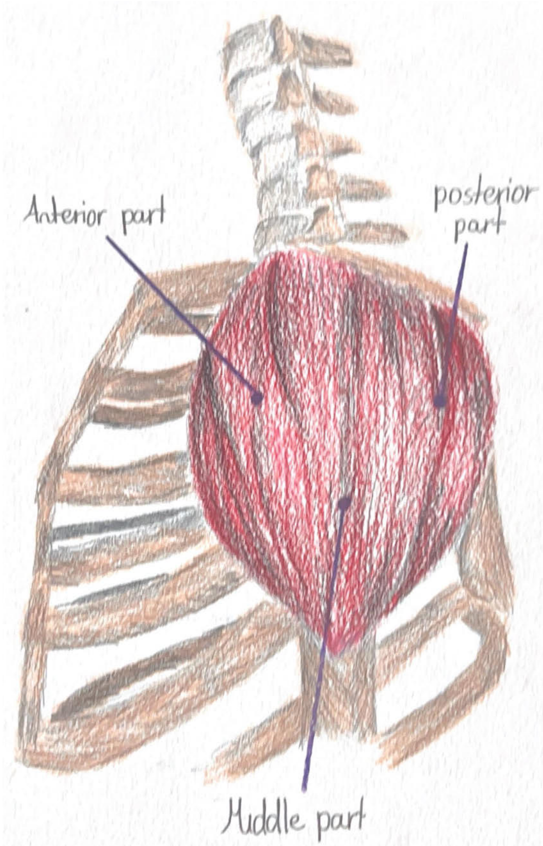


Figure 1. The deltoid muscle. Anterior, middle and posterior parts. Illustrated by Stella Lehtimäki.

The axillary nerve innervates the deltoid muscle. (Figure 2). It originates from the brachial plexus (upper trunk, posterior division, posterior cord) and carries fibres from the C5 and C6 roots. The nerve travels through the quadrilateral space, winds around the posterior humerus to innervate the deltoid and teres minor muscles, and carries sensation to the upper lateral shoulder.

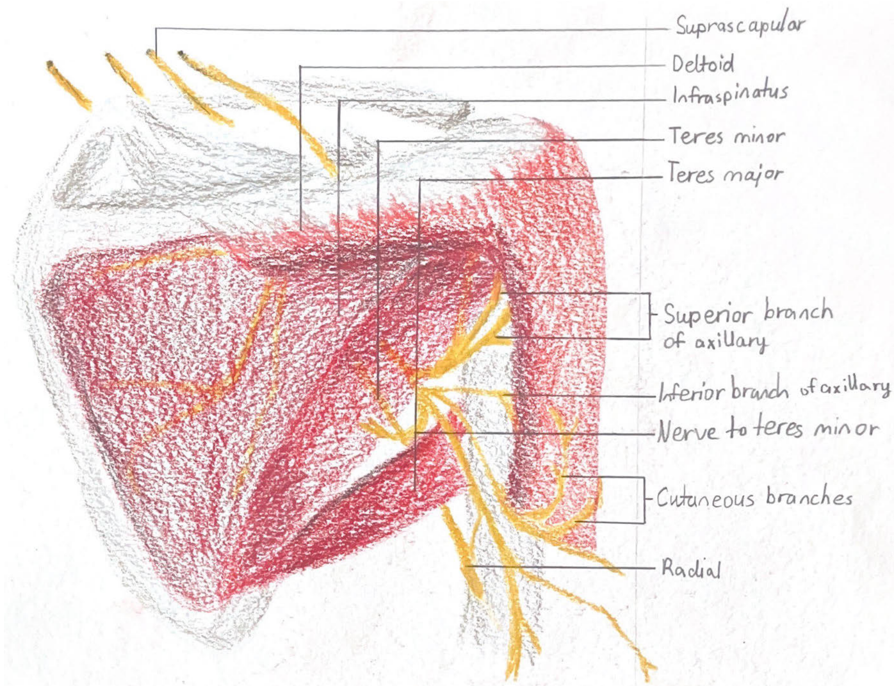


Figure 2. Anatomy of the axillary nerve. Illustrated by Stella Lehtimäki.

The rotator cuff consists of four muscles: the subscapularis, supraspinatus, infraspinatus, and teres minor. (Figure 3).

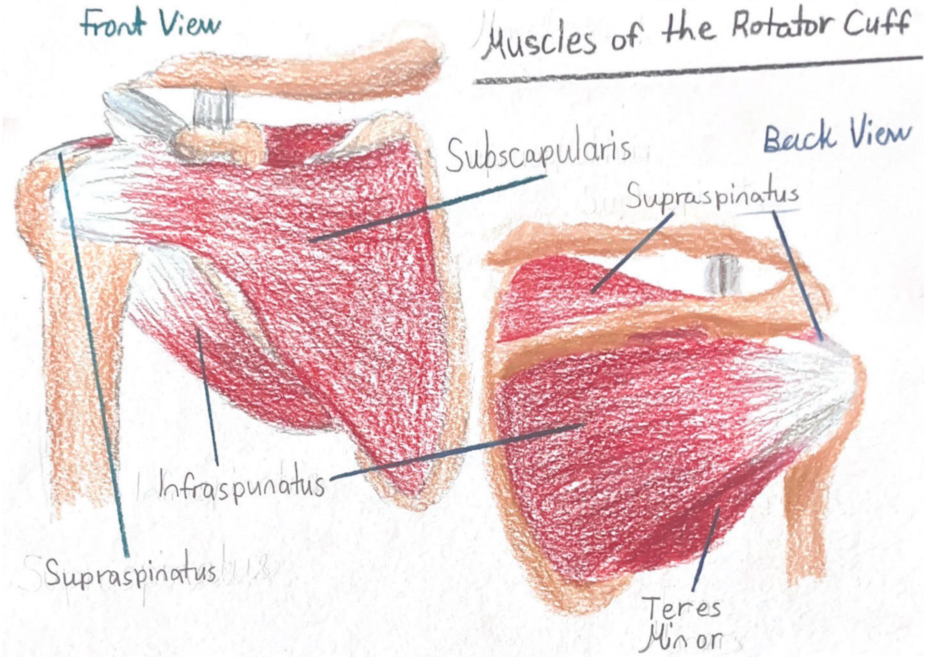


Figure 3. Muscles of the rotator cuff. Illustrated by Stella Lehtimäki.

The rotator cuff muscles start from the scapula and form a sock-like structure around the humeral head. These muscles function together as a dynamic fulcrum in the native shoulder to pull the humeral head in the centre of the glenoid. The supraspinatus and infraspinatus muscles serve as downward pushing forces as the deltoid is lifting the arm. The subscapularis muscle's primary function is internal rotation; the secondary function is that as the arm is raised, it pulls the humerus forward and downward. The suprascapular nerve innervates the supraspinatus and infraspinatus muscles. The subscapular muscle is supplied by the upper and lower subscapular nerves. The teres minor rotates the arm externally at the shoulder joint and is innervated by a branch of the axillary nerve.

In the classic anatomy article of Inman et al. from 1944, the normal shoulder movement is well described: "We may say in summary, that during early phases of elevation of the arm, the sternoclavicular joint passes through its greatest ranges of movement, and in the terminal phase, the acromioclavicular. At the glenohumeral and scapulothoracic articulations, the ratio, from almost the beginning to the termination of the arc, is respectively two to one, so that every 15 degrees of elevation, the glenohumeral contributes 10 degrees, and the scapulothoracic 5 degrees," not that the first 90 degrees of abduction of flexion is from the glenohumeral joint and the other 90–180 degrees from the scapulothoracic (Inman et al. 1944).

2.2 Pathoanatomy and biomechanics

2.2.1 Glenohumeral osteoarthrosis

Osteoarthrosis (OA) of the shoulder is defined as progressive damage of the glenohumeral joint with bony erosions, some with osteophytes, and a loss of function of the glenohumeral joint. OA often appears alongside intact rotator cuff muscles, and CTA is referred to as OA with a damaged rotator cuff (Stanborough et al. 2022). OA can be classified into primary and secondary types. Primary osteoarthrosis is idiopathic, generally occurring without any preceding joint injury or disease, often seen in older individuals as part of the natural aging process (Kobayashi et al. 2014, Oh et al. 2011). In contrast, secondary osteoarthrosis is a result of known factors such as previous trauma, joint instability, or inflammatory diseases (Gerber et al. 2003). OA is a degenerative joint disease marked by a gradual breakdown of joint tissues, including the cartilage, leading to the progressive destruction of the joint architecture and function (Biljlsma et al. 2011). The progressive nature of OA can significantly impair mobility and quality of life. In young patients highly shoulder demanding activities may be a potential risk factor for developing eccentric OA. Eccentric OA could be secondary due to a muscular imbalance between internal and external rotators caused by improper weight training (Plachel et al. 2023).

2.2.2 Cuff tear arthropathy

Neer et al. introduced the cuff tear arthropathy term in 1977 and later described the clinical aspect of the disease in detail (Neer et al. 1977, Neer et al. 1983). A historical review by Stig Brorson (2019) showed that these pathoanatomical and biomechanical changes, later termed CTA, were already well understood and clearly described in nineteenth-century medical literature (Adams 1857). CTA is described as a massive rotator cuff tear, proximal migration of the humerus resulting in femoralization of the humeral head and acetabularization of the acromion, biceps pathology and osseous changes such as glenoid erosion, loss of glenohumeral articular cartilage, and eventually humeral head collapse (Brorson 2019).

Halverson introduced the term “Milwaukee shoulder” in 1981. Neer considered the CTA and Milwaukee shoulder to be the same condition (Halverson et al. 1981, Neer et al. 1983). In the Milwaukee shoulder, hydroxyapatite crystals accumulate in the shoulder joint, leading to heightened collagenase and protease activity and consequent joint destruction.

It has been estimated that only 4% of patients with a complete tear of the rotator cuff end up developing CTA (Neer et al. 1983). Neer believed that both nutritional and mechanical factors play a role. Loss of the enclosed joint space leads to extravasation of synovial fluid, altered intra-articular pressure, and impaired nutrition of the articular cartilage. Pain and inability to move the joint leads to osteoporosis and eventually collapse of the subchondral bone of the humeral head. Mechanical factors result from the tear of the cuff, leading to loss of dynamic stabilisation and concavity compression. A massive rotator cuff tear involving more than two tendons can allow migration of the proximal humerus and wear of the glenohumeral articular cartilage, glenoid, acromion, acromioclavicular joint, and coracoid.

A decrease of compression forces, such as occurs with a massive rotator cuff tear, creates inability to resist the superior translational forces of the deltoid. Superior migration of the humeral head may occur, leading over time to cuff tear arthropathy (Ecklund et al. 2007).

2.3 Clinical manifestation

2.3.1 Glenohumeral osteoarthrosis

A typical symptom in OA patients is pain, which worsens during activities involving shoulder motion. Often there is no pain at rest in the upright position, but when sleeping it may be difficult to find a painless posture, leading to loss of sleep.

Loss of range of motion, especially external rotation, is another key symptom alongside anterior capsular contraction. Internal rotation and forward flexion are often also limited. (Ibounig et al. 2021).

2.3.2 Cuff tear arthropathy

Patients with CTA often complain of chronic, progressive shoulder pain that worsens during and after activity. The pain is often worse at night. Elderly women are more likely than men to have CTA (Ecklund et al. 2007). Patients also complain of weakness and difficulty lifting the arm, limiting normal daily activities (Feeley et al. 2009). Decreased active and passive range of motion, especially with elevation and external rotation, are typical clinical findings (Zeman et al. 1998). In some patients, severely changed biomechanics can lead to pseudoparalysis of the shoulder (Jensen et al. 1999). Physical examination often reveals the classic signs of a rotator cuff tear, like atrophy of the supraspinatus and infraspinatus muscles.

2.4 Imaging

2.4.1 Radiography

Radiographs are the most common form of radiological examination of patients with shoulder complaints. The radiographic series should include an anteroposterior (AP) view of the shoulder in internal rotation, “true” or Grashey AP external rotation, and axillary (or axial or Westpoint) and outlet view (“Y” view with 10–15º of caudal angulation). The “true” AP view is taken by angulating the X-ray tube 35–45º laterally, which allows better evaluation of the glenohumeral joint space. This view enables evaluation of the superior migration of the humeral head and measurement of the acromiohumeral distance, also known as the acromiohumeral interval (AHI) (less than 7 mm suggesting rotator cuff pathology) (Moosikasuwan et al. 2005). An axillary view is a tangential view of the glenohumeral joint and is used to analyse the glenoid morphology with the arm in the abducted position. In primary OA the finding is typically asymmetrical posterosuperior joint narrowing, and in secondary OA axial, symmetric, and diffuse joint space narrowing. The glenoid bone stock can also be evaluated, which is critical in the preoperative assessment of shoulder arthroplasty, especially with RA (rheumatoid arthritis) and OA.

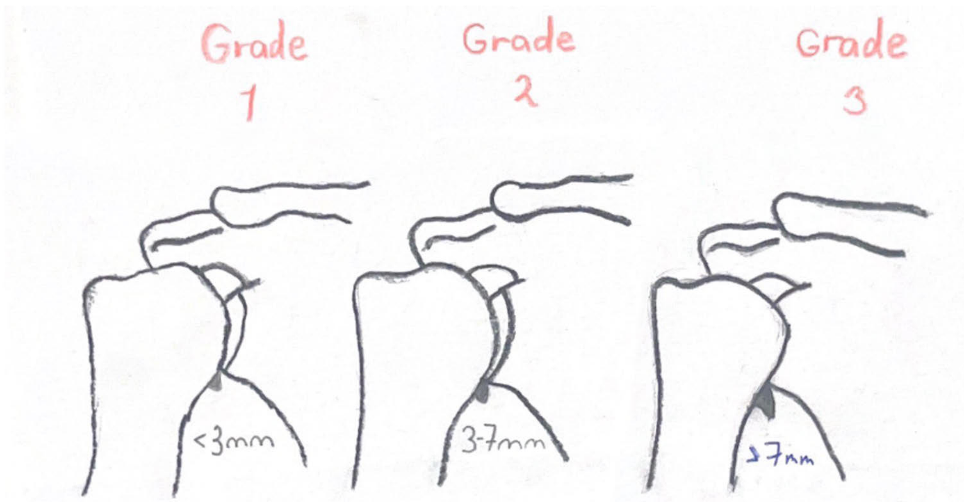
Classifications on radiographs help to estimate the severity of OA and CTA. The Kellgren-Lawrence system for classification of general OA is a five-grade evaluation system (Kellgren et Lawrence 1957) (Table 1). The Samilson-Prieto classification is specific to shoulder OA (Samilson et Prieto 1983) (Figure 4). The classification of CTA has been described by Hamada et al (Hamada et al. 1990) (Figure 5).

It is important to highlight that radiographic classification is a general guideline for evaluating OA and CTA severity, alongside clinical and physiological examination. The primary clinical feature of pain as a main indication for surgery is not related to radiological parameters (Kircher et al. 2010). In the same study by Kircher et al. (2010), the size of caudal humeral osteophytes was predictive of function.

Radiographs are the most useful, easy to obtain, and cost-effective screening modality in diagnosing shoulder OA and CTA in deciding among different treatment options.

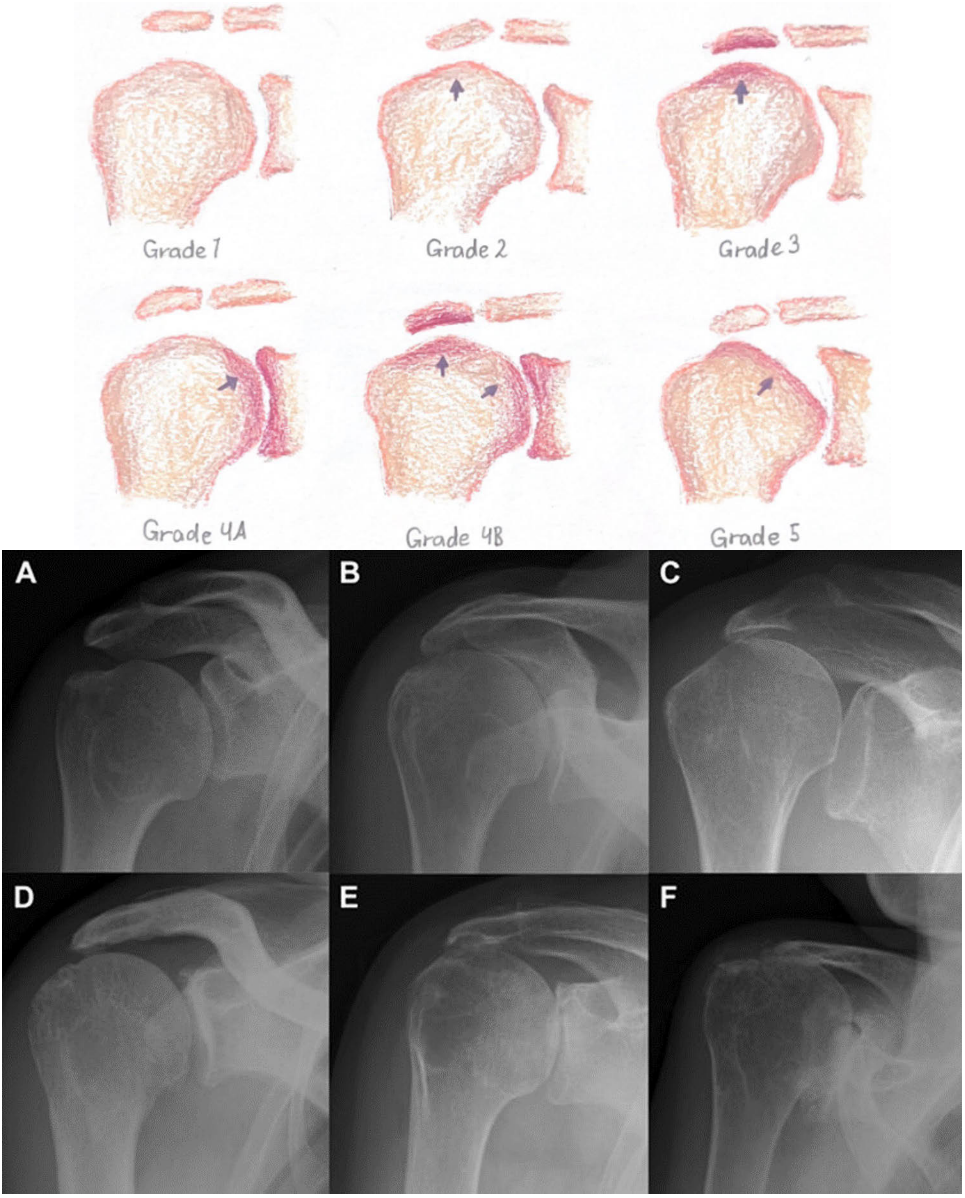
Table 1. The Kellgren-Lawrence classification of OA.

Grade 0:	Definitive absence of X-ray changes of OA
Grade 1:	Doubtful joint space narrowing and possible osteophytic lipping
Grade 2:	Definitive osteophytes and possible joint space narrowing
Grade3:	Moderate multiple osteophytes, definitive narrowing of joint space, some sclerosis, and possible deformity of bone ends
Grade 4:	Large osteophytes, marked narrowing of joint space, severe sclerosis, and definitive deformity of bone ends



Grade 1:	Mild arthrosis, inferior humeral and/or glenoid exostosis<3 mm in height
Grade 2:	Moderate arthrosis: inferior humeral and/or glenoid exostosis measuring 3–7 mm, slight glenohumeral irregularity
Grade 3:	Severe arthrosis: inferior humeral and/or glenoid exostosis measuring >7 mm and glenohumeral joint narrowing and sclerosis

Figure 4. Modified Samilson-Prieto classification of shoulder OA. Illustrated by Stella Lehtimäki. (Samilson et Prieto, 1983).



Grade 1/A:	Acromionhumeral interval (AHI) >6 mm
Grade 2/B:	AHI <6 mm
Grade3/C:	AHI <6 mm with acetabulisation
Grade 4A/D:	Glenohumeral osteoarthrosis without acetabulisation
Grade 4B/E:	Glenohumeral osteoarthrosis with acetabulization
Grade 5/F	Collapse of the humeral head

Figure 5. Modified Hamada classification of CTA. Illustrated by Stella Lehtimäki. (Hamada et al. 1990). Radiograph Hamada classification reprinted with permission Hasegawa et al. 2022.

2.4.2 Computer tomography

Radiographs are of limited value in glenoid quantification due to the 2D (dimensional) imaging orientation. In shoulder arthroplasty it is important to determine the glenoid bone stock, glenoid version, and inclination (Werner et al. 2017; Sharifi et al. 2020). CT is commonly performed preoperatively and enables 3D planning.

The modified Walch classification defines glenoid bone loss in the axial plane and the Favard classification in the coronal plane. (Bercik et al. 2016) (Favard et al. 2017) (Figures 6 and 7).

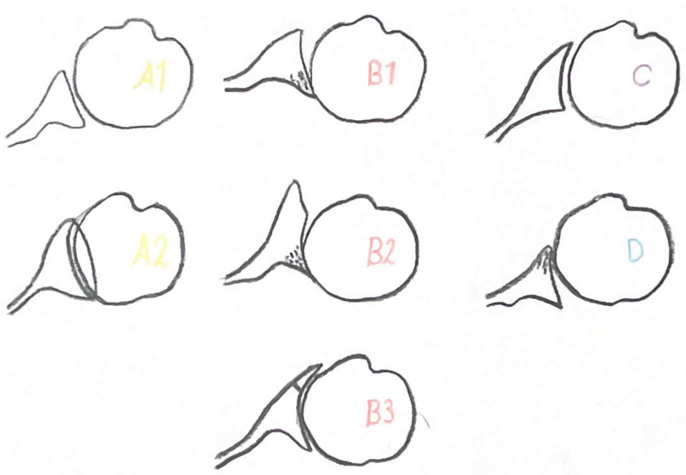


Figure 6. Modified Walch classification. Illustrated by Stella Lehtimäki after Bercik et al. 2016, with permission.

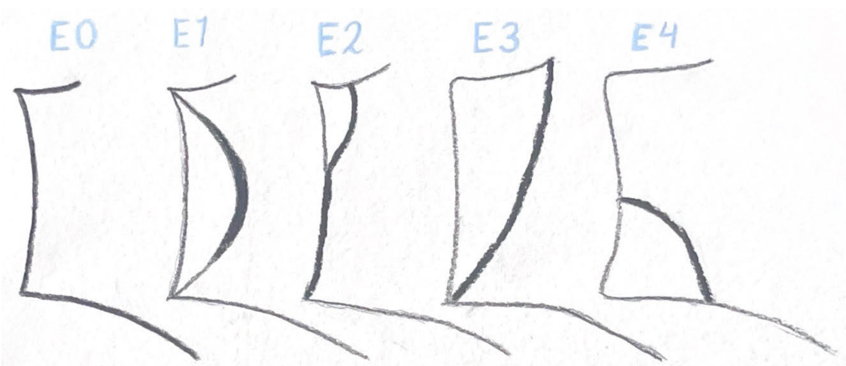


Figure 7. The Favard classification. Illustrated by Stella Lehtimäki from Favard et al. 2007.

Both the Walch and Favard classifications guide the orientation of glenoid bone loss and the need for grafting either with bone or metal augment.

The Friedman line is a line drawn from the scapular trigonum to the glenoid centre. In the neutral scapular version, it is aligned with the scapular body. When they deviate, the angle is defined as either anteversion or retroversion as shown in Figure 8 (Friedman et al. 1992).

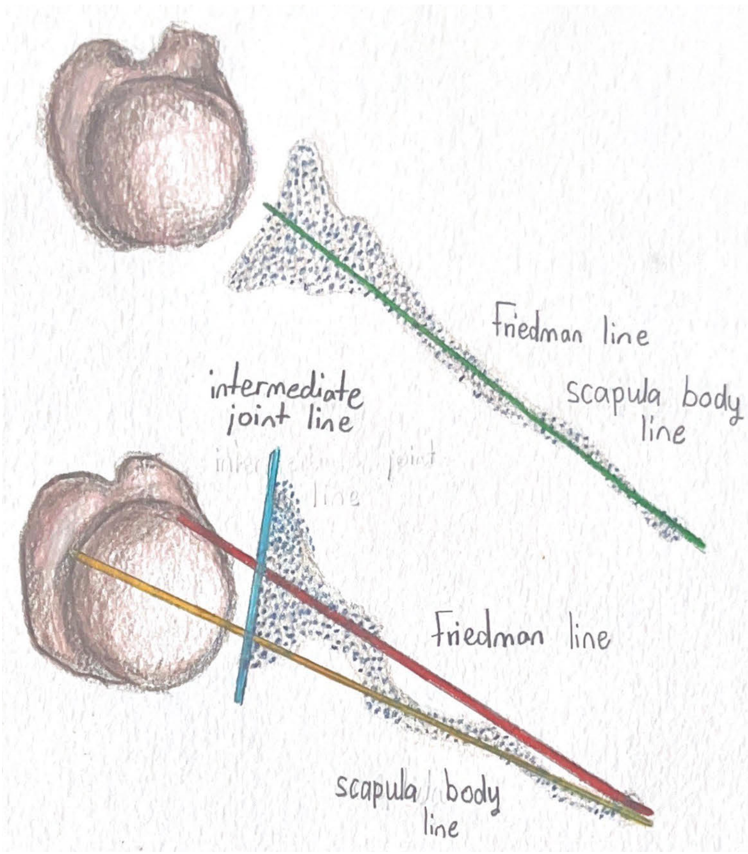


Figure 8. Friedman line. Top: neutral scapular version; the Friedman and scapular body lines are aligned. Bottom: retroverted glenoid cavity showing deviation of the Friedman line from the scapular body line. Illustrated by Stella Lehtimäki.

The Friedman method does not take into account the posterior eroded glenoid, also known-as a neoglenoid. Methods to measure retroversion and subluxation in biconcave glenoids have been validated (Kidder et al. 2010; Rouleau et al. 2010) (Figure 9).

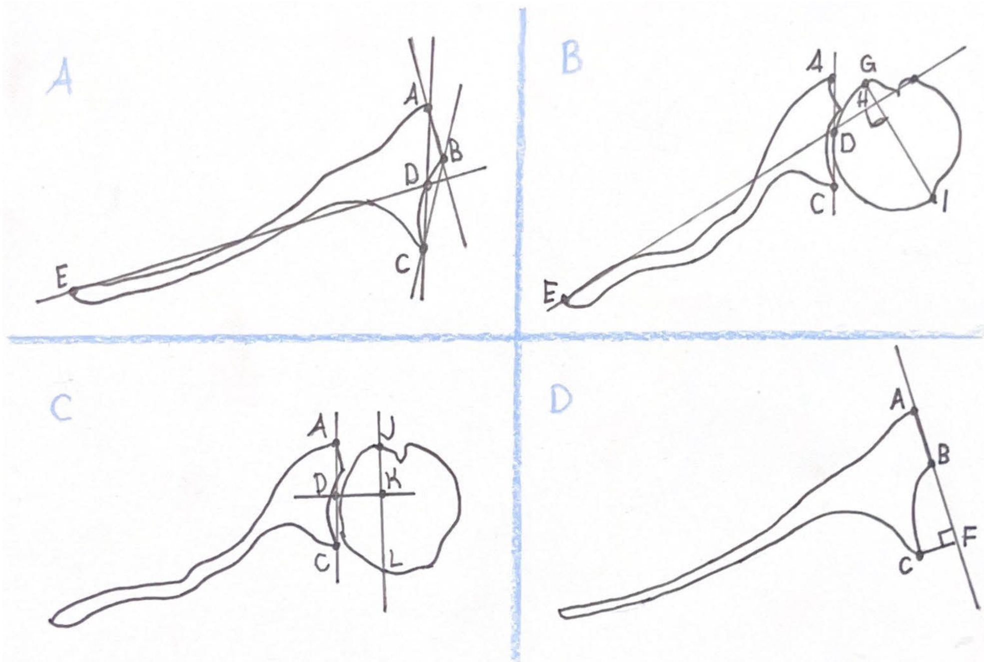


Figure 9. Illustrated by Stella Lehtimäki. Reprinted with permission from Walch et al. 2012.

A. Retroversion (RV) according to the Friedman line (ED): AB represents the native glenoid or paleoglenoid (RV1 angle), BC is the posterior eroded surface or neoglenoid (RV3) angle), and AC is the intermediate glenoid (RV2 angle).

B. Subluxation with regard to the scapular body (scapular axis) or Friedman line (ED): the percentage of the humeral head posterior to that line (HI/GI) is assessed at the longest anteroposterior diameter of the head on a line perpendicular to the scapular axis.

C. Subluxation with regard to the “mediatrice” line (DK), drawn as a perpendicular line to the intermediate glenoid (AC) passing through its middle (subluxation/glenoid): a percentage of the humeral head posterior to that line is measured at the larger anteroposterior diameter (KL/JL).

D. Depth of glenoid erosion: the CF depth magnitude (in mm) corresponds to the perpendicular distance between the posterior border of the glenoid erosion and the paleoglenoid reference line (AF), and its rate (%) is calculated as the rate of CF/AF. Reprinted with permission from Walch et al. 2012.

CT is useful in determining the rotator cuff muscle atrophy and fatty degeneration in the sagittal plane. The Goutallier classification is used to quantify the amount of fatty degeneration of the rotator cuff muscles (Goutallier et al. 1994). (Figure 10.)

0 1 2 3 4

Figure 10. Goutallier classification. Grade 0 = normal muscle without fatty streaks. Grade 1 = muscle containine some fatty streaks. Grade 2 = fatty infilrtation is prominent but with more muscle than fat. Grade 3 = fat as much as muscle. Grade 4 = more fat than muscle. Printed with permission from Gueniche et Bierry, 2019.

2.4.3 Magnetic resonance imaging (MRI)

MRI plays a role in whenever the cuff integrity is unclear and is indicated to evaluate rotator cuff tendon integrity and muscle atrophy. Another way of getting information on the status of the rotator cuff is CT arthrography if MRI is not available or is otherwise contraindicated. The accuracy of CT arthrography in evaluating rotator cuff tears is similar to that of MRI (Omoumi et al. 2012), but it is a more invasive procedure with greater radiation exposure. MRI is rarely needed in the diagnosis of CTA.

2.5 History of shoulder arthroplasty

2.5.1 Early history of shoulder arthroplasty

The first shoulder arthroplasty was performed in 1893 by Jules Émile Péan (Figure 11) on a 37-year-old baker suffering from shoulder joint tuberculosis. The implant was made of platinum and rubber. The initial clinical result was excellent, but resection arthroplasty was performed 2 years later because of infection. The removed implant is currently displayed in the Smithsonian Institution in Washington D.C (Figure 12) (Bankes & Emery 1995).

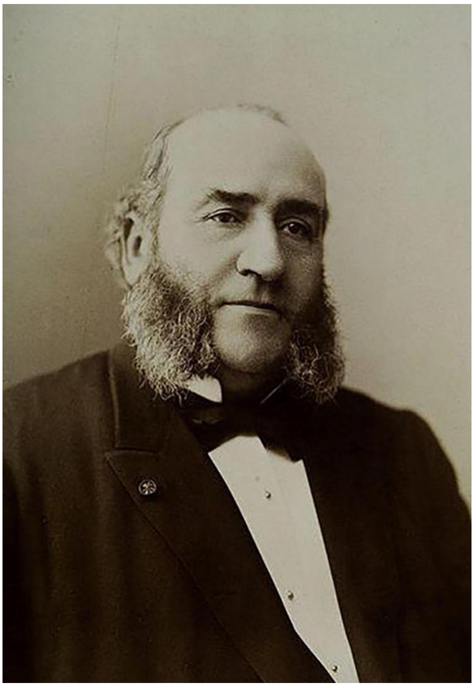


Figure 11. Jules Émile Péan. Reprinted with permission from Markatos et al. 2019.

Figure 12. The first shoulder prosthesis. Reprinted with permission from Willems 2021.

The first modern-era anatomic metal shoulder hemiprosthesis was introduced in 1950 by Krueger (1951) for a patient with avascular necrosis of the humeral head, with good clinical results.

The two "grand old men" of shoulder arthroplasty development in the 20th century were Charles Neer (1917-2011) and Paul Grammont (1940-2013). Neer developed an anatomic shoulder prosthesis for fracture-dislocations. In 1955, he reported (Neer 1955) that 11 of 12 patients with a Vitallium prosthesis were out of pain. Neer demonstrated satisfactory results for avascular necrosis, fractures, and a single case of osteoarthrosis with the "Neer 1 prosthesis" (Neer 1994).

The "Neer 2" was a total nonconstrained shoulder prosthesis for osteoarthritis affecting also the glenoid side. In a series of 46 minimum 2-year follow-up patients, there were 20 excellent, 20 satisfactory, and six unsatisfactory results (Neer 1974). Neer noted that the anatomic shoulder arthroplasty gave less satisfactory results for patients with cuff deficiency (Neer et al. 1982). Without a functional rotator cuff when using a conventional total shoulder arthroplasty (TSA), an unopposed deltoid contraction creates a force vector that progressively displaces the humeral head superiorly. This phenomenon leads to migration of the humeral head to the acromion and superior part of the glenoid.

In the 1970s, the first versions of constrained and semi-constrained models were developed for cuff-deficient arthritic shoulders. The idea was adapted from the hip joint, ball and socket model. The first reversed prosthesis was introduced by Reeves in 1972 (Reeves et al. 1972), with a fixed centre of rotation (COR) on the glenoid side. Gliding surfaces were non-anatomic: a ball on the glenoid side and a socket on the humeral side. Originally there were several RSA models, most of which did not end up in wide clinical use due to their high revision rate (Bayley and Kessel 1982, Brostrom et al. 1992). The most common reason for failure was instability. The lateralised COR on the glenoid side also resulted in excessive torque and shear forces.

2.5.2 History of RSA and common misconceptions

In his Reverse Shoulder Arthroplasty textbook, Derek Pupello cites the writings of Boulahia et al. (Boulahia A et al. 2002) on the origins of RSA and some common misconceptions (Pupello 2016): “Earlier attempts using a reverse shoulder prosthesis design were burdened by early loosening of the glenoid component caused by a laterally offset centre of rotation resulting in a rocking horse phenomenon occurring at the glenoid bone interface.” The rocking horse phenomenon was originally published by Franklin et al. (1988) and actually concerned glenoid loosening in total anatomic shoulder arthroplasty, not RSA. The second misconceived sentence was, “The laterally located centre on the rotation of the early reverse design prosthesis causes early loosening.” In the development process of RSA, glenoid side fixation methods varied, as well as the constraint of the implants. The lateralised COR was widely used and repeated in the literature without clear evidence supporting it. The early patient series were small and heterogeneous, and the causes of glenoid failure were not reported. Some of the studies did not report any glenoid side failures at all. High failure rates were referred to in early studies, which contained more constrained anatomic prostheses than reverse (Boileau et al. 2005).

Pupello found that 75% (24 of 32) of the current RSA literature contains at least one quotational error. Even I referred to the Bouhalia study in Study II of this thesis, but on the basis of good early results did not refer to early failures (Bouhalia et al. 2002)

2.6 The Grammont-style RSA and its biomechanics

The second of the 20th-century “grand old men” of shoulder surgery, Paul Grammont, introduced his revolutionary RSA idea in 1987 (Grammont et al. 1987) (Figure 13).

Figure 13. Reprinted with the permission of Pascal Boileau 2011.

There are four original principles behind the novel shoulder arthroplasty having overcome the earlier reasons for failure, ending up with one of the most successful orthopaedic implants ever (Figure 14).

- Reliance of the prosthesis motor of movement and stability on the deltoid muscle
- Medialized and distalized COR
- Lowering of the humerus relative to the glenoid to increase deltoid muscle tension
- Convexity of the glenoid component with complementing concavity of the humeral component.

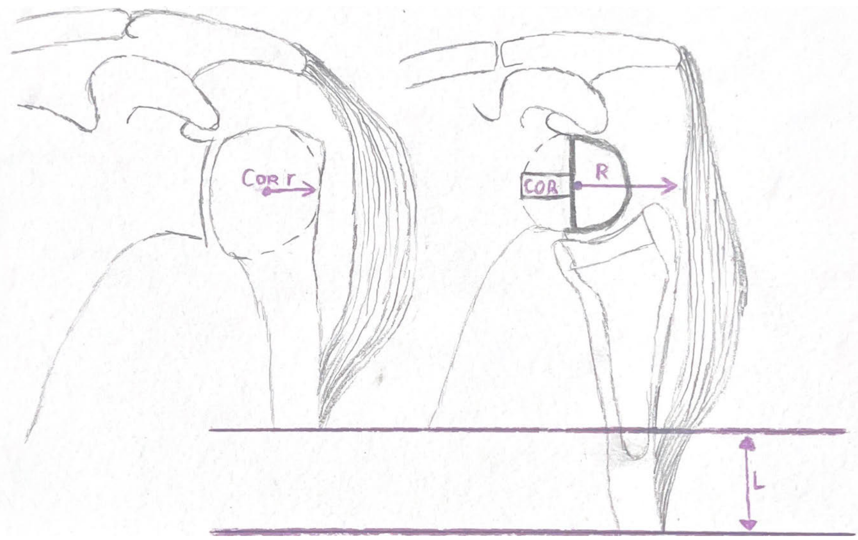


Figure 14. 1a normal shoulder. 1b shoulder with RSA. (L) lowering the humerus lengthens the deltoid fibres. This increases the strength of the deltoid. R<r. The COR is medialised with the RSA; the lever arm is greater to initiate elevation with RSA. Illustrated by Stella Lehtimäki with permission from Boileau et al. 2005.

These principles are based on a stable construct that allows the delta to compensate for an absent rotator cuff. This design of first Grammont style prosthesis was featured with two-thirds of a sphere fixed on the glenoid. The glenohumeral COR was medialised but remained lateral to the native glenoid. The prosthesis consisted of two components. The glenoid component was a metallic or ceramic 42mm large ball with cement fixation. (Figure 15). The humeral component was socket-shaped and made from polyethylene. It was also fixed with cement inside the humeral medulla.

Figure 15. The first Grammont reverse shoulder prosthesis design from 1985. (Published with permission. Reprinted from Boileau P, Watkinson DJ, Hatzidakis AM, et al. Grammont reverse prosthesis: design, rationale, and biomechanics. J Shoulder Elbow Surg 2005;14(Suppl 1):147S–61S; with permission from Elsevier.)

The modern design of RSA, the Grammont second-generation prosthesis, Delta III, was introduced in 1991. In this prosthesis the two-thirds sphere was replaced with a hemisphere. This solution placed the COR directly on the surface of the glenoid articular surface, decreasing the lateral offset of the glenohumeral articulation and thereby decreasing the shearing forces on the glenoid component. The fixation was changed from cemented to non-cemented by a circular glenoid baseplate with a central peg and additional divergent screw fixation. The humeral side was either cemented or non-cemented.

On the humeral side, the shaft was inlayed in the proximal humerus. The component featured a small polyethylene cup covering less than half of the glenosphere. The neck-shaft angle was a non-anatomical inclination of 155°. The uncemented Delta III has five parts: the glenoid base plate, the glenosphere, the polyethylene humeral cup, the humeral neck, and the humeral stem (Figure 16).

Figure 16. The Delta III prosthesis. (Reprinted from Boileau P, Watkinson DJ, Hatzidakis AM, et al. Grammont reverse prosthesis: design, rationale, and biomechanics. J Shoulder Elbow Surg 2005;14(Suppl 1):147S–61S; with permission from Elsevier.)

The Delta III has shown successful results in numerous end-stage degenerative shoulder problems (Werner et al. 2005, Boileau et al. 2006, Simowitch et al. 2007, Stechel et al. 2010, Castricini et al. 2013). In November 2003, the United States Food and Drug Administration (FDA) approved RSA for use in the US. Since then, the indications for RSA have broadened to other diagnoses than CTA: glenohumeral osteoarthritis, failed conventional total shoulder arthroplasty (TSA), fracture sequela, RA, irreparable rotator cuff tears, proximal humerus tumours, and PHF.

2.6.1 Theoretical weaknesses of the Grammont-style RSA

Despite good clinical results, the Grammont-style RSA has some biomechanical drawbacks. First, the excessive medialization is biomechanically unfavourable, as it may cause slackening of the intact cuff muscles, possibly leading to instability and problems with deficient active external and internal rotation. Active external rotation is essential for normal daily activities such as eating, drinking, washing, grooming, holding a phone to the ear, and even shaking hands. Shortening of the rotator cuff associated with RSA may also compromise the scapulohumeral rhythm (Walker et al. 2015), with a greater proportion of the scapular rotation occurring relative to the native shoulder.

Second, the inferior displacement of the humerus leads to tightening of the deltoid muscle. Intra-operative determination of deltoid tensioning is difficult and has several unfavourable biomechanical effects. Over-tensioning of deltoid muscle fibres, by as much as 20% with some RSA prosthetic designs, may lead to reduced deltoid wrapping around the greater tuberosity (Roche et al. 2013). This may have negative implications for joint stability and deltoid moment arm length, reducing the range of motion. Another negative impact of this over-tensioning could be axillary nerve damage, resulting in an inactive deltoid muscle, loss of the benefits of the surgical procedure, and risk of luxation of the joint. Acromion or scapular stress or fatigue fractures are possible, especially in patients with severe osteoporosis. This is a serious RSA-related complication for which there is no currently accepted optimal treatment option. Progressive distension of the deltoid muscle can deteriorate the clinical results after approximately 6 to 8 years (Guery et al. 2006).

Third, scapular notching and polyethylene wear may lead to clinical problems. Scapular notching is a common radiographic finding after RSA and infers a bony erosive lesion of the inferior scapula neck. Scapular notching is analysed in greater detail in Chapter 2.10.3.

Given these three limitations of the Grammont-style prosthesis, several biomechanical solutions have been developed over the past two decades to address these issues.

2.7 New generation RSA prosthesis

2.7.1 Factors affecting range of motion

Over the past two decades, thanks to saw bone models, cadaver studies, computer models, and the introduction of software for three-dimensional (3D) CT analysis and preoperative 3D planning, there is now a better understanding of the biomechanics of RSA and possible weaknesses of Grammont-style RSA (Bauer et al. 2023, Bauer et al. 2023). In achieving maximal-function range of motion (ROM) after RSA, the goal is to increase the impingement-free ROM, i.e., the arc of motion between the humeral and glenoid components before the polyethylene contacts the scapula or the greater tuberosity contacts the acromion. Despite ongoing efforts to improve the implant feature and positioning, some patients still have a poor ROM after RSA.

Gutierrez et al. (2007 and 2008) published several articles analysing the factors related to impingement-free ROM. After working with saw bone models, the results were validated through computer-model simulations. These papers describe a hierarchy of factors with the most significant impact on increasing the impingement-free ROM (Gutierrez et al. 2007 and 2008) (Figure 17).

2.7.2 Glenoid side mechanics

The first and most effective factor is lateralization of the COR, which increases the superomedial space over the glenosphere. Increasing the superomedial space allows more space for abduction before the superolateral rim of the humeral insert impinges on the superior glenoid or acromion. The glenoid offset is the amount of lateral projection of the glenoid component from the reamed surface relative to its COR. Lateralization of the COR can be achieved with either the baseplate or the glenosphere itself. There are several options for achieving lateral offset of the glenoid, two of which relate to the hemispherical design: the glenosphere diameter size and lateral offset. Increasing the lateral offset so that the COR is over the native glenoid surface means that the required deltoid force for abduction increases, creating greater shear forces at the glenoid-implant interface (Henninger et al. 2012). An overly lateralized COR may be a risk factor for acromial stress fractures (Paszicsnyek A et al. 2022).

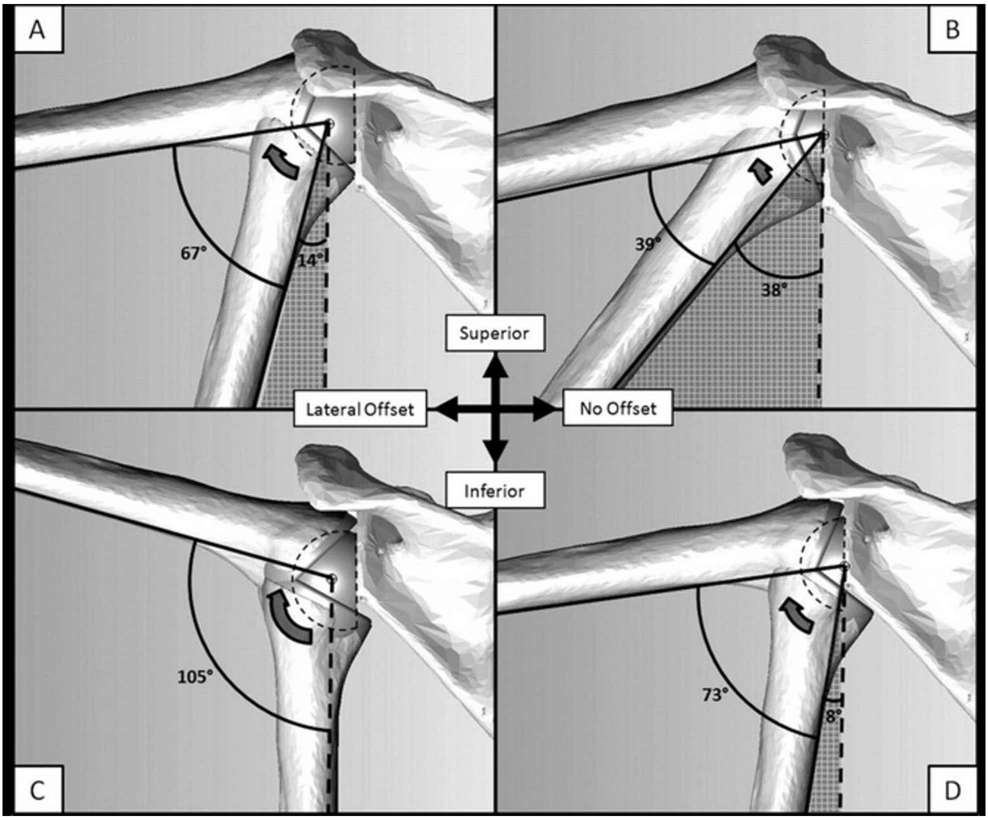


Figure 17. How the position and lateralization of the glenosphere affects abduction. A: Superior glenosphere position with lateral offset. B: Superior glenosphere position without lateral offset. C: Inferior glenosphere position with lateral offset providing the best abduction-adduction range. D: Inferior glenosphere position without lateral offset. Reprinted with permission from Gutierrez et al. 2008.

The second most effective factor in increasing abduction is distalization of the glenosphere. The surgeon can achieve this in several ways. First, the goal is to position the baseplate of the glenosphere as low as possible, with the outline of the baseplate flush with the inferior rim of the glenoid and perpendicular to the supraspinatus fossa line. For optimal positioning of the base plate, Boileau et al. advocated use of the RSA angle, defined as the angle between the inferior part of the glenoid fossa and the perpendicular to the floor of the supraspinatus (Boileau et al. 2019) (Figure 18).

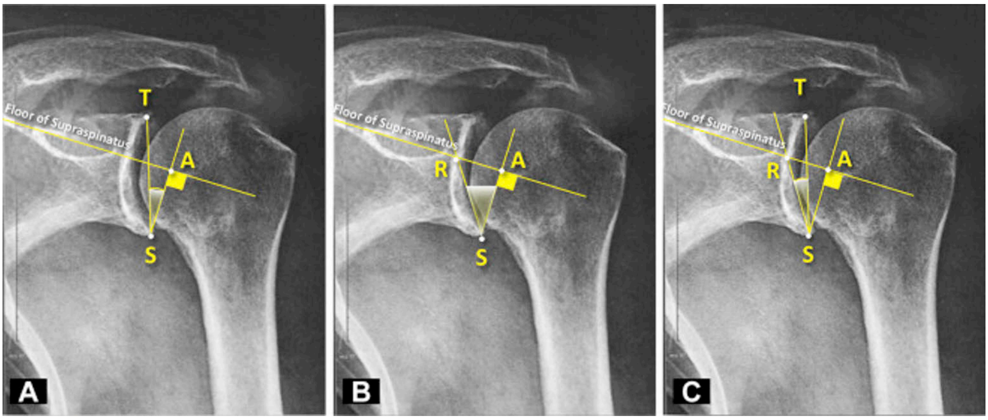


Figure 18. Measurements of total shoulder arthroplasty (TSA) angle (A) and RSA angle (B) on plain anteroposterior radiographs. The RSA angle was defined as the angle between the inferior part of the glenoid fossa and the perpendicular to the floor of the supraspinatus. The TSA angle is a variation of the β-angle. The difference between the TSA and RSA angles is shown by the RSA angle (C). Reprinted with permission from Boileau et al. 2019.

Another way to achieve distalization of the glenosphere is to choose a base plate with a smaller diameter (e.g., 25 mm over 29 mm), which distalizes the glenosphere even further. Finally, the ultimate way to maximize distalization of the glenosphere is to choose an eccentric glenosphere (Athwal et Faber 2016). An eccentric glenosphere offers the possibility to achieve an additional inferior positioning of a few millimetres compared to a concentric glenosphere by off-centre attachment of the glenosphere (Torrens et al. 2020).

The third relevant factor for increasing abduction is inferior tilting of the glenosphere. However, the inferior tilt should not be over-corrected, as it may lead to impingement of the scapula (Edward et al. 2012).

The fourth largest effect was achieved by changing the neck shaft angle from 130º to 150º. This is described in more detail in the next chapter.

The fifth factor enabling a rather minimal increase in abduction was increasing the glenosphere size from 36 to 42 mm.

2.7.3 Humeral mechanics

On the humeral side, various aspects of the humeral implant design affect the biomechanics of the RSA, such as humeral offset, neck-shaft angle, onlay versus inlay design, humeral liner thickness, and constraint. The humeral offset is defined as the distance between the axis of the humeral shaft and the centre of the polyethylene tray (Figure 19).

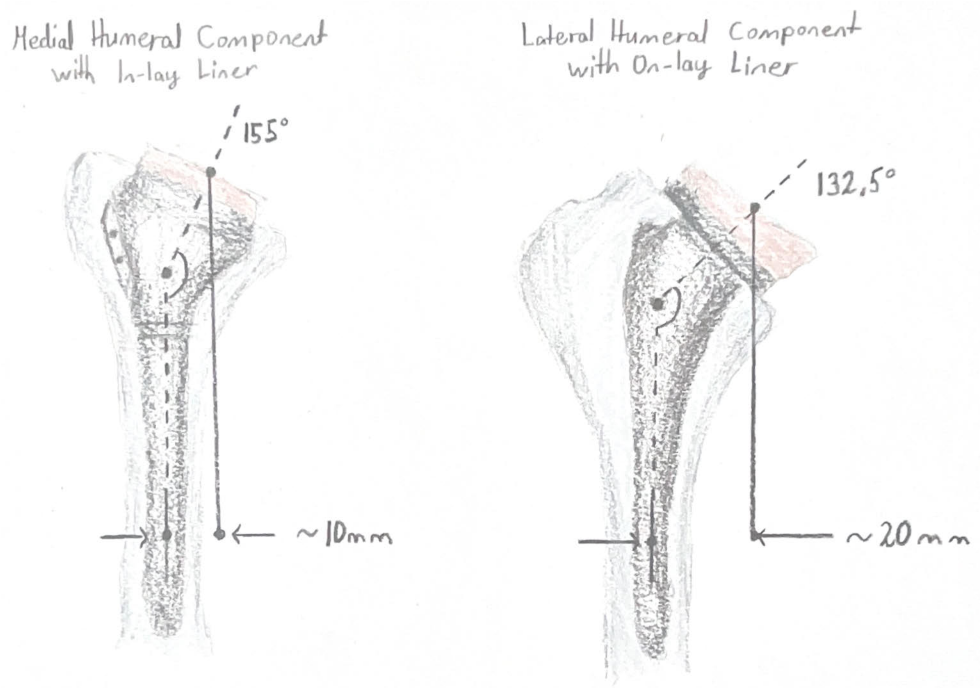


Figure 19. The humeral offset is defined as the distance between the axis of the humeral shaft and the centre of the polyethylene tray. The figure shows how a different neck-shaft angle increases the humeral offset. Right: example of a humeral onlay component. Left: a humeral inlay component. Illustrated by Stella Lehtimäki after Roche 2023, with permission.

Lateralization of the humeral component increases the deltoid wrapping effect (Roche et al. 2013). The term wrapping refers to the action of the middle deltoid winding around the lateral proximal humerus, generating a stabilizing compressive force; in other words, the humerus is further compressed against the glenosphere, increasing joint stability. Another advantage of an increased humeral offset compared to the Grammont-style prosthesis is the ability to re-tension the remaining rotator cuff muscles and tendons, potentially improving active external and internal rotation.

Humeral lateralization can be achieved by reducing the humeral neck-shaft angle from the Grammont 155º to 145º or 135º, decreasing the humeral liner constraint, or using an onlay stem instead of an inlay stem (Figure 18).

The advantages of an inlay stem include greater bony contact with the proximal humerus; however, a disadvantage is additional reaming of the metaphyseal bone and increased risk of fracture of the greater tubercle. A further disadvantage is increased scapular notching and less rotation. An onlay stem preserves proximal bone and minimizes damage to the remaining rotator cuff. Further, lateralization of the humerus increases the tension of the rotator cuff and lengthens the deltoid moment arm. An onlay stems offer the possibility of conversion from TSA to RSA (Kelly et al. 2023).

The motivation for reducing the neck-shaft angle to 135° or 145° is to minimize notching, at least in theory. However, this also lessens the impingement-free ROM at the end of abduction, because the lateral side of the greater tuberosity makes earlier contact with the lateral side of the scapula (Werner et al. 2017).

The humeral constraint is defined as the depth-to-width ratio of the humeral polyethylene liner. Roche et al. (2009) found that each 0.0125 mm interval reduction in the humeral constraint increases the overall range of motion by 4º, but also shortens the jump distance by 0.5 mm. There is a trade-off between decreasing the humeral constraint to provide greater impingement-free ROM and having a shorter jump distance and instability.

Summary of factors increasing ROM, according to Gutierrez:

1. Lateralization of the COR of the glenosphere
2. Distalization of the glenosphere
3. Inferior tilting of the glenosphere
4. Changing the humeral neck shaft angle from 130 to 150 degrees
5. Increasing the glenosphere size from 36 to 42 mm.

2.7.4 The Routman classification

A classification system was developed by Routman et al. (2015), who introduced a scheme based on the glenosphere and humeral implant offset. The glenoid component is considered medialized if its COR is 5 mm or less from the reamed glenoidal facet (MG) and lateralized if the COR is greater than 5 mm from the reamed glenoid facet (LG). (Figure 19).

The humeral component is categorized in the same manner by humeral offset. The humeral component is defined as medialized if its offset is 15 mm or less (MH). The humeral component is defined as lateralized if its offset is more than 15 mm (LH). Combining these features provides four different options (MG/MH, LG/MH, MG/LH and LG/LH) (Figure 20).

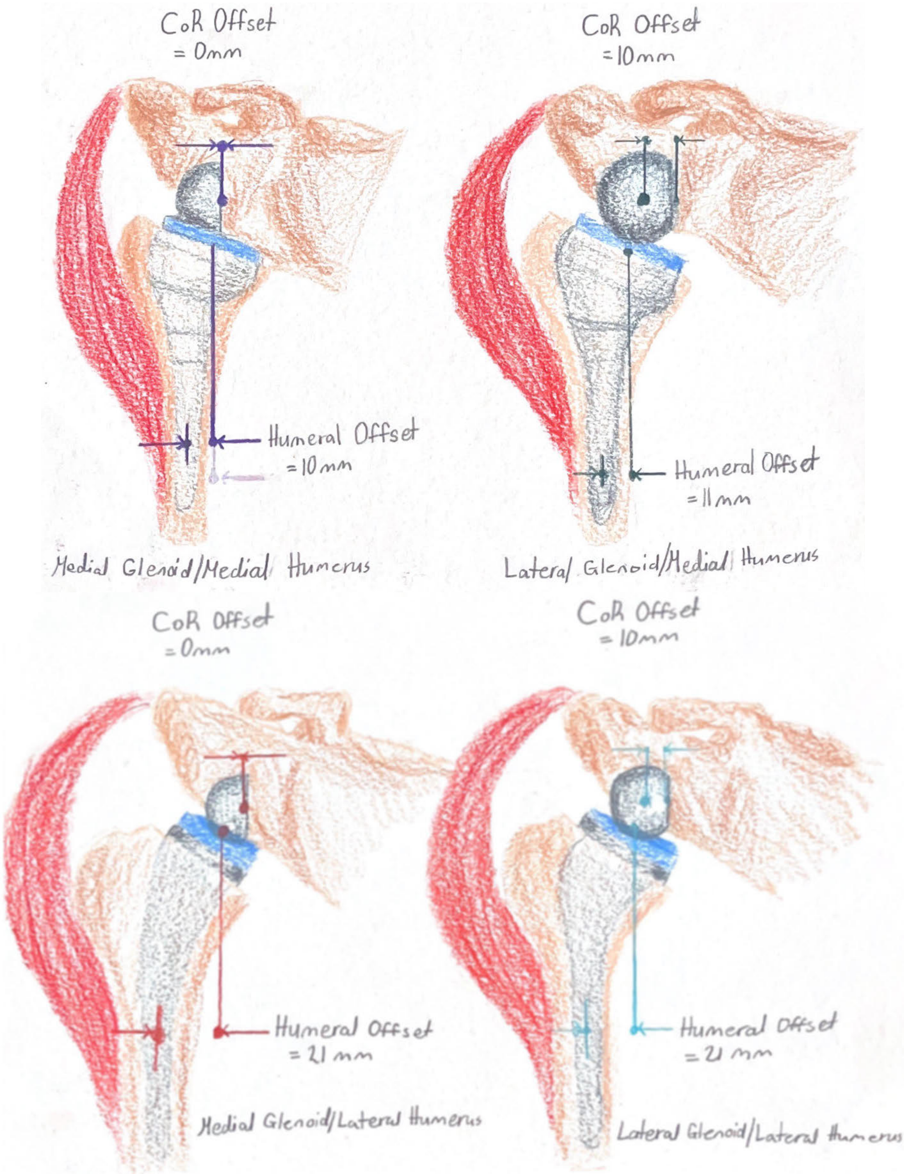


Figure 20. The classification system was developed by Routman et al. (20159 by introducing a scheme based on the glenosphere and humeral implant. Illustrated by Stella Lehtimäki.

MG/MH

The Grammont Delta III prosthesis is considered an MG/MH-type prosthesis with the most medial positioning of the COR and humerus component. The medialized COR maximizes the deltoid moment arm, resulting in good forward flexion. However, it also shortens the rotator cuff muscles and compromises rotation.

Scapular notching is the major concern due to the valgus neck-shaft angle. With this type of prosthesis, repair of the subscapularis tendon is recommended to improve joint stability (Edwards et al. 2009). In case of severe bone loss on the glenoid side, the MG/MH configuration may give unsatisfactory clinical results. In a recent meta-analysis addressing subscapularis tendon repair in RSA, the findings indicated a reduction in implant stability when a medialized implant was used. In other outcome measures, including ROM, there was no clinically significant difference whether the subscapularis tendon was repaired or not (Bethell et al. 2023).

LG/MH

This type of prosthesis has a typical inlay humeral component design and a lateralized glenoid component. This combination LG/MH provides better tensioning of the rotator cuff muscles, aiming for better functional internal and external rotations. This setting also improves deltoid wrapping. The bony increased-offset RSA (BIO-RSA) technique involves bone grafting on a noneroded glenoid to achieve lateralization of the COR without increasing the implant offset.

MG/LH

This type of prosthesis increases the deltoid moment arm by medializing the COR. Tensioning of the rotator cuff muscles is achieved by lateralizing the humerus, typically with an onlay humeral component. Repairing the subscapularis tendon can be difficult in this setting, and the literature on this is inconclusive (Edwards et al. 2009; Friedman et al. 2017; Roberson et al. 2018).

LG/LH

This combination increases the risk of postoperative acromial or scapular spine stress fracture (Wong et al. 2016; Ascione et al. 2018).

Werthel et al. (2019) published a descriptive analysis of the amount of lateralization provided by 22 different implants currently available. This may be helpful for surgeons selecting implants (Figure 21).

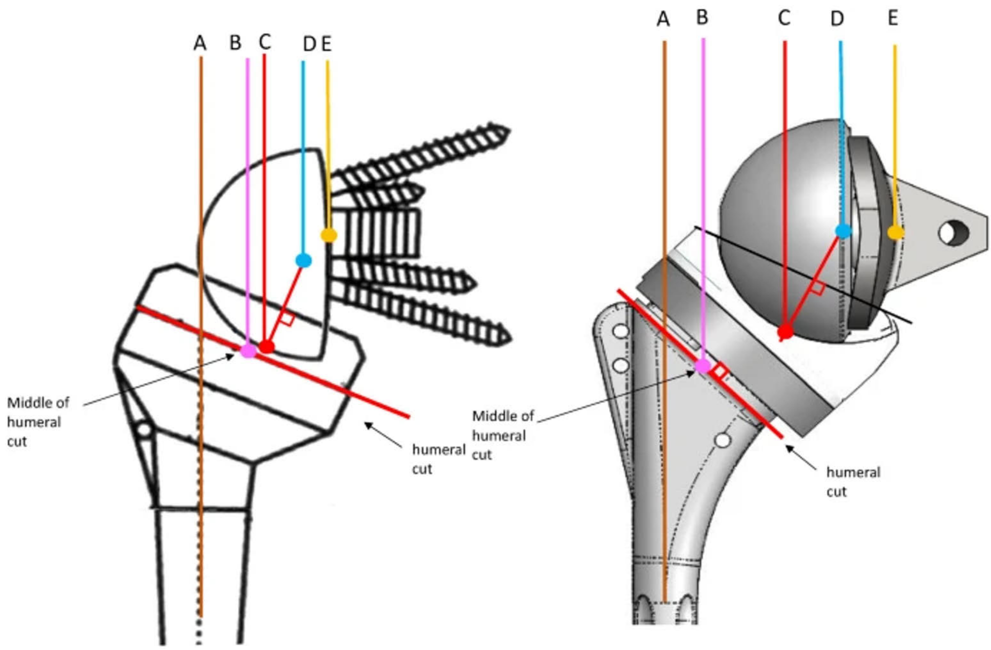


Figure 21. Descriptive analysis by Werthel et al. of 22 implants available on the market. A is a vertical line passing through the middle of the diaphysis of the humeral stem. B is a horizontal line passing through the middle of the surface of the humeral implant at the level of the humeral cut. C is a vertical line passing through the "pivot point", defined as the deepest point of the articular surface of the humeral insert measured perpendicular to the surface of the humeral insert. D in a vertical line passing through the COR of the joint. E is a vertical line passing through the bone-glenoid baseplate interface. The humeral lateral offset (distance AC) was defined as the sum of the humeral stem offset (distance AB) and the humeral insert offset (distance BC). The glenoid lateral offset (distance CE) was defined as the sum of the "perceived radius of the glenosphere" (distance CD) and the COR offset (distance DE). The global lateral offset (distance AE) was defined as the sum of the glenoid lateral offset and the humeral lateral offset. Left: templates of a medialized implant (Delta III (DePuy, Warsaw, IN)). Right: a very highly lateralized implant (Arrow (FH Ortho, Heimsbrunn, France). Reprinted with permission froom Werthel et al. 2019.

2.7.5 Patient-specific factors on RSA biomechanics

Patients have a different bony morphology in the scapula and humerus and varying muscle sizes and volumes, with diverse impacts on RSA biomechanics. One example affecting impingement and ROM is the length and angles of the scapular neck. Some studies have reported that a shorter scapular neck and wider scapular neck angels can reduce ROM and increase scapular notching after RSA (Middernacht et al. 2008; Roche et al. 2013; Paisley et al. 2014).

2.7.5.1 Scapular orientation and posture

Normal shoulder function is highly dependent on scapulothoracic ROM. As people age, they have a greater tendency to develop thoracic kyphosis, with the scapula often being located more anteriorly, internally rotated, and in a more protracted position. This leads, in a normal native shoulder, to decreased overhead ROM. The scapular posture has been overlooked in biomechanical studies of RSA, because the scapula is almost always considered static and somewhat stuck in the torso, which is not true in real life.

Moroder et al. (2020) studied scapular positioning in the supine CT scans of 100 patients. They concluded that in patients with kyphosis, implantation of the humeral component with increased retrotorsion leads to neutral opposition of the RSA components and extensive internal rotation of the scapula. They proposed a distinction between three posture types (A-C) for enhanced appraisal of scapulothoracic orientation (Figures 22 and 23).

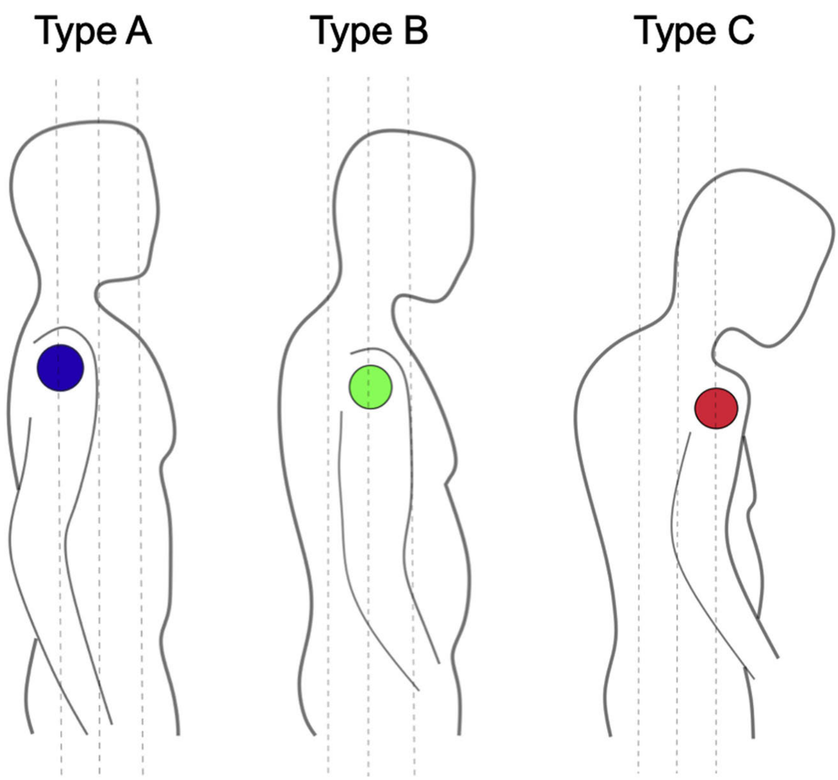


Figure 22. Three posture types: Type A normal, Type B slight kyphosis, Type C kyphosis. The COR is indicated by the coloured circles. (Moroder et al. 2020)

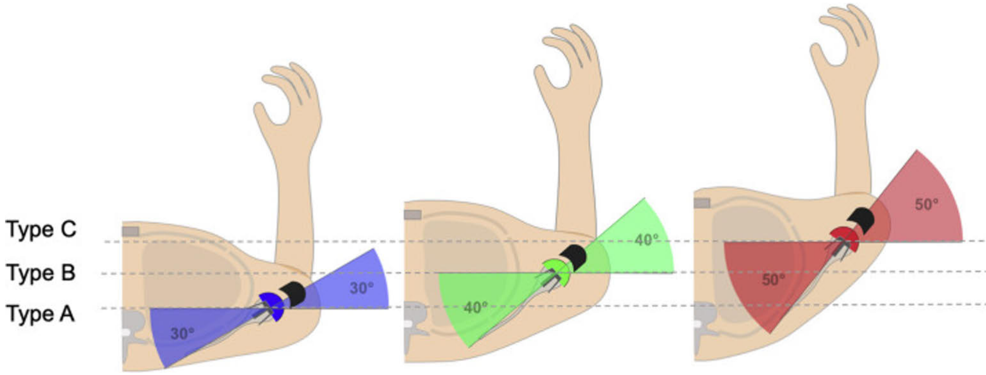


Figure 23. RSA in three different posture types, axillary view. The arm is kept in the neutral position. The humeral component retrotorsion (black rectangle with concave and convex sites) must match the scapular internal rotation to reach perfect opposition to the glenosphere (type A, blue; type B, green; type C, red). The displayed angle for each type reflects its mean measurement in the sturdy cohort (Moroder et al. 2020).

2.8 Expanded indications for RSA

2.8.1 Glenoid bone loss

Glenoid bone loss is a technical challenge and may deteriorate clinical results in patients undergoing shoulder arthroplasty. It has been estimated that up to 40% of reverse shoulder arthroplasties face this challenge (Klein et al. 2010, Tashjian et al. 2018). Possible explanations for these poorer outcomes are glenoid component loosening, compromised soft tissue tensioning, and reduced bone stock leading to ultimate failure.

Eccentric reaming is an option for mild bone loss, for instance, with <15° retroversion. The anterior paleoglenoid is reamed to the level of the posterior surface. Excessive reaming should be avoided, as it can lead to excess medialization or component instability if there is insufficient bone stock.

Several studies with eccentric reaming have shown good results including pain relief, improved ROM and PROMs (Klein et al. 2010; McFarland et al, 2016; Mizuno et al. 2013).

2.8.1.1 Glenoid bone grafting

In cases of severe glenoid bone loss where correction of the deformity is not possible with eccentric reaming alone, grafting with a bone auto- or allograft may improve the stability and survival of the glenoid side implant. Although there are different surgical techniques (Tashjian et al. 2018; Tashjian et al. 2020), the main aim is to achieve penetration of the baseplate central peg into at least 10 mm of native glenoid bone to improve survival of the component (Lopiz et al. 2017).

In primary RSA, structural bone grafting has shown good results. Ernstbrunner et al. (2017) reported no revisions in a cohort of 41 patients with bone grafts. Glenoid bone graft incorporation was observed in 78% of patients. Pain relief was successful and shoulder function and stability were restored. Tashjian et al. (2018, 2020) reported good, similar results after auto- or allograft in patients with glenoid defect.

Graft survival and resorption can be difficult to identify on CT scans due to implant metal artefacts. In a cadaver study by Ferreira et al. (2015), the sensitivity was 38% and accuracy 46%. The resorption gap width was consistently underestimated.

In shoulder arthroplasty revisions, RSA with bone graft is often the method of choice. Other indications are persistent pain due to glenoid erosion, instability, and decreased function. Boileau et al. described bony increased-offset-reverse shoulder arthroplasty (BIO-RSA), which aims to lateralize the native glenoid surface and thus lengthen the scapular neck to achieve better external rotation and avoid notching. This technique gave good long-term results (mean follow-up time 75 months) with no component loosening, 83% of patients feeling satisfied, and humeral bone graft incorporation achieved in 96% of cases (Boileau 2020). However, comparing BIO-RSA with the Grammont-style traditional prosthesis showed that only scapular notching in radiographs was significantly lower, all other parameters (DASH, ASES score, Constant score, and rotational ROM) not being statistically different (Athwal 2015).

2.8.1.2 Metal-augmented glenoid

Metal-augmented glenoid baseplates are commercially available and are technically less challenging, with no risk of non-union or resorption (Figure 24).

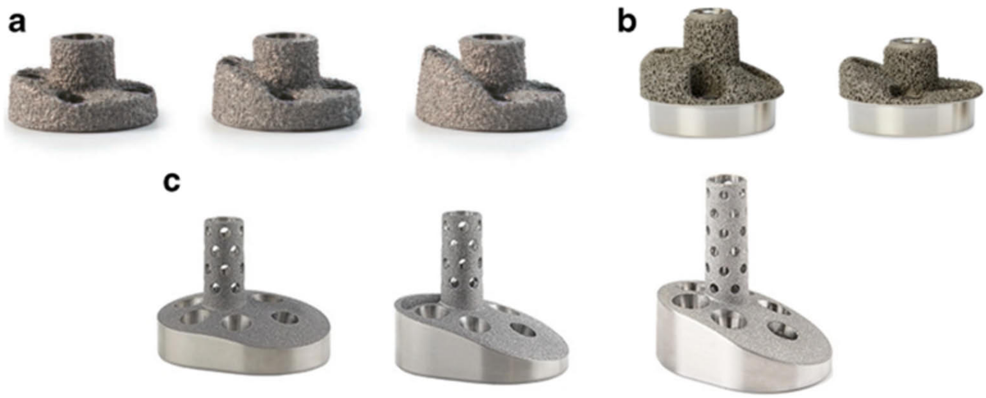


Figure 24. Different designs of RSA augmented baseplates. a) Zimmer Biomet Comprehensive Shoulder System (Zimmer Biomet, Warsaw, IN). b) Tornier Aequalis and Perform reversed half-wedge augments and full-wedge-augmented baseplates (Stryker, Wright Medical Group, N.V. Memphis TN). c. Exactech Equinoxe Reverse System (Exactech Inc, Gainesville, FL). Reprinted with permission from Mourad et al. 2020.

Only one systematic review compares glenoid bone grafting with augmented glenoid prosthesis in primary RSA with glenoid bone loss. Both methods produced excellent ROM and functional outcomes. Augmented glenoid base plates may confer fewer complications and revisions (Wilcox et al. 2022).

Another systematic review compares RSA using either bone graft or augmented baseplates for the management of glenoid bone loss and deformity. In conclusion, both treatments improve overall clinical outcomes with relatively low complication and revision rates (Lanham et al. 2023).

There are no long-term studies on the augmented glenoid.

2.8.2 Proximal humerus fracture

The treatment of displaced PHF remains controversial. The key message of a recent Cochrane review (Handoll et al. 2022) was that patients did not find that surgery provided better shoulder function than non-surgical treatment for most types of displaced fractures. Surgery may in fact result in a higher risk of follow-up surgery complications. There is not enough evidence to suggest that surgery would be the best option.

PHFs are the third most common non-vertebral fragility fractures after the hip and wrist. A typical patient is an elderly female with a PHF following a simple fall. Surgical treatment involves head-preserving techniques with locking plates or locking intramedullary nails. When head-preserving techniques are too challenging because of poor bone quality or fragmentation, the alternative is a joint replacement with hemiarthroplasty (HA) or RSA.

In epidemiological studies the incidence of PHF is growing, especially among elderly females (Kim 2012; Kannus et al. 2017; Sumrein et al. 2017; Court-Brown et al. 2018; McLean et al. 2019; Leino et al. 2022). Most PHFs are treated non-surgically. The incidence of operative treatment is dropping in Nordic epidemiological studies, especially the use of locking plates and HA. It has been shown in randomized control studies (RCTs) and meta-analyses that there is no difference in functional outcome between non-operative treatment and locking plate or HA in the treatment of PHF. However, after surgical treatment there is a significantly higher risk of complications and reoperations of up to 45% (Launonen et al. 2015; Rangan et al. 2015; Handoll et al. 2022; Launonen et al. 2023). These complications clinically manifest as functional impairment, presenting with considerable pain and stiffness. RSA has shown good functional results in the treatment of CTA. Encouraged by these results, the use of RSA in the treatment of proximal humerus fractures in the elderly is rising (Brorson et al. 2022; Leino et al. 2022). However, the evidence comparing non-operative treatment and RSA is scarce. In an RCT study by Lopiz et al. (2019) of 3- and 4-part fractures in an elderly (mean age 80 years) cohort of 59 patients, RSA had only minimal benefits over non-operative treatment. At the short term-term follow-up, the main advantage of RSA appeared to be less pain perception (Lopiz et al. 2019). There are several ongoing RCT trials comparing non-operative treatment with RSA, such as the Deltacon Nordic, ReShaPE, and PROFHER 2 (Smith et al. 2017; Launonen et al. 2019; Rangan et al. 2023). Hopefully, in the near future we will have level-1 evidence for RSA in the treatment of proximal humerus fractures before the use of RSA expands beyond its necessity.

2.9 Results of RSA

Most of the reported clinical RSA outcome studies are retrospective, especially the most reviewed ones (Mercurio et al. 2022). There are also some RCT studies, as reported in Chapter 2.7.2, and register studies as mentioned in Chapter 2.7.3.

2.9.1 Clinical results of RSA

The annual number of implanted RSAs has grown exponentially over the past two decades (Kim et al. 2011; Dillon et al. 2017; Harjula et al. 2018; Mayfield et al. 2023). Complication and revision rates have dropped thanks to improvements in surgical technology, implant positioning, and component design. Long-term results of RSA reported by De La Salle et al. (2023) with follow-up of 8.9±0.6 years (range 7.4-10.3) showed an absolute Constant score (CS) of 59.0 ±16.2, age-/sex-adjusted CS of 76.6±41.2, and American Shoulder and Elbow Surgeons (ASES) score of 77.1±20.3.

Long-term results of the Delta Xtend RSA with a mean follow-up time of 10 years reported by Bassenset et al. (2018) showed that a mean age- and sex-adjusted CS (aCS) of 44.6% (SD 19.2) preoperatively increased significantly after surgery to 75.8% (SD 12.5) at 3 months and 91.1% (SD 11.8) at 5 years. At the latest follow-up the mean aCS was 79.9% (SD 17.7), which was significantly lower than aCS at 5 years postoperatively. An overall survival rate of more than 97% was seen at 8 years of follow-up.

In a French multi-centre retrospective study involving six shoulder-specialized hospitals, there were 1911 RSAs with a mean follow-up time of 5.6± 3.9 years (range 2–20). Of these, 266 had at least one complication leading to 64 reoperations and 110 revision surgeries. At 10 years, the prosthetic survival without revision surgery was 91% for primary RSAs and 80.9% for revision RSAs for failed arthroplasty. Fracture sequelae and tumours had the lowest 10-year survivals (83.9% and 53.1%). Younger patients had a lower 10-year prosthetic survival. Male patients had significantly lower survival rates than females (72.3% vs 84.5% at 10 years) (Chelli et al.2022).

Sheth et al. (2022) reported a minimum 10-year survival of Grammont-style prostheses inserted at a single-surgeon high-volume arthroplasty centre. Of 471 patients, 93 attended the 10-year follow-up; 56% of them were very satisfied, 26% satisfied, 14% dissatisfied, and 4% very dissatisfied. The survival rate for all 471 RSA patients was 88% at 5 years and 81% at 10 years.

In another minimum 10-year prosthetic survival study (Bacle et al. 2017), the mean duration of follow-up was 12.5 years. The 10-year overall survival rate for revision was 93%. Long-term survival was good, but there was CS deterioration compared to the mid-term results of the same cohort (Wall et al. 2007). Deterioration was 55±16 points and 86±26 points, respectively, both having decreased significantly compared with the scores at mid-term follow-up at a minimum of 2 years ($p<0.001$ and $p=0.025$, respectively) (Bacle et al. 2017)

2.9.2 RCT studies of RSA

There were 51 RSA RCT matches in PubMed in August 2024. However, most of them are not related to clinical studies. The most important clinical biomechanical RCT studies are described briefly in this chapter.

The first such study was published by Edwards in 2012. Its purpose was to determine whether inferior tilt of the glenoid component lessened the amount of radiographic scapular notching after RSA. The secondary goal was to determine whether inferior tilt had any effect on clinical outcome. The conclusion was that it did not reduce scapular notching and there were no clinical differences between the groups (Edwards et al. 2012).

Poon et al. published an RCT study in 2014 on the hypothesis that inferior positioning of the COR with eccentric glenosphere design deceases the adduction deficit impingement and scapular notching and improves clinical outcome. They concluded that there were no differences in notching rates or clinical outcomes between concentric and eccentric glenospheres.

Greiner et al. (2015) evaluated the clinical outcome of RSA by looking at the rotational function of patients with CTA treated with RSA with or without bony lateralization and 1 cm autologous bone graft (BIO-RSA). There were no statistically significant differences in overall clinical scores between both groups. All patients showed improved functional results.

Torrens et al. (2016) evaluated the development of scapular notching in RSA by comparing larger (42 mm) with smaller (38 mm) glenospheres. They concluded that glenosphere size has no significant influence on functional outcomes measured with the CS. Larger glenospheres significantly lessened the development of scapular notching compared to smaller glenospheres, by 12.1% and 48.8% respectively.

Torrens et al. (2020) analysed whether small 38 mm eccentric glenospheres were comparable to large centric 42 mm glenospheres in terms of scapular notching. They found no significant differences, and the functional outcomes were comparable between the two groups.

Van de Kleut et al. (2022) compared BIO-RSA and metal-augmented glenoid baseplates by assessing clinical outcomes and baseplate migration using model-based radio stereometric analysis. After a 2-year follow-up, both groups provided stable initial fixation with no substantial clinical outcomes.

Southam et al. (2023) compared ROM and clinical and radiological outcomes between two groups: 1) RSA with lateralized glenosphere and 2) RSA with non-lateralized and distalized glenosphere. The conclusion was that both groups had significant improvement in functional outcome and ROM. There were no significant differences between the groups at 2-year follow-up.

Wiater et al. (2024) studied whether humeral external rotation and internal rotation are affected by the humeral component version (neutral or 30° of retroversion) after RSA 2 years postoperatively. They found no difference between the groups.

2.9.3 Register studies of RSA

The first shoulder implant registry started in Finland in 1980. Shoulder registries now exist in the United Kingdom, Denmark, Norway, Sweden, Finland, the Netherlands, New Zealand, Australia, Germany, Portugal, and the Kaiser Permanente in California. The registries were established to detect poor prosthetic design at an early stage and ensure that implants can be tracked afterwards. Registries are used not only for implant surveillance but also to assess the incidence, indication, type of procedure and revision. However, the registries are only as accurate as their data content. They generally cover surgeon-derived measures and key outcomes such as revision, but there is a greater trend toward patient-reported outcome measurements (PROM) to analyse clinical outcomes. For example, acromion fracture is a devastating complication of RSA and most are treated conservatively, yet they are not shown in register studies.

The challenges facing national arthroplasty registries are data collection of different variables and difficulty making comparative analyses (Karelse et al. 2021). A future challenge will be to agree on similar datasets of variables and outcome measurements, which would improve the statistical strength of studies with very high numbers of cases.

The Nordic Arthroplasty Register Association (NARA) began in 2007 with hip and knee arthroplasties. In 2016, Rasmussen et al. published the first collaborative report on shoulder arthroplasty data in the Nordic countries.

The advantage of registries is the possibility of detecting outlier components. For instance, problems with metal-on-metal hip prostheses were detected by AOANJRR and NJR annual reports and led to the worldwide recall of these components (AOANJRR 2007, NJR 2009).

In an Australian register study, lower surgical volume was associated with higher all-cause revision rates in the early postoperative period after RSA for OA and throughout the follow-up period after RSA for CTA. Lower volume is <10 arthroplasties per year and high volume >30 per year; 78% of surgeons undertake fewer than 10 procedures per year (Brown et al. 2020).

Similar results were found in the National Joint Registry in the United Kingdom. Surgeons who perform more than 10.4 shoulder replacements yearly were associated with lower rates of revision surgery and reoperation, lower risk of serious adverse events, and shorter hospital stays (Valsamis et al. 2023).

An Australian register study concluded that glenospheres <38 mm can be expected to increase revision rates in primary RSA. The optimum size of glenospheres is gender-, age-, and prosthesis-specific, with lower revision rates for females with 38–40 mm glenospheres and for males with >40 mm glenospheres (Page et al. 2022).

2.10 Complications of RSA

2.10.1 Periprosthetic joint infection

The overall incidence and number of RSA implantations have grown rapidly over the past decade (Kim et al. 2011; Dillon et al. 2017; Harjula et al. 2018; Mayfield et al. 2023). Inevitably, the absolute number of prosthetic joint infections (PJIs) associated with RSA has been rising. According to the Australian register, PJI is the second most common reason for revision during the first 2 years and the most common reason for revision after 2 years (AOANJRR 2023). PJI is the most devastating complication of total joint arthroplasty. Early and reliable PJI diagnosis is important to prevent consequences like sepsis, chronic pain, and instability.

The incidence of PJI after primary reverse shoulder arthroplasty has been reported to be as low as 0.5% and as high as 6.7%, and in RSA up to 15% (Zumstein et al. 2011; Richards et al. 2014; Morris et al. 2015; Villacis et al. 2016; Kang et al. 2019; Moeini et al. 2019; Belay et al. 2020; Kunutsor et al. 2020).

Male gender, recent weight loss, nutritional deficiency, drug abuse, previous non-arthroplasty surgical history, acute trauma, alcohol overuse, revision arthroplasty, diabetes mellitus, liver disease, iron-deficiency anaemia, preoperative corticosteroid injections, and RA are factors that have been associated with increased risk of infection after RSA (Padegimas et al. 2015; Seok et al. 2022; Schoell et al. 2024).

PJI in shoulder arthroplasty remains a diagnostic challenge because of low-virulence pathogens and the need for consistent data for a diagnostic algorithm and definition. At the 2018 International Consensus Meeting on Orthopedic Infections, an international group drew up a consensus definition for shoulder periprosthetic joint infection. The definition includes a sinus tract from the skin to the prosthesis surface, gross intra-articular pus, or two positive microbiological cultures with an identical pathogen. A periprosthetic infection is definitely present if one of these criteria applies. PJI may still be present even if these criteria do not apply. The Consensus Meeting has summarized criteria for probable, possible, and unlikely shoulder infection (Garrigues et al. 2019) (Tables 2 and 3).

Table 2. Minor criteria for definition of shoulder PJI. Reprinted with permission from Garrigues et al. (2019).

Minor criteria for defintion of shoulder PJI	
Minor criteria Weight	
Unexpected wound drainage	4
Single positive tissue culture with virulent organism	3
Single positive tissue culture with low-virulence organism	1
Second positive tissue culture (identical low-virulence organism	3
Humeral loosening	3
Positive frozen section (5 PMNs in ≤5 high power fields)	3
Positive preoperative aspirate culture (low or high virulence)	3
Elevated synovial neutrophil percentage (>80%)	2
Elevated synovial WBC count (>3000 cells/μL)*	2
Elevated ESR (>30 mm/h)	2
Elevated CRP (>10 mg/L)	2
Elevated synovial α-defensin level	2
Cloudy fluid	2

PMN: polymorphonuclear leucocytes; WBC: white blood cells; ESA erythrocyte sedimentation rate; CRP: C-reactive protein.
*Beyond 6 weeks after recent surgery

Table 3. Clinical scenarios of the International Consensus Meeting diagnostic criteria in practice. MSSA: methicillin-sensitive *Staphylococcus aureus*: ESR: erythrocyte sedimentation rate; CRP: C-reactive protein. Reprinted with permission from Garrigues et al. (2019).

No.	Scenario	Definition
1	Painful shoulder arthroplasty with the following: -positive aspirate culture (*Cutibacterium acnes*): 3 points -1 of 5 intraoperative cultures positive (*C acnes*): 1 point -Humeral loosening	Probable PJI
2	Painful shoulder arthroplasty with the following: -No aspirate completed -Persistent unexpected wound drainage: 4 points -2 of 5 intraoperative cultures positive (*C acnes*): 1+3=4 points	Probable PJI
3	Painful shoulder arthroplasty with the following: -Dry aspirate -2 of 5 intraoperative cultures positive (MSSA) -Elevated ESR -Elevated CRP	Definite PJI
4	Painful shoulder arthroplasty with the following: -Well-fixed components -2 of 5 intraoperative cultures positive (*C acnes*): 1+3=4 points -All other test results negative	Possible PJI
5	Painful shoulder arthroplasty with the following: -Persistent unexpected wound drainage: 4 points -1 of 5 intraoperative cultures positive (*C acnes*): 1 point -all other results negative	Unlikely PJI
6	Painful shoulder arthroplasty with the following: -Persistent unexpected wound drainage: 4 points -1 of 5 intraoperative cultures positive (MSSA): 3 points -All other test results negative	Probable PJI

Cutibacterium acnes, formerly *Propionibacterium acnes,* is the most common pathogen in shoulder PJI, and polymicrobial infections are frequent. For clinicians, the difficulty diagnosing low-virulent C. acnes PJI is due to the slow-growing nature and frequent absence of typical local and systemic signs of infection (such as redness, swelling, induration, and fever). Inflammatory markers such as serum C-reactive protein (CRP), synovial fluid white blood cell count, and serum erythrocyte sedimentation rate (ESR) are often indifferent in patients with suspected PJI.

Some patients develop classic infectious symptoms such as drainage, purulence, or erythema.

C. acnes bacterium is an anaerobic, slow-growing gram-positive rod residing in pilosebaceous glands, particularly densely in the axilla of the shoulder, neck, and back. It is associated with chronic postoperative complications and low-grade infections. However, it is unclear whether it represents a contaminant or causes true infection.

The number of culture-negative PJIs after shoulder surgery has been reported to be higher than after hip and knee surgery (Berbari et al. 2007; Buchalter et al. 2017; Torrens et al. 2018). In hip and knee surgery PJI detection, sonication has proved to be more sensitive than tissue culture, with sensitivities of 78.5% and 60.8%, respectively (Trampuz et al. 2007). According to the literature, the role of sonication in shoulder PJI diagnostics is controversial; several studies have shown no added value (Grosso et al. 2017; Torrens et al. 2020; Padolino et al. 2021), while a few have reported a slightly positive value (Piper et al. 2009; Akgün et al. 2020). All the studies were retrospective.

Treatment options for periprosthetic shoulder infection are debridement, antibiotics, and implant retention (DAIR); one-, two-, or multiple-stage revision; definite treatment with antibiotic spacers; resection arthroplasty and chronic antibiotic suppression (Verhelst et al. 2011; Klatte et al. 2013; Hsu et al. 2016; Buchalter et al. 2017; Dennison et al. 2017).

In a recent systematic review and meta-analysis, one-stage revision showed better results for infection control, with fewer clinical complications and possibly better clinical outcomes (Rodriges-Lopez et al. 2024). Two-stage revisions are more harmful for patients, with worse clinical outcomes. A one-stage revision may be contraindicated if there is glenoid bone loss. However, the DAIR approach has a higher rate of infection recurrence compared to one- and two-stage revisions.

Resection arthroplasty and a permanent spacer showed no difference in infection control or functional outcome (Verhelst et al. 2011).

Antibiotic treatment is self-evident after revision surgery and should last from 4–6 weeks (Osmon et al. 2013) to 3 months for a low-virulence organism (C. acnes) (Boisrenoult et al. 2018).

2.10.2 Instability/dislocation after RSA

Dislocation rates after RSA range from 1.5% to 31% (Cheung et al. 2011; Gallo et al. 2011; Trappey et al. 2011; Zumstein et al. 2011; Chalmers et al. 2014; Chae et al. 2018).

The literature describes patient-related risk factors such as a body mass index (BMI) greater than 30 kg/m^2, male gender, subscapularis deficiency, surgical approach, bone loss around the tuberosity, history of traumatic native shoulder instability, and inadequate soft tissue tensioning (Sirveaux et al. 2004; Boileau et al. 2005; Seebauer 2007; Gutierrez et al. 2008; Gerber et al. 2009; Affonso et al. 2012; Chalmers et al. 2014; Teusink et al. 2015; Chae et al. 2018).

Implant-specific risk factors have also been described in the literature such as malpositioning of the components (superior baseplate inclination), mechanical impingement, smaller glenosphere diameter, humeral socket constraint (small socket depth), medialized COR offset, and humeral stem anteversion (Stephenson et al. 2011; Chae et al. 2018; Tashjian et al. 2018).

In 2022, two systematic reviews were published by Loucas et al. (2022) and Olson et al. (2022). The review by Loucas et al. included 12 studies with 3810 patients. The pooled rate of dislocation after RSA was 40%. The most important patient-related factors were younger age, male gender, and BMI over 30. Surgical approach or biomechanical factor, particularly glenosphere diameter, were not significant factors for dislocation, whereas subscapularis deficiency was (Loucas et al. 2022).

The review by Olson et al. included 17 studies with 7885 RSAs. The dislocation rate was 2.5%. Dislocation was more common in revision RSA. Proximal humerus fracture and fracture sequelae as a diagnosis had a higher risk of instability. Subscapularis repair was a protective factor against instability (Olson et al. 2022).

The primary treatment option is usually a closed reduction attempt under general anaesthesia and temporary immobilization. More than half of dislocated RSA shoulders have a successful outcome (Teusink et al. 2015).

RSA instability is often due to insufficient deltoid tension in the vertical (humeral shortening) and/or excessive medialization in the horizontal plane. Boileau 2016 published a treatment algorithm for instability after RSA (Boileau 2016) (Figure 25).

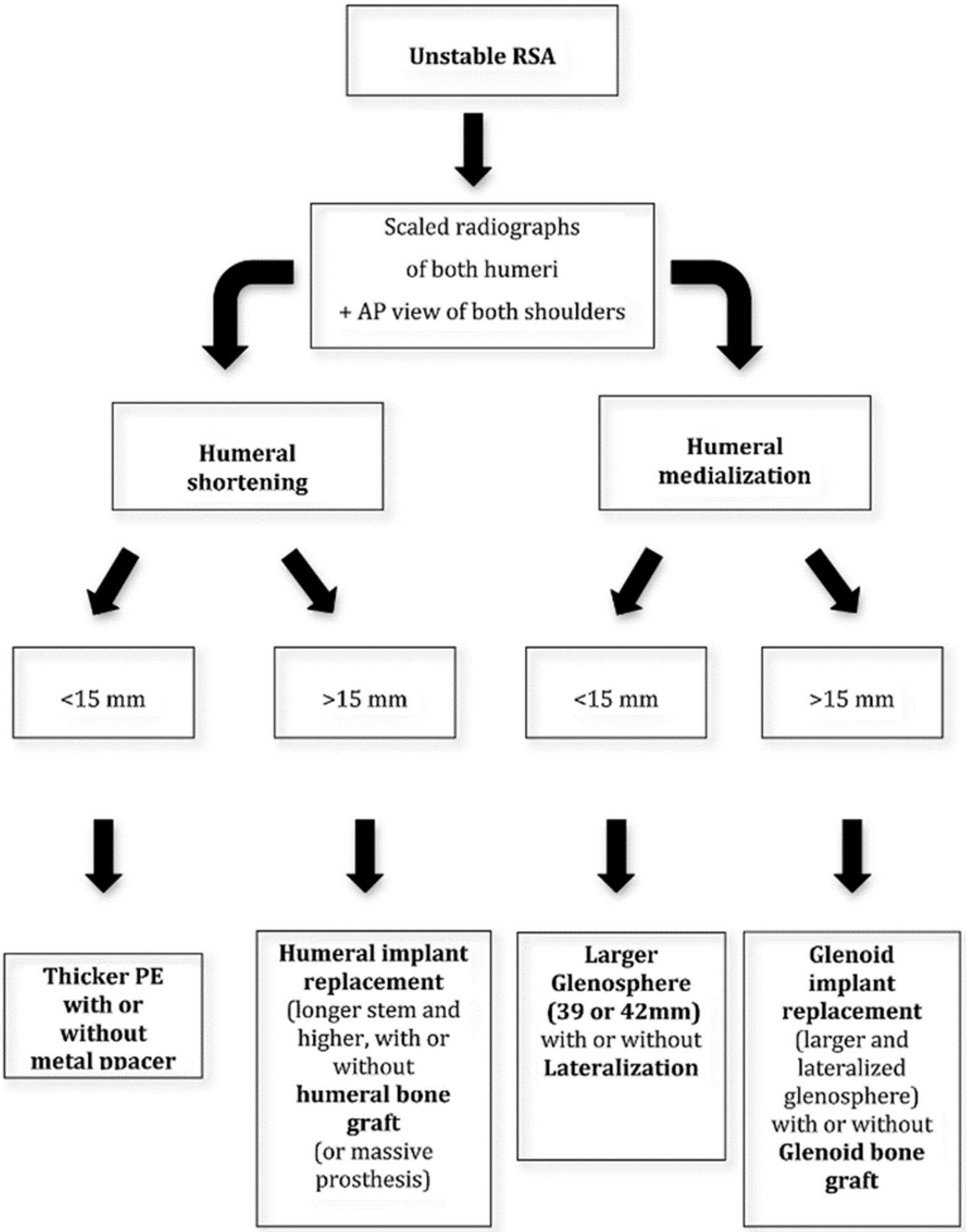


Figure 25. Treatment algorithm for instability after RSA. Reprinted with permission from Boileau (2016).

The best treatment for RSA instability is to avoid it during the primary operation.

2.10.3 Scapular notching

Scapular notching refers to friction-type impingement and/or erosion of bone along the inferior lateral scapular neck just medial to the glenoid baseplate. Scapular notching is caused by contact between the inferior medial rim of the humeral implant and the scapular neck below the glenoid component during adduction and external rotation. The term 'scapular notching' was first used by Sirveaux in 1997 in his medical thesis supervised by Molé (Sirveaux 1997). The scapular notching phenomenon was initially described by Sirveaux et al. in 2004 (Sirveaux et al. 2004) (Figure 26).

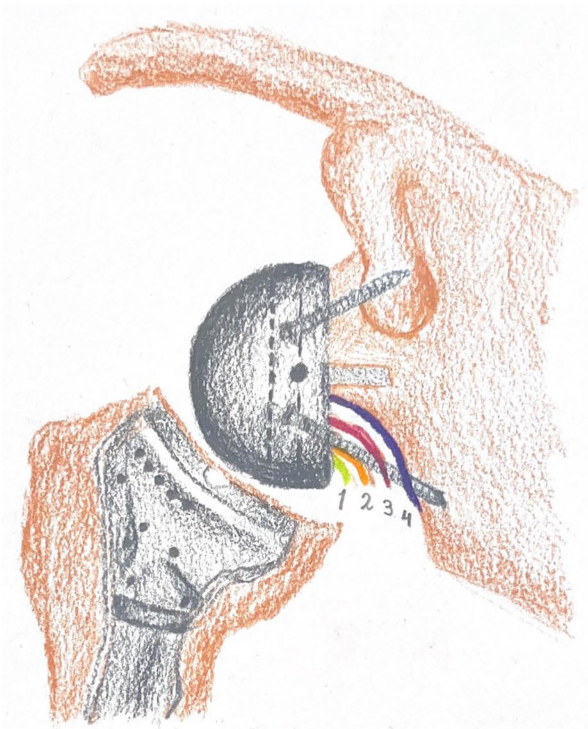


Figure 26. Scapular notching. Radiographic classification by Sirveaux in four grades: 1. The bone defect does not reach the lower screw of the baseplate. 2. The bone defect reaches the lower screw. 3. The bone defect covers the lower screw. 4. The bone defect reaches the central peg of the baseplate. Illustrated by Stella Lehtimäki with permission from Levigne et al. 2008.

In clinical practice, radiographic evaluation of notching is done from plain radiographs. A true Grashey antero-posterior view is obtained with the X-ray beam tangential to the glenoid baseplate to view it in profile. An axillary view is also recommended when grading the notching.

The clinical importance of notching has been contradictory. The reported incidence of scapular notching is very high, varying from 0% to 96% (Cuff et al. 2008; Werner et al. 2005). Some mid- to long-term studies report a high incidence of scapular notching but without a negative impact on clinical results. Some long-term studies indicate that deterioration of clinical results is associated with scapular notching (Sagodhi 2011). Other studies indicate that notching evolves during the first 2 years and stays relatively stable thereafter (Simowitch et al. 2007). On the other hand, some studies indicate that scapular notching also evolves after 2 years (Cuff et al. 2008, 2012). The negative effect of scapular notching is that it can produce synovitis and inflammation, creating pain with loss of motion and osteolysis from particle debris. High grade 4 notching can erode the glenoid bone, resulting in loosening of the glenoid component and ultimately revision or conversion to hemiarthroplasty. In a recent systematic review and meta-analysis of outcomes and complications in primary RSA, the rate of scapular notching appeared to be decreasing. The overall rate of scapular notching in the review was 14.4% (Galvin et al. 2022). This decrease may be associated with implant design improvements, such as a lateralized COR, and a more anatomic neck angle of 145° or 135°. The downside of these lateralization improvements has been increased rates of acromion and scapular fractures.

Scapular notching is one of the major concerns in RSA and one of the main motives for developing new implant designs. Still, the number of complications from scapular notching leading to revision surgery for baseplate failure is very small and occurs mostly years after the primary operation. In a long-term follow-up study by Spiry et al. (2021), it was concluded that scapular notching evolves over time and that severe notching increases the risk of glenoid loosening. Clinical outcomes deteriorate more than 9 years after surgery, and the shoulder does not become truly symptomatic until the implant starts to shift. Understanding the factors related to scapular notching is of paramount importance for surgeons treating younger patients.

2.10.4 Acromion stress fracture after RSA

Acromion stress fracture is a unique complication of RSA. The incidence in RSA patients has been reported to be between 1% and 7% (Katzer et al. 2004; Boileau et al. 2005; Frankle et al. 2005; Werner et al. 2005; Cuff et al. 2008; Walch et al. 2009; Hattrup et al. 2010; Crosby et al. 2011; Hamid et al. 2011). RSA is a non-anatomical solution for many shoulder problems, the key element being the deltoid muscle. Acromial stress fractures may result from excessive stress on the deltoid and cause stress fractures in the scapular spine.

Levy has proposed a classification system for acromion fractures (Figure 27).

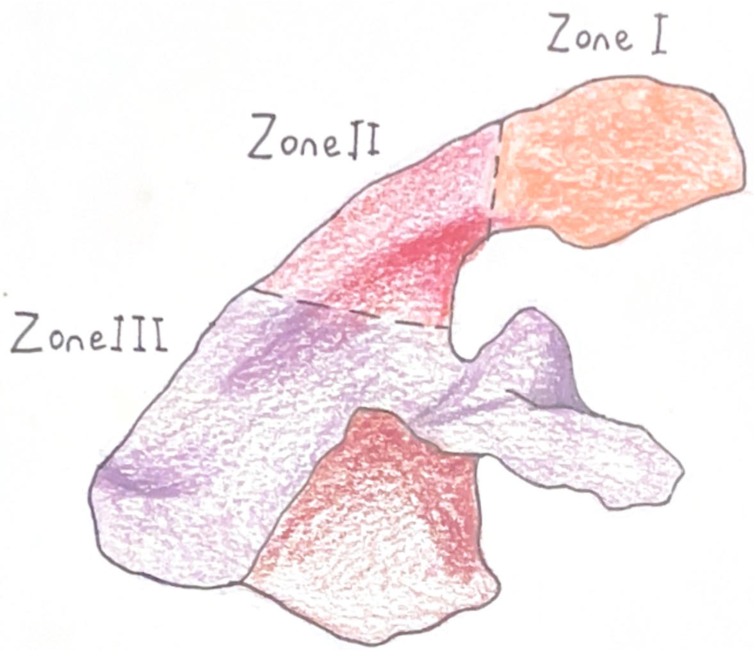


Figure 27. The Levy classification system for acromion fractures. Reprinted with permission from Levy et al (2013). Illustrated by Stella Lehtimäki.

Levy concluded that an acromion stress fracture can be missed on plain radiographs. If a fracture is suspected clinically and sudden pain is elicited by palpating the acromion or scapular spine, a CT scan will be helpful in identifying and diagnosing these fractures (Levy 2013).

Patient-related factors increasing the risk of acromion stress fractures are female gender, osteoporosis, and acromial anatomy (Shah et al. 2020; Taylor et al. 2020; Moverman et al. 2021).

A systematic review of biomechanical studies concluded that glenoid lateralization was associated with increased acromion and spinal strain, whereas inferiorization reduced strain. Some of the results were controversial; humeral-sided lateralization may increase or decrease acromion or scapular spine strain (Paszicsnyek et al. 2022).

From a biomechanical point of view, some studies suggest that a lateralized humeral component is associated with a decreased risk of acromial fracture after RSA (Werthel et al. 2018; King et al. 2019; Cho et al. 2020; Routman et al. 2020; Schenk et al. 2020; Shah et al. 2020).

The Grammont-style prosthesis has been reported to have a 1.3% rate of scapular fracture (Neyton el al. 2019). On the other hand, there are studies suggesting that a lateralized and distalized humeral onlay prosthesis may add to the risk of acromial fracture after RSA (Werner at al. 2017; Ascione et al. 2018; Haidamous et al. 2020; Shah et al. 2020).

Several studies found no association between implant design and risk of acromion fracture after RSA (Marigi et al. 2020; Shah et al. 2020; Zmistowski et al. 2020).

Treatment for Levy type I and II fractures is conservative, with an abduction sling for several weeks. Open reduction and internal fixation can be considered with patients with Levy type III fractures if the patient has significant pain, shoulder dysfunction, and/or instability (Colliton et al. 2021).

A meta-analysis by Cui et al. (2023) evaluated clinical outcome after a conservatively treated acromion stress fracture. There were no good-quality studies in the analysis, which concluded that patients are expected to have reduced shoulder function compared to non-fracture patients. Levy type III scapular spine fractures have the worst outcomes.

2.10.5 Failed RSA

As numbers of shoulder arthroplasties continue to rise, so, after a few years, does the burden of revision surgery. Revision RSA surgery is challenging and requires understanding of the causes of failure such as infection, instability, component loosening, and glenoid and humeral bone loss. According to Boileau (2016), the failure rates are RSA instability 38%, infection 22%, humeral complication 21%, glenoid side complication 13%, and other 6%. On the glenoid side, bone grafting is often considered and required. On the humeral side, corticotomy may be required for component removal. The results of RSA revision are inferior to primary RSA, and complications and further revisions are common. However, revision RSA surgeries still bring about notable improvements in pain, motion, and function (Zumstein et al. 2011; Boileau 2016).

Shoulder function is restored in 90% of revision cases, but Boileau (2016) concluded that revision RSA surgery is a difficult and risky operation with complication and reoperation rates of between 10% and 50%. The mean anterior elevation of patients was 107º and the mean-adjusted CS 62. It therefore makes sense to refer patients to tertiary hospitals with experience and understanding of complications.

A meta-analysis by Chalmers et al. (2019) on RSA revision found that revised patients were able to achieve 106º flexion, a mean ASES score of 63, and a mean Single Assessment Numeric Evaluation score of 52.

2.11 Knowledge gap

The aim of this thesis was to investigate the risks and risk factors associated with RSA in patients with CTA, OA and PHF in the Nordic countries using national register data. Unlike retrospective studies, which focus on highly specialized centers, registry data provides a broader, nationwide perspective that reflects outcomes from various clinical settings. This enables a more comprehensive understanding of RSA outcomes, considering a wider range of patient demographics and healthcare environments.

One of the key strengths of this study lies in the inclusion of various factors such as age, gender, arthroplasty brand, diagnosis, and revision details, which can help predict the risks of RSA surgery. By analyzing these variables, we can better inform future patients about their potential risks and outcomes, thereby enhancing preoperative counseling.

In addition, much of the past research on RSA has focused on addressing complications such as scapular notching and limited ROM, particularly in internal and external rotations. Our study aimed to explore whether radiological parameters could predict ROM outcomes, with the goal of making these predictors useful in clinical practice. We also included a diverse patient population to ensure the findings would be relevant in real-world settings.

Finally, this thesis also examines bone grafting techniques used at Turku University Hospital, where two different methods have been applied in a large series of cases. Bone grafting plays an essential role in addressing complex RSA cases, particularly when there are significant bone defects. This part of the study provides valuable insights into how challenging cases are managed and the outcomes of these less common but crucial procedures in RSA.

3 Aims

The aims of this thesis were:

1. To evaluate the prosthetic survival of RSA and the risk factors for revision in CTA and OA patients based on NARA register data.
2. To evaluate the prosthetic survival of RSA and the risk factors for revision in PHF patients based on NARA register data.
3. To investigate the correlation between radiographic geometry, clinical glenohumeral ROM, and other clinical results after RSA in patients operated on at Turku University Hospital, and to report the clinical results in these patients.
4. To investigate clinical and radiological outcomes of RSA with structural bone graft in patients operated on at Turku University Hospital

4 Materials and Methods

4.1 Patients

4.1.1 Studies I and II

Studies I and II are observational registry studies and are based on anonymous register data from the Nordic Arthroplasty Register Association (NARA). The dataset includes information on patient demographic characteristics (age, gender, and diagnosis: information on the primary operation (operation date, arthroplasty type, and implant model); and in the case of revision, the date of and reason for revision. If more than one diagnosis or reason for revision had been reported, a hierarchy was used so that only the single most important diagnosis or reason for revision was registered in the common dataset (Rasmussen et al. 2016).

In Study I, data were obtained from the national shoulder arthroplasty registries in Denmark, Norway, and Sweden from 2004–2013.

In Study I there were certain challenges defining patients with CTA. First, no clear definition of CTA exists. Furthermore, the Norwegian dataset is based on a common joint form without the possibility to report CTA as a primary diagnosis. Therefore, to capture all patients treated with RSA for a rotator cuff-insufficient shoulder, we included patients with either CTA or OA as the primary diagnosis.

In Study II, anonymous data from the national shoulder arthroplasty registries in Denmark, Norway, Sweden, and Finland from 2004–2016 were merged into a combined dataset under the umbrella of the NARA. Fracture sequelae were defined as fractures reported as non-union or malunion with previous osteosynthesis or together with OA or humeral head necrosis, and acute fractures were defined as all fractures not categorised as fracture sequelae, regardless of time from injury to operation. Data on cases with RSA and acute fracture were identified and extracted for analysis.

4.1.2 Study III

In Study III was a retrospective cohort study, all patient files containing operational codes for total shoulder arthroplasty at Turku University Hospital during 2007–2013 were obtained. Consecutive patients with primary RSA for CTA, OA, or RA using two mechanically different prosthesis designs—the Delta Xtend (DePuy Synthes, Warsaw, IN, USA) with a 155°neck-shaft angle and the Zimmer Biomet trabecular metal TM reverse (Biomet, Warsaw, IN, USA) with a 150° neck-shaft angle—were included in the analysis. Both prosthesis models were inlay models. TM reverse has a lateralized metal augmented glenoid and Delta Xtend medialized "on the bone" glenoid.

4.1.3 Study IV

In Study IV was a retrospective cohort study, all patients who had been operated on using RSA with glenoid bone graft were identified from Turku University Hospital operative database from January 2014 to December 2019. The inclusion criteria were that the structural bone graft was under the baseplate and around the central peg, and the bone graft was 100% between the baseplate and native bone and visible on plain radiographs.

4.2 Methods

4.2.1 Studies I and II

The NARA was established in 2007 by arthroplasty representatives from Sweden, Norway, and Denmark with the overall aim of improving the quality of research and thus enhancing the prospects of quality improvement in arthroplasty surgery. Finland joined NARA in 2010 (Mäkelä et al. 2019). A group of shoulder surgeons met in 2014 to examine the feasibility of merging data from the Nordic national arthroplasty registers by defining a common minimal dataset. They agreed on a dataset containing patient demographic characteristics (age, gender, and diagnosis), information on the primary operation (date, arthroplasty type, and arthroplasty brand), and data on any revisions (date, reason for revision, and new arthroplasty brand) (Rasmussen et al. 2016). The mortality rate within 1 year after the operation was 4.3%, with a total of 243 deaths in the cohort.

4.2.2 Study III

Preoperative radiographs were analysed for CTA according to Hamada (Hamada et al. 1990) and critical shoulder angle (CSA) (Moor et al. 2013). Postoperative and follow-up radiographs were analysed for scapular geometry around the COR of the RSA. The primary outcome was on the alpha angle (α-angle), the angle between the line of the supraspinatus fossa and the line between the COR and lateral edge of the acromion. And the secondary outcome was beta-angle (β-angle) between the lines from the lateral of the acromion to the COR and from there to the superior edge of the greater tubercle (Figure 28). The outcomes were chosen to see if there would be a simple method to predict the ROM from 2D radiographs. Parameters including the lateralization angle (LSA), distalization angle (DSA), and glenosphere inferior offset from the inferior glenoid (GIO) were also measured (Boutsiadis et al. 2018). Notching was analysed according to Sirveaux at the follow-up radiographs (Sirveaux et al. 2004).

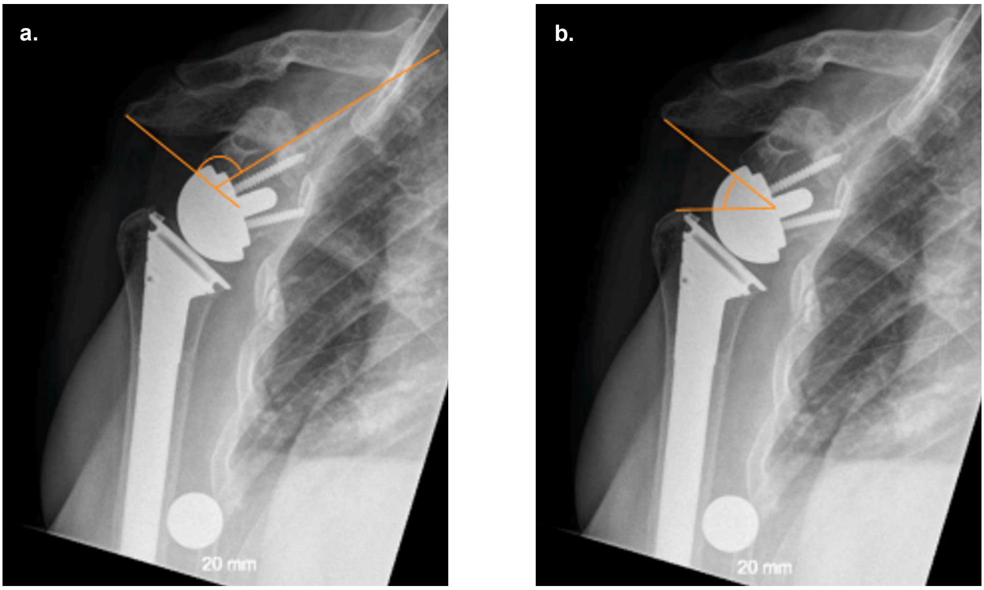


Figure 28. Alpha and beeta angles. **a.** α-angle between the line from the supraspinatus fossa and lateral aspect of the acromion to the COR. **b.** β-angle between the line lateral aspect of the acromion and the line form the lateral aspect of the tuberculum major to the COR.

Patients received one of four prosthesis designs: Delta Xtend (DePuy Synthes, Warsaw, IN, USA) with a 155° neck-shaft angle, Aequalis Reversed II (Wright Medical-Tornier Group, Memphis, TN, USA) with neck-shaft angle 155°, Tornier Flex reverse (Wright Medical-Tornier Group, Memphis, TN, USA) with neck-shaft angle 145°, and Zimmer Biomet trabecular metal TM reverse (Biomet, Warsaw, Indiana) with a 150° neck-shaft angle.

4.2.3 Study IV

Patients received one of four prosthesis designs: Delta Xtend (DePuy Synthes, Warsaw, IN, USA) with a 155° neck-shaft angle, Aequalis Reversed II (Wright

Medical-Tornier Group, Memphis, TN, USA) with neck-shaft angle 155°, Tornier Flex reverse (Wright Medical-Tornier Group, Memphis, TN, USA) with neck-shaft angle 145°, and Zimmer Biomet trabecular metal TM reverse (Biomet, Warsaw, Indiana) with a 150° neck-shaft angle.

Two operative techniques were used for glenoid bone grafting, and in both techniques auto- and allografts were used.

The first technique is similar to the method described by Tashjian et al. (2018). Briefly, the humeral head is resected using the standard approach. The glenoid is then exposed, and the glenoid surface is prepared and decorticated according to the surgeon’s preference and the patient's specific anatomical requirements. A pin is drilled for the baseplate, ensuring sufficient bone stock on the glenoid and achieving the appropriate height and inclination. The humeral head is prepared based on the surgeon’s technique, and a central hole is drilled. The baseplate is placed on the pin, which is temporarily fixed with K-wires. The baseplate with a long peg is inserted, ensuring that the peg penetrates at least 1 cm into native bone.

The second technique follows the procedure presented by Boileau e al. (2017). In this approach, an autograft is harvested from the humeral head using a specific reamer. In revision cases, a fresh-frozen femoral allograft is utilized. The choice of glenosphere size, as well as whether it is centered or eccentric, and the fixation method for the humeral side (cemented or cementless), is determined based on the surgeon’s preference.

The reason for bone grafting varied. There where glenoid lateralisation, glenoid bone loss and retroversion correction.

A total of 37 patients (39 shoulders) returned for final clinical and radiological follow-up.

Preoperative data on gender, age, operative side, smoking, BMI, and prior operations were recorded together with intraoperative data on diagnosis, prosthesis design and central peg length, and bone graft type. For the purpose of this study, patients were called for a follow-up, and pain-VAS, operation related complications, CS, and WOOS index were recorded.

The primary outcome was bone incorporation and lucency around metaglene central peg.

Preoperative radiographs, CT scans, and postoperative and follow-up radiographs (true AP and axillary views) were analysed by an experienced shoulder surgeon and a musculoskeletal radiologist. The following parameters were measured and recorded from preoperative images: the Hamada classification (Hamada etal. 1990), glenoid defect according to Walch and Favard (Bercik et al. 2016; Favard et al. 2017), degrees of glenoid retroversion, and CSA (Moor et al. 2013). Follow-up images were analysed for CSA, length of the metaglene central peg in the native bone, bone-graft incorporation (bone incorporated, partially incorporated and fully resorbed), radiographic lucency around the metaglene construct (no lucency, partial lucency, component loose), scapular notching according to the Sirveaux classification (Sirveaux et al, 2004), humeral component loosening (no lucency, partial lucency, component loose), and presence of acromion fracture (no fracture, fracture).

4.3 Statistical analysis

4.3.1 Studies I and II

Descriptive statistics were used to report demographic data. The Kaplan-Meier method was used to illustrate the unadjusted cumulative survival rate, and the log-rank test was used for comparison. Cox multiple regression analysis was used to calculate the adjusted revision rate for gender, arthroplasty brand, age (<70 years or >70 years), and year of surgery in Study I. In Study II, Cox multiple regression analysis was used to calculate the adjusted hazard ratio (HR) for revision for gender, age group (<60, 60–75, >75 years), country of operation, and year of surgery (2004–2009, 2010–2013, and 2014–2016). The level of statistical significance was set as $P<.05$, and all P values were two-tailed.

4.3.2 Studies III and IV

Continuous variables were summarized with mean and standard deviation (SD). In Study III, the glenosphere size-adjusted Pearson correlation (partial correlation) between the radiographically measured parameters and the active and passive ROM and clinical outcome was calculated. In Study IV, the Pearson correlation (partial correlation) between the type of bone graft and radiographically measured parameters and clinical outcome was calculated. In both Studies III and IV, the statistical significance level was set at $p=0.05$ (two-tailed). The analyses were performed using SAS software version 9.4 for Windows (SAS Institute Inc., Cary, NC, USA).

The continuous variables in the data are described using means and SD for normally distributed and accompanied by medians if non-normally distributed. The normality of the empirical distributions was tested using the Kolmogorov-Smirnov test. Discrete variables are presented using observed frequencies and proportions using the available observations as the denominator.

The baseline variables of gender, age, BMI, smoking status, type of surgery (primary/revision), diagnosis, Hamada classification, Walch and Favard defect classification, glenoid retroversion and pre-operative CSA were analysed using Student’s t-test if normally distributed and the Wilcoxon rank-sum test with continuity correction if non-normally distributed. Clinical background variables of WOOS, VAS and CS, and follow-up measures of follow-up time, CSA, Sirveaux classification, incorporation of bone graft, and lucency around the metaglene central peg were analysed similarly.

The main outcomes of bone incorporation and lucency around the metaglene central peg were analysed with analysis of covariance (ANCOVA) if there was a continuous response. In case of a categorical response, a multinomial logistic regression model was fitted using the highest or most desirable value as reference class. Both analysis setups were adjusted for follow-up time and type of graft (auto-/allo-) and fitted for each background variable individually. A type III F test was calculated for the overall effects in the model for justification to continue to pairwise comparisons. Background variables used in the modelling were height, weight, BMI, dominant side, gender, smoking status, operated side, diagnosis, surgery type (primary/revision), previous procedure, reverse design, and age at time of surgery. All analyses were performed using R version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria)

5 Results

5.1 Study I

In Study I, a total of 19,857 shoulder arthroplasties were reported in Denmark, Norway, and Sweden from 2004–2013 and included in the common dataset. There were 3828 RSAs (19 %), and of these 1904 had either CTA (n=1312, 69%) or OA (n=592, 31%) as a diagnosis.

There were 1284 women (67 %). The mean age was 74 years (SD 8 years; range 35–97), and 505 patients were younger than 70 years. The mean follow-up time was 32 months (range 0–119 months). The yearly number of different arthroplasty brands used is shown in Figure 29.

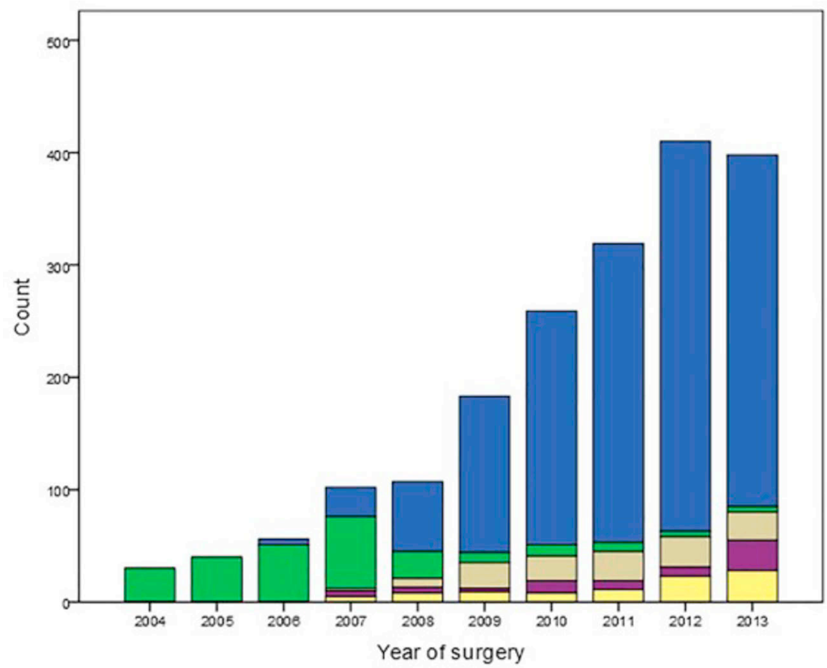


Figure 29. Arthroplasty brand, number of operations, and year of operation. DePuy Delta Xtend is shown in *blue*; Delta Mark III in *green*; TESS (Biomet, Warsaw, IN, USA)in *light brown*; Aequalis Reverse II (Wright Medical, Memphis, TN, USA) in *purple*; and other brands in *yellow*.

The most commonly used arthroplasty brands were Delta Xtend (DePuy Synthes, Warsaw, IN, USA) (n=1366) and Delta Mark III (DePuy Synthes) (n=246, 13%).

Totally, 95 RSAs (5%) were revised. The overall yearly survival rate was 91% (Figure 30).

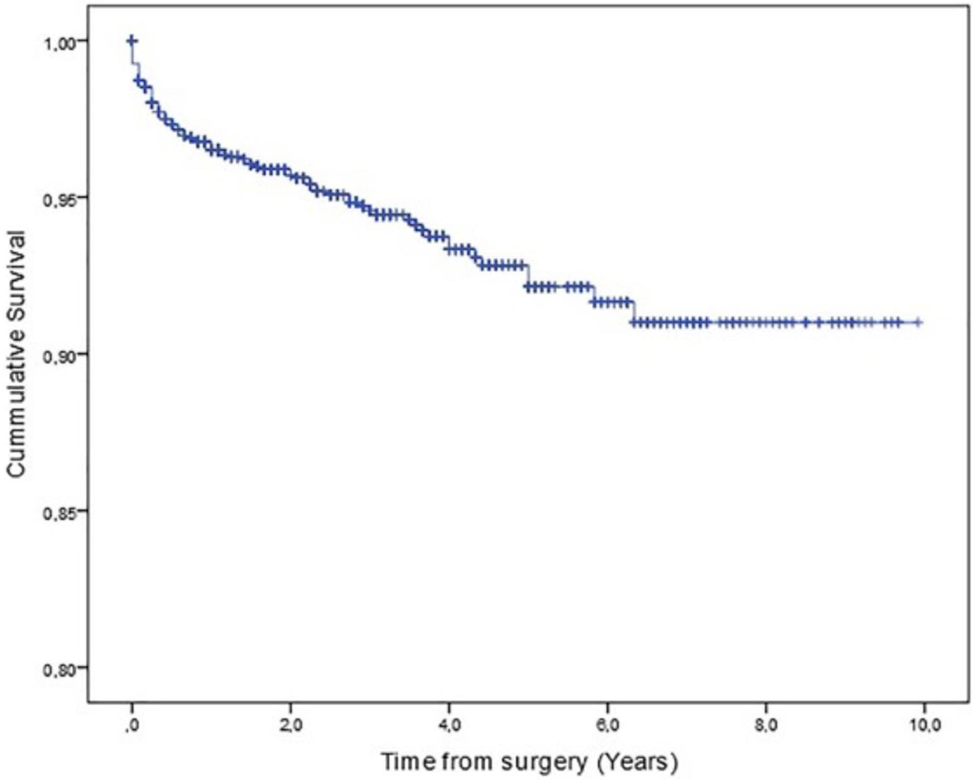


Figure 30. Survival curve of all primary RSAs for CTA.

The most common reasons for revisions were infection (n=42), loosening (n=16), and instability (n=12) (Table 4). The mean time from primary operation to revision was 14 months (SD 18 months; range 0–79 months). Of the revisions, 48 (51%) occurred less than 6 months after the primary operation. Men had a significantly increased risk of revision compared with women (risk ratio 3.8.; 95% confidence interval 2.4–6.1). (Figure 31).

Table 4. Reasons for revision and prevalence.

Reason for revision	Frequency (cumulative %)	Overall risk	Female/male, n (%)	Median age (range), yr	Mean time to revision (range), mo
Infection	42 (44%)	2.2%	11 (0.9)/31 (5)	73 (54-86)	7 (0-60)
Loosening	16 (17%)	0.8%	9 (0.7)/7 (1,1)	72 (60-87)	16 (0-60)
Instability	12 (13%)	0.6%	5 (0.4)/7 (1.1)	76 (59-88)	7 (0-70)
Other	12 (13%)	0.6%	6 (0.5)/6 (1)	73 (63-85)	3 (0-76)
Missing	10 (11%)	0.5%	4 (0.3)/6 (1)	74 (54-88)	9 (0-53)
Periprosthetic fracture	3 (3%)	0.1%	2 (0.2)/1 (0.2)	82 (72-89)	4 (1-5)

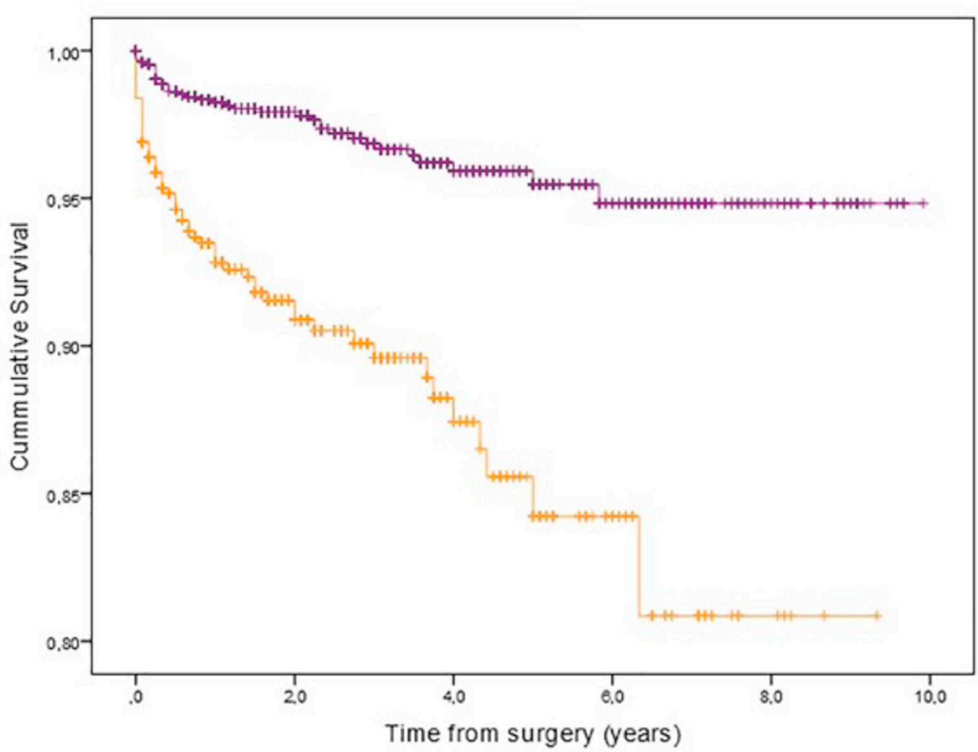


Figure 31. The 10-year survival rates for men and women were 0.95 and 0.81, respectively, with P<.001. Purple is female, yellow is male.

Patient age and year of operation were not significantly associated with risk of revision. Overall, 50 Delta Xtend implants (4%) and 29 Delta Mark III implants (12%) were revised. The 10-year survival rates for these implants were 0.95 and 0.86, respectively. This difference was statistically significant, with P=.004. The risk of revision of the Delta Mark III was 2.1 (95% confidence interval 1.1-4.3) compared with the Delta Xtend (Figure 32).

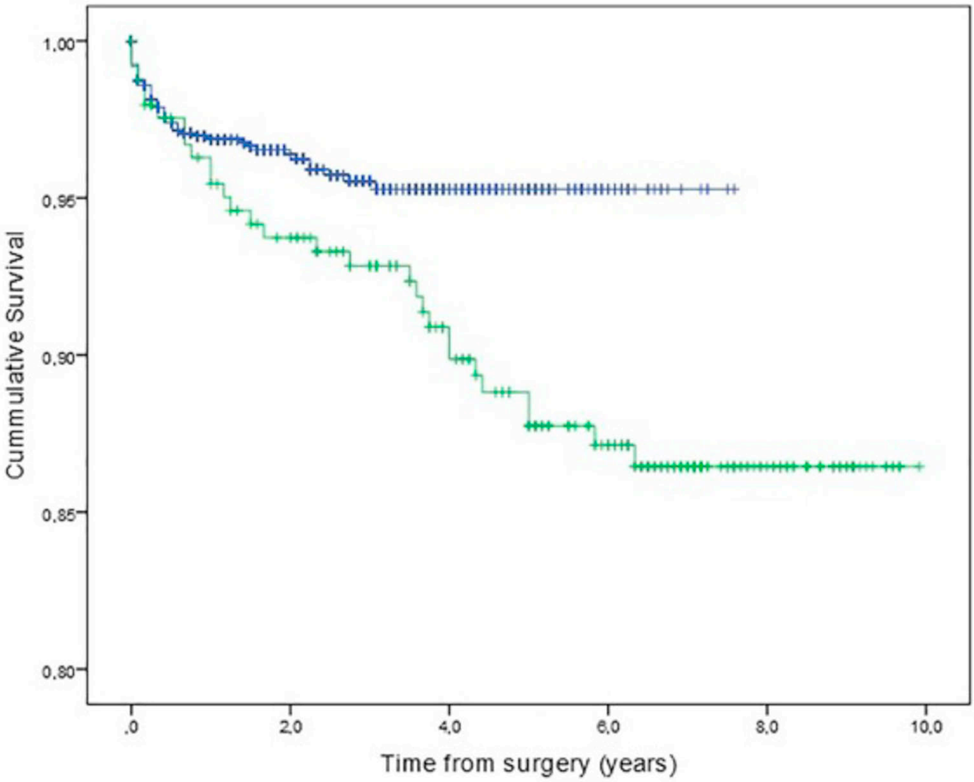


Figure 32. Survival curves of two most commonly used arthroplasty brands; Delta Xtend (*blue*) and Delta Mark III (*green*).

5.2 Study II

In Study II, a total of 8938 RSAs were registered in Denmark, Norway, Sweden, and Finland during 2004–2016.

There were 1282 female patients (84%) and 241 male patients (16%). The average age was 77 years (SD 8.5 years; range 49–89 years), and the average follow-up time was 2.5 years (range 0–11.6 years). During the follow-up time the yearly number of arthroplasties increased (Figure 33).

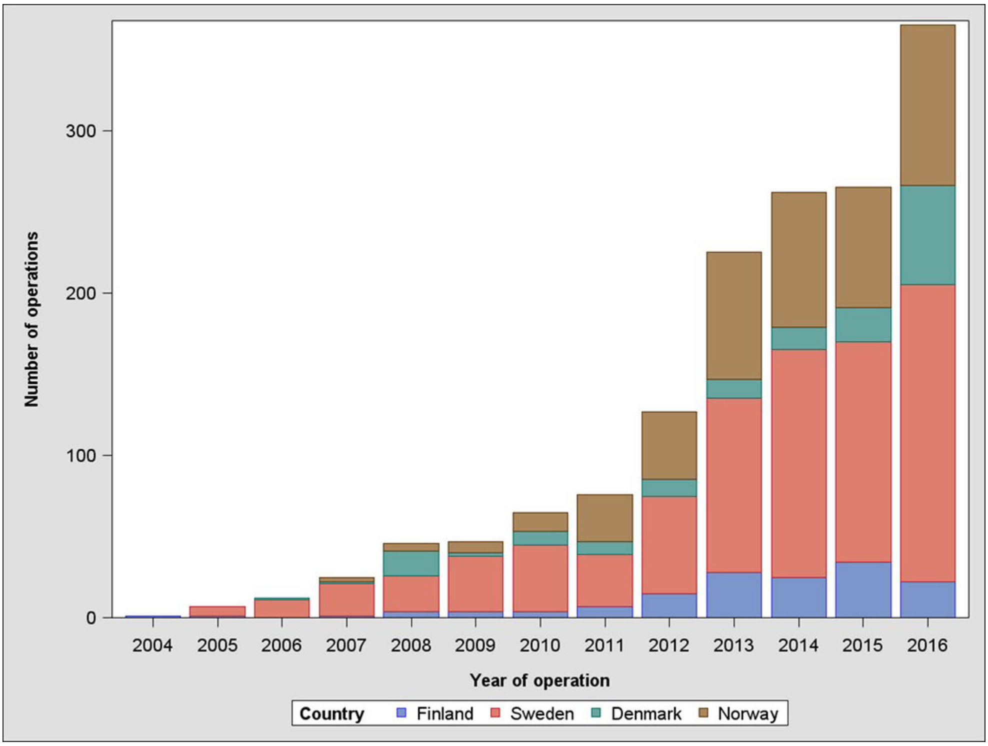


Figure 33. Number of RSAs for proximal humeral fracture in the Nordic countries in 2004–2016.

There were 33 (2%) revisions. In 11 cases (0.7%), the most common reason for revision was instability. Fracture and infection were reasons for revision in six cases (0.4%) and five cases (0.3%), respectively (Figure 34).

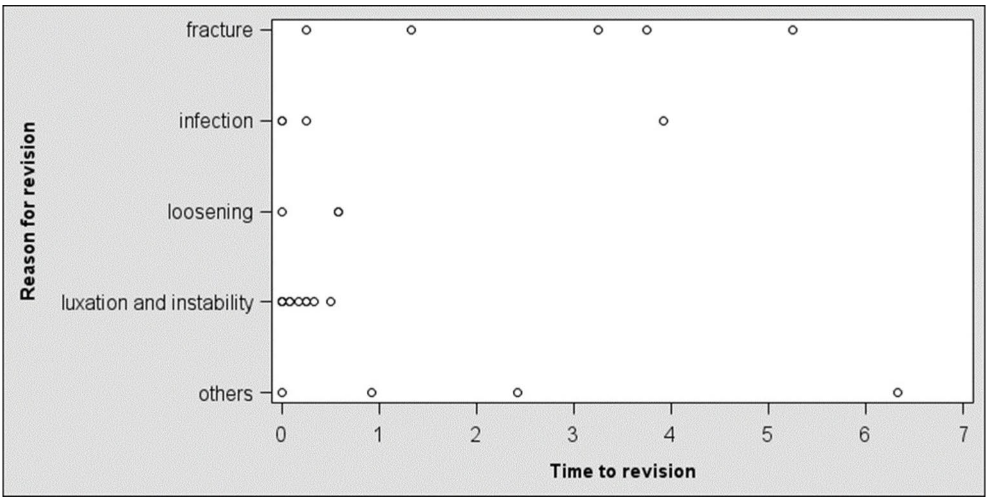


Figure 34. Reason and time of revision (years) after RSA for PHF.

The overall 5-year cumulative survival rate was 97% (CI, 95.5% and 98%) (Figure 35).

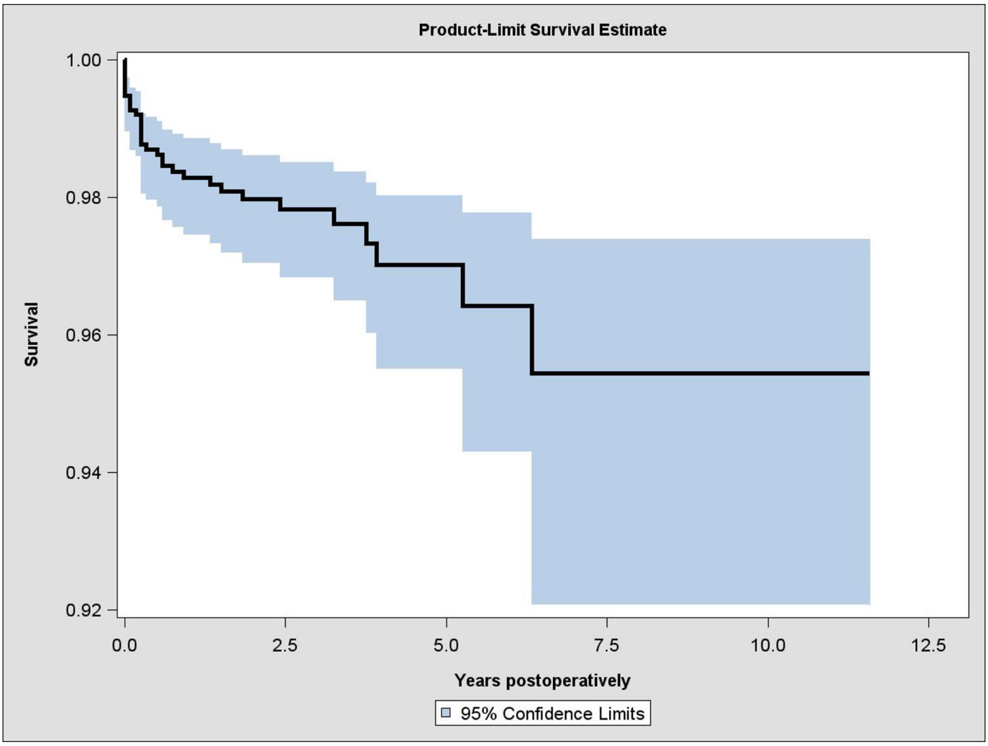


Figure 35. Cumulative survival of RSA for PHF.

The most commonly used arthroplasty brand in this cohort was Delta Xtend (DePuy Synthes, Warsaw, IN, USA). The comparative analysis is presented with the four most common brands, the Delta Xtend, Aequelis reverse (Stryker) (n=182), Biomet Comprehensive reverse (Biomet, Warsaw, IN, USA) (n=89), and Lima SMR Reverse Shoulder Prosthesis (Lima Corporate, Udine, Italy) (n=75). The HR for revision of each brand compared with the Delta Xtend was 1.33 (P=.720, 4.36 (P=.030), and 13.11 (P<.001), respectively. (Figure 36).

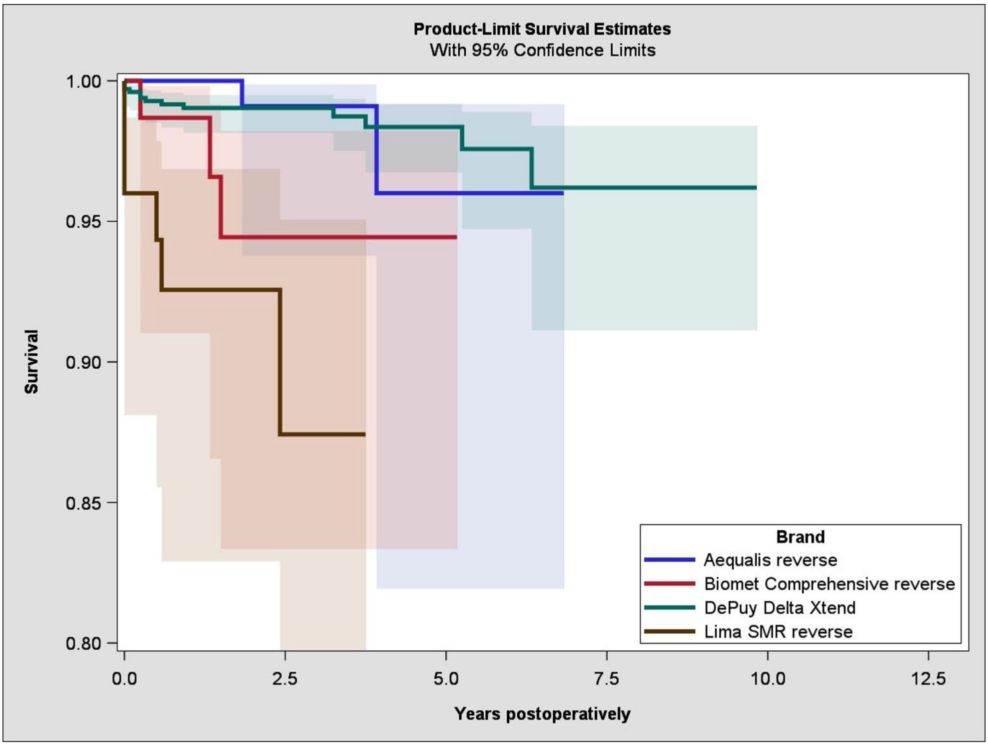


Figure 36. Survival of four most common RSA brands for PHF.

Patient age younger than 60 years and male gender were associated with slightly higher risks of revision. The difference did not reach statistical significance (HR of 2.02 with P=.075 and HR of 3.23 with P=.057, respectively). The year of operation and country of surgery were not statistically significantly associated with the risk of revision.

5.3 Study III

There were 91 shoulders with primary RSA for CTA (n=48), OA (n=10), or RA (n=28) and other (n=5) that were available for analysis. The average age of the patients was 73 years (SD 9) and 77% of them were female. The mean follow-up time was 38.7 months (SD 20; range 12–83). There were 44 Zimmer Biomet trabecular metal and 47 Delta Xtend prostheses. Only centric glenosphere components and 36 mm, 38 mm, 40 mm and 42 mm glenosphere size were used were used and the mean glenosphere size was 39 mm (SD 2.6). The Hamada grading was 3 preoperatively (SD 1.4, range 0–5). Preoperatively measured CSA was 37° (SD 7, range 20–55). Postoperative measurements were mean α-angle 127° (SD 14, range 94–168) and β-angle 54° (SD 11, range 19–80). The LSA and DSA angles were 81° (SD 15, range 39–132) and 52° (SD 13, range 16–97), respectively. The mean postoperative GIO was 3 mm (SD 3, range 3). The Sirveaux notching grades at follow-up were grade 0 in 23 cases, grade 1 in 35, grade 3 in 11, and grade 4 in five cases. Scapular fracture with tilted acromion was found in nine shoulders at follow-up.

The mean clinical outcomes at follow-up were CS 53 (SD 18), WOOS 67.20 (SD 24), VAS 2 (SD 3), active flexion 118° (SD 26), active abduction 104° (SD 32), active external rotation 41° (SD 22), and active internal rotation 77° (SD 21). The mean passive flexion was 135° (SD 19), passive abduction 112° (SD 21), passive external rotation 54° (SD 24), and passive internal rotation 89° (SD 21).

There was a statistically significant correlation between the preoperative radiographically measured CSA and post-operative α-angle, LSA, and DSA angles (Table 5). There was no statistically significant correlation between the measured glenosphere size-adjusted geometrical parameters and ROM and clinical outcome. The measured GIO did not significantly correlate with the detected notching ($r=0.17$, $p=0.1518$). Notching correlated statistically significantly with the measured α-angle ($r=0.38$, $p=0.0013$) and preoperative CSA ($r=0.34$, $p= 0.0008$).

Table 5. Mean values and Pearson's correlation of radiographic geometric parameters and measured α-angle.

α-angle	**127° (SD 14)**	**-**
β-angle (mean)	54° (SD 11)	r=-0.49 (p<0.0001)
CSA (mean)	37° (SD 7)	r=0.50 (p=0.0001)
LSA (mean)	8°1 (SD 15)	r=0.36 (p=0.0008)
DSA (mean)	52° (SD 13)	r=-70 (p<0.0001)

5.4 Study IV

A total of 38 shoulders (34 patients) of 62 (56 patients) were available for clinical and radiological follow-up (drop-out rate 39%) at mean 34 months (SD 21; range 12-89) postoperatively.

There were 25 women (74%) and nine men (26%) and their mean age at the time of surgery was 69 years (SD 11; range 45–85). There were 14 Delta Xtend (DePuy Synthes, Warsaw, IN, USA), 17 Aequalis Reversed II (Wright Medical-Tornier Group, Memphis, TN, USA), two Tornier Flex reverse (Wright Medical-Tornier Group, Memphis, TN, USA), and five Trabecular Metal reverse (Zimmer Biomet, Warsaw, Indiana) prostheses. Only centric glenosphere designs were used with 26 autogenic (ATg) and 12 allogenic (ALg) bone grafts. There were 11 revisions and 27 primary RSA operations, and there were statistically significantly more index revisions in the ALg group (p<0.0001). Patient demographics in groups ATg and ALg are presented in Table 6.

Table 6. Patient demographics from Study IV.

	ATg (N=26)	ALg (N=12)	p
Males/females, n (%)	5 (19%) / 21 (81%)	5 (42%) / 7 (58%)	0.2347 ^{F}
Age, mean (SD) [median]	73 (7.8) [75]	60 (10.9) [60]	0.0007 ^{W}
BMI, mean (SD)	29.0 (5.41)	27.5 (4.11)	0.3631 ^{t}
Smoking, yes/no, n (%)	2 (8%) / 24 (92%)	1 (8%) / 11 (92%)	1.0000 ^{F}
Primary/revision, n (%)	26 (100%) / 0	1 (8%) / 11 (92%)	< 0.0001 ^{F}
Operative indication, n (%)			
Inflammatory arthritis	1(4%)	1 (8%)	
Instability	1 (4%)	0	
Cuff tear artrhopathy	8 (31%)	0	
Osteoarthritis	15 (58%)	0	
Revision arthroplasty	0	11 (92%)	< 0.0001 ^{F}
		9	HSA to RSA
		1	TSA to RSA
		1	RSA to RSA

^{W} Wilcoxon rank-sum test
^{t} Student's t-test
^{F} Fisher's exact test

The most frequently occurring preoperative Hamada class was 4 (range 1–5) and the glenoid defect A2 and E1 according to Walch and Favard, respectively. The mean degree of glenoid retroversion was 18 (SD 15) and the mean CSA was 31 (SD 8). Bone defects were statistically significantly greater in the ALg group according to both Walch and Favard (p=0.0378 and p=0.0101, respectively). The preoperative imaging data in groups ATg and ALg are shown in Table 7.

Table 7. Preoperative imaging data from Study IV.

	ATg (N=26)	**ALg (N=12)**	**p**
Hamada, n (%)			
1	3 (12%)	2 (20%)	
2	1 (4%)	1 (10%)	
3	0	0	
4	20 (77%)	5 (50%)	
5	2 (8%)	2 (20%)	0.2848 F
Walch, n (%)			
A1	0	1 (13%)	
A2	14 (58%)	2 (25%)	
B1	0	0	
B2	5 (21%)	0	
B3	1 (4%)	1 (13%)	
C	4 (17%)	4 (50%)	
D	0	0	0.0378 F
Favard, n (%)			
E0	3 (12%)	0	
E1	20 (77%)	1 (20%)	
E2	2 (8%)	3 (60%)	
E3	1 (4%)	1 (20%)	
E4	0	0	0.0101 F
Retroversion, mean (SD)	16.3 (14.4)	23.5 (16.3)	0.2407 t
CSA, mean (SD)	30.4 (4.9)	33.9 (11.9)	0.3931 t

W Wilcoxon rank-sum test
t Student's t-test
F Fisher's exact test

The mean CSA at follow-up was 27° (SD 12). The central peg of the metaglene component was fixed in the native glenoid at a mean depth of 17.4 mm (SD 4; range 9–26). The bone graft was fully incorporated, partially incorporated and fully resorbed in 16 (42%), 18 (47%), and two (5%) cases respectively. There was no radiographic lucency around the metaglene construct nor humeral component loosening in either group. Scapular notching was present in 11 cases (29%). At follow-up there was one case with a radiographically detectable acromion fracture in the ATg group, one case with a tuberculum majus fracture and transient brachial plexus palsy, and one case with instability requiring revision surgery in the ALg group. The pain VAS, CS, and WOOS scores were statistically significantly better in the ATg group compared to the ALg group. Follow-up radiographic and clinical data are presented in Tables 8 and 9, respectively.

Table 8. Radiological follow-up data from Study IV.

	ATg (N=26)	ALg (N=12)	p
Years of follow-up, mean (SD)	2.6 (1.7)	3.3 (1.7)	0.2914 ^{t}
CSA, mean (SD)	28.1 (7.0)	24.0 (19.5)	0.5081 ^{t}
Sirveaux, n (%)			
No notching	17 (65%)	9 (82%)	
Slight notching	7 (27%)	1 (9%)	
Notching up to the lower screw	0	0	
Notching above the lower screw	2 (8%)	1 (9%)	
Notching reaching the central peg	0	0	0.5126 ^{F}
Incorporation of bone graft, n (%)			
Graft fully incorporated	13 (50%)	3 (30%)	
Graft partially incorporated	12 (46%)	6 (60%)	
Graft resorbed	1 (4%)	1 (10%)	0.3956 ^{F}
Length of central peg in native glenoid (mm), mean (SD)	17.0 (3.2)	14.3 (3.5)	0.0334 ^{t}

^{t} Student's t-test
^{F} Fisher's exact test

Table 9. Clinical results of Study IV.

	ATg (N=26)	ALg (N=12)	p
Pain VAS, mean (SD) [median]	0.38 (1.10) [0.00]	1.62 (2.55) [0.40]	0.0121 ^{W}
Constant, mean (SD) [median]	68.3 (9.6) [67.5]	55.9 (23.9) [58.0]	0.0267 ^{W}
WOOS, mean (SD) [median]	89.2 (12.8) [93.6]	71.7 (21.3) [73.7]	0.0054 ^{W}

^{W} Wilcoxon rank-sum test
^{t} Student's t-test

There was no statistically significant difference in bone graft incorporation between the two groups. Nor were there statistically significant correlations between bone graft incorporation and the studied parameters.

6 Discussion

6.1 The studies I and II

The main finding in Studies I and II was a relatively low risk of revisions after RSA for CTA and OA. The survivorship was 91% during the study period. This proportion is lower than in previous studies (Werthel et al. 2017). In Study I, male gender was associated with an increased risk of revision; the finding was statistically significant. This is in accordance with previous studies (Fevang et al. 2009, Singh et al. 2012).

In Study II, male gender did not incur a statistically significant risk of revision; there was only a tendency. Another finding from Study II was increased utilization of RSA for acute PHFs in the Nordic countries, especially for the treatment of elderly female patients. The same trend is seen worldwide (van der Merve et al. 2017; Dillon et al. 2019; AOANJRR 2021). This could be explained by an increase in low-energy fractures, as well as by a marked change in surgeon behaviour regarding the advocated treatment (Court-Brown 2006). According to our register studies (Studies I and II), RSAs increased 10-fold in Scandinavia during our 10-year study period.

Our revision rate was lower than the rates in previously published reports (Zumstein et al. 2011; Richars et al. 2014; Morris et al. 2015; Boileau et al. 2016; Villacis et al. 2016; Kang et al. 2019; Moeini et al. 2019; Belay et al. 2020; Knutsor et al. 2020). Possible explanations might be improvements in patient selection and implant development, together with increasing surgeon understanding of the nuances of surgical techniques. In Study I, the most common reason for revision was infection, and a higher infection prevalence seems to be one factor explaining higher revision rates among men than women. In previous studies, men reportedly had an increased risk of infection after open shoulder surgery compared with women (Richards et al. 2014, Werthel et al. 2017). This difference is potentially due to abundant colonization by *Cutibacterium acnes* (formerly known as *Propionibacterium acnes*) in male skin (Mook et al. 2015). Because of difficulties related to the detection of the low-virulence pathogen, the true incidence of revision for infections may be underestimated by registry data (Gundtoft et al. 2015). Therefore, it is possible that missing data on the reason for revision in our cohort includes undetected infections.

Young age has previously been associated with a high risk of revision after RSA (Morris et al. 2015). However, neither of our register studies (I and II) showed this correlation with revision risk. The relatively low total number of revisions, especially among younger patients and older males in our cohort, together with the hierarchy used for reasons for revision, may partly explain this difference compared with previous studies (Anakwenze et al. 2017).

In previous cohorts with heterogeneous operative indications, instability has been reported to be the most common reason for revision and has been associated with young age, post-traumatic conditions, and revision surgery (Bohsali et al. 2017). In contrast to previous reports, we included primary RSA for CTA and OA only, and there were few revisions because of instability. In the Australian registry, instability has been reported to be the most common reason for revision in CTA patients (AOANJRR 2018). There may be other factors contributing to instability, such as soft-tissue coverage and surgical approach; however, our data did not allow us to analyse these factors. In Study II, the leading cause of revision of RSA in our cohort was instability, followed by fracture and infection. Instability after proximal humerus fracture may be related to the initial fracture, suboptimal positioning of the RSA implant, or inferior stability due to a tear of the subscapularis tendon or lack of healing of the tuberosities. Most of these revisions occurred early, within 1 year after surgery, and thereafter revisions were less frequent. This finding is in line with the results of previous reports by Dillon et al. (2019) and Nogure et al. (2019). Despite the low overall number of fractures leading to revision of RSA in our cohort, the incidence was higher than other reports on RSA for CTA (Lehtimäki et al. 2018).

The Delta Mark III arthroplasty brand was associated with a significantly higher risk of revision than the Delta Xtend. The very early survival curves for these two brands were similar, but after 1 year, survival differed markedly. This finding is in line with a previous report on the poorer modular mechanical properties and design of the Delta Mark III implant (Werner et al. 2005). This may also represent the early learning curve in both patient selection and the technical procedure for RSA in Scandinavia.

However, the year of surgery did not affect the revision rate. The later-introduced Delta Xtend prosthesis has shown a similarly good survival rate to that in the Australian registry (AOANJRR 2017) data. The Delta Mark III is no longer available in Scandinavia. The Delta Xtend was used in a high number of cases and had a low revision rate according to both Studies I and II. The apparent routine use of one predominant brand in the Nordic region makes it difficult to compare with other brands and therefore to detect differences in prosthetic survival. However, in the report using Australia register data, the risk of revision is similar to our findings, with the SMR prosthesis having the highest risk of revision compared with other brands (AOANJRR 2018). A comminuted PHF is characteristic in frail elderly female patients with a higher mortality rate; the 1-year mortality rate was 4% in our cohort. Previously, an even higher rate of 10% has been reported for PHF patients, independent of the treatment algorithm (Gallinet et al. 2018). This difference may represent a potential selection of healthier patients for RSA surgery in our cohort. No consensus exists on treatment strategies for PHF. Spross et al. (2019) published a treatment algorithm, without high-level comparative evidence, for the use of RSA in comminuted fractures in elderly patients with osteoporotic bone.

6.2 Study III

In Study III, the main finding was that none of the radiographically measured geometrical parameters were statistically significantly associated with the clinical ROM or post-operative outcome scores. Roberson et al. (2019) have previously reported similar results. A postoperative 2D radiographically measured obstacle-free sector around the COR does not significantly correlate with glenohumeral or shoulder ROM or clinical results after RSA. The clinical results of RSA in our series were comparable to the published literature (Al-Hadithy et al. 2014; Bacle et al. 2017; Kennon et al. 2020). The COR based α-angle in our study statistically significantly correlated with the previously reported CSA angle. This implies that the preoperatively measured scapular morphology, i.e., CSA angle, determines the positioning of COR in RSA, while the glenosphere implants in our series were systematically positioned in relation to the native glenoid. Despite the pre- and postoperatively detected variability in radiographic geometry, we did not find a statistically significant correlation between measured positioning of RSA COR (α-angle) and active shoulder ROM, and moreover with the passive glenohumeral ROM with fixed scapula, the α-angle is dependent on both the lateralization and distalization of the COR. However, it does not take into account the positioning of the humerus in relation to the COR. A large glenosphere pushes the humerus distally away from the scapula, and there are previous reports of a positive correlation between glenosphere size and ROM (Mollon et al. 2016; Muller et al. 2018; Werner et al. 2018). Therefore, we adjusted the statistical analyses according to the glenosphere size. Moreover, we also measured the β-angle and active or passive ROM. Contrary to our findings, radiographic geometry has been previously reported to influence ROM in RSA (Boutsiadis et al. 2018, Ferrier et al. 2018). Especially LSA allegedly positively correlates with both postoperative active ROM and also CS, although this correlation could be regarded as weak and arbitrary (Boutsiadis et al. 2018). There were 46 patients divided in four groups (10-13 patients in a group), so the power of the study is pretty low. Nevertheless, the LSA and DSA angles do not take into account the COR, which in our opinion should be the key interest when planning for RSA. In clinical practice it would be very helpful to have a clinically relevant target position for the COR of implants to optimize the outcome of RSA. Helmkamp et al. (2018) have reported that prosthetically lateralized COR yields an increased postoperative external rotation and decreased scapular notching. We did not find significant differences in ROM or notching between the prosthesis models. There was a positive and statistically significant correlation between the CSA and α-angle and notching at follow-up. The finding was also independent of glenosphere size and inferior offset. A pronounced acromion overhang may be associated with other unknown factors, such as a short glenoid neck, potentially contributing to the increased risk of notching. Notching was not associated with ROM or clinical outcome in our study.

There is a need for more basic research into both normal and pathological shoulder function. In particular, the traditional view that the scapula is a passive structure anchored to the trunk, as proposed by Neer in the 1980' wiht the acromioplasty, may have steered our understanding of shoulder mechanics in an unproductive direction.

6.3 Study IV

In Study IV, the main finding of the study was that the structural bone grafts healed with no sign of radiological loosening around the glenoid component and with satisfactory clinical results. There was no statistically significant difference in follow-up radiological component survival between the autograft and allograft group. Despite 47% of the grafts being only radiographically partially incorporated in the native glenoid, none of the metaglene components showed signs of radiographic loosening. In previous reports, the failure rate of structural glenoid bone grafts has been quite high. Ho et al. (2020) reported a graft resorption and component failure rate of up to 25% at a median of 14 months. In their study, radiographic failure was associated with retroversion on the glenoid, contrary to our findings, and it may be that there were differences in the technical aspects of the procedure. In a recent meta-analysis, both primary RSA with glenoid bone graft and metal augmented glenoid techniques had good clinical outcomes (Wilcox et al. 2022). In our series, no metal augments were used and all and the metaglenes were securely fixed to the native glenoid vault with a long central peg.

There are reports of a potential benefit of always lateralizing the glenoid to gain a better ROM (Boileau et al. 2011). Nevertheless, active ROM is dependent on soft tissues and musculature, and therefore the theoretically optimal bony geometry may not result in better clinical results (Lehtimäki et al. 2021). Glenosphere lateralization may also decrease notching, however with no influence on the functional outcome (Athwal et al. 2015). In our series the rate of notching was similar to those previously reported (Paul et al. 2019). It is also noteworthy that excessive lateralization and distalization of the glenosphere may lead to acromion stress fracture and complications of RSA (Werner et al. 2017; Ascione et al. 2018; Haidamous et al. 2020; Shah et al. 2020). In the one RCT study of the topic, there was no difference between BIO-RSA and metal augmented wedge glenoid component at 2 years follow-up. Stable fixation and no difference in clinical parameters.

6.4 Limitations of the studies

In Studies I and II, the follow-up time was relatively short. According to Favard et al., clinical results deteriorate after 10 years and longer follow-up is needed. In registry Studies I and II, the incomplete coverage of national registry data is a limitation. However, the Swedish, Norwegian, and Danish registries have been estimated to cover 80–90% of shoulder prostheses, which is still high; therefore, we do not think this has created any bias in our results (Rasmussen et al. 2016). There is a possiblitity that surgeons have an interest in underreport the revision procedures, this should to taken into consideration when interpreting the results Rasmussen et al. 2021). Given the heterogeneity of the national data the common dataset is highly condensed, and we had no further patient-related data (medical, radiographic, surgical, etc.) available or data on patient-reported outcomes, which may have confounded our findings. As with all registry studies, the only outcome we were able to evaluate was revision operation. There might have been other complications that did not lead to revision surgery but compromised the end result. Such as acromion fracture, fragile patients can be left with instable RSA, loosening of the component does not necessarily lead to a revision with morbid patients and nerve damage does not usually lead to revision surgery.

The main strength of the study is the comprehensive inclusion of consecutive primary RSAs for CTA, OA, and fracture patients in Scandinavia. The high number of RSAs represents the evolution of clinical practice in Scandinavia. Further development of these large registries is of paramount importance. A systematic registry study clearly outperforms sporadic small-sized studies in terms of power, for example, when investigating the factors related to a relatively low revision risk. The NARA collaborative network enables us to further follow up the patients, expand the collaboration, and generate a common and more comprehensive national registry dataset.

In Studies III and IV, one limitation is the retrospective nature of the studies. Also, the drop-out rate was high in both studies. The data were based on 2D radiographs from real life and the quality of the radiographs was not optimal in every case. A major limitation of both studies is the lack of accurate data on preoperative and perioperative functional status of the patients. In Study IV we did not have follow-up CT data for precise evaluation of the glenoid bone stock, although radiographs are reliable in the assessment of radiolucent lines and component loosening (Bach et al. 2005).). Although the CT scan analysis has improven in time and maybe radiosterometric analysis might offer some improvements in the future. The patient population was highly heterogeneous, with multiple potentially confounding factors. On the other hand, our study represents a true clinical consecutive patient population.

7 Summary/Conclusions

1. The risk of revision after RSA for CTA and OA was low. Male gender was associated with a significantly increased risk of revision. The most common reason for revision after RSA for CTA or OA was infection.
2. The short-term risk of revision after RSA for PHF was low. The main reason for revision of RSA for this indication was instability.
3. Postoperative radiographically measured two-dimensional geometry does not significantly correlate with the glenohumeral ROM, and other clinical results after RSA were comparable with literature.
4. Glenoid bone grafting in conjunction with RSA is a safe and reliable method to restoring the glenoid bone stock in short term follow-up. There was no significant difference in radiological outcomes between auto- and allograft bone grafting techniques.

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