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REVERSE SHOULDER ARTHROPLASTY (E CRAIG AND C CHAMBERS, SECTION EDITORS)

Reverse Total Shoulder Arthroplasty: Implant Design Considerations

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Abstract

Purpose of Review Our understanding of the reverse total shoulder arthroplasty (RTSA) has grown exponentially since Grammont first introduced his design in 1985. There are a multitude of implant-related variables to consider when performing RTSA. The purpose of this article is to provide a review of these design considerations.

Recent Findings Current literature demonstrates that the traditional Grammont prosthesis has over 90% survivorship at 10 years. Despite these promising results, there have been concerns raised over the significant rate of scapular notching observed. As a result, the traditional RTSA design has been modified to minimize this complication and maximize impingement-free motion. Modern RTSA designs with a cementless, curved, short-stemmed eccentric onlay humeral component combined with a large, lateralized glenosphere placed in 10° of inferior tilt with > 3.5 mm of inferior overhang have been found to provide excellent results. However, all implant design features must be considered on a case-by-case basis to optimize outcome for each patient.

Summary Humeral and glenoid implant design variables have evolved as the biomechanics of RTSA have been further elucidated. Consideration of these variables allows the surgeon to maximize joint efficiency, improve impingement-free range of motion, decrease the risk of scapular notching, preserve bone stock, and minimize the risk of instability.

Keywords Glenosphere · Humeral tray · Lateralization · Neck-shaft angle

Introduction

There has been a substantial increase in the utilization of reverse total shoulder arthroplasty (RTSA) in the United States (US) following its approval by the Food and Drug Administration (FDA) in 2003 [1, 2]. In 2011, RTSA accounted for 42% of all primary shoulder arthroplasties performed in the US [3]. Although originally indicated for patients with rotator cuff arthropathy, indications for RTSA have expanded to include severe glenohumeral osteoarthritis, revision arthroplasty, irreparable rotator cuff tears, rheumatoid arthritis, tumors, proximal humerus fractures, and fracture sequelae [4–11]. Despite its growing popularity, early versions of RTSA had high failure rates due to glenoid component loosening and implant breakage [12]. The underlying design flaw of these earlier reverse prostheses was that they were highly constrained and lateralized the shoulder's center of rotation, which resulted in unacceptable forces and ultimately failure at the bone-implant interface [12, 13]. However, in 1985, Dr. Paul Grammont revolutionized shoulder arthroplasty when he introduced his original reverse prosthesis design, which was based on four key principles: (1) the center of rotation of the glenohumeral joint placed medial and inferior (in relation to the native center of rotation), (2) the prosthesis must be inherently stable, (3) the deltoid lever arm must be effective from the onset of motion, and (4) the glenosphere must be large and the humeral cup small to allow for a semi-constrained articulation [13, 14]. In theory, medializing the center of rotation and lengthening the humerus would tension the deltoid and allow for compression between the glenosphere and humeral socket, thereby stabilizing the articulation and enhancing recruitment of the deltoid muscle fibers for a more efficient deltoid lever arm [15]. In 1987, Grammont published the results of his first prototype, which was composed of a cemented glenosphere and inverted polyethylene humeral stem. All eight patients were noted to be pain-free; however, function varied with five patients achieving 100 to 130° of forward elevation and three having less than 60° of elevation [14]. Grammont's prosthesis continued to evolve

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with the next iteration called the Delta, due to the effective role of the deltoid in obtaining function and maintaining stability. The Delta III (DePuy International Ltd, Warsaw, IN), the current generation, has the longest reported outcomes of any reverse shoulder prosthesis currently marketed and is comprised of five components: a glenoid baseplate, Co-Cr glenosphere, polyethylene humeral cup, humeral neck, and humeral stem [16, 17]. As our understanding of the biomechanics of the reverse shoulder prosthesis evolves, advancements in RTSA design continue to be made. The purpose of this review is to provide a summary of the implant design considerations when performing a RTSA.

Glenoid

Lateral Offset

Although medializing the center of rotation addressed glenoid baseplate loosening, which was the primary mode of failure prior to the Grammont prosthesis, it did result in high rates of scapular notching. This was originally believed to occur due to mechanical impingement of the superomedial humeral prosthesis against the inferior scapular neck during adduction [13]. However, more recent studies have suggested that internal and external rotation with the arm at the side may play significant role in the development of notching [18]. The incidence of scapular notching reported within the literature varies from 4.6 to 96% [19–22]. The impact of notching on clinical outcomes remains unclear as several studies have implicated it in the development of bone loss [23–25], osteolysis [25], and aseptic loosening[22, 23, 25], while others have reported no adverse effect on clinical outcomes[26, 27]. Lateralization of the implant's center of rotation has been proposed to decrease scapular notching, improve soft tissue tension, and increase impingement-free range of motion. It is important to keep in mind that this is a relative lateralization of the center of rotation compared with the implant designed by Grammont, but still medialized compared with the native glenohumeral joint. Lateralization on the glenoid side can be achieved using metal (e.g., lateralized baseplate or glenosphere) or bone (bony increased-offset reverse shoulder arthroplasty [BIO-RSA]) augmentation [21, 28]. In either case, lateralization results in increased torque at the glenoid-baseplate interface potentially leading to excessive motion, loosening, and ultimately failure [29–32]. In cases where lateralization is achieved using bone augmentation, these increased shear forces can result in graft resorption and non-union [28]. More recent lateralized baseplate designs have attempted to mitigate the shear forces at the bone-implant interface by using multiple locking screws and long metallic posts or threaded post baseplates [33]. Greiner and colleagues [34] conducted a prospective randomized study comparing the clinical outcomes of lateralized versus non-lateralized RTSA prostheses using bone augmentation (i.e., BIO-RSA) and noted a statistically significant improvement in active external rotation in the lateralized RTSA group. Similarly, a recent multicenter prospective study by Hasan et al. [35] noted that RTSA using a lateralized glenosphere was associated with improvements in external rotation that exceeded the minimal clinically important difference for RTSA and had low rates of scapular notching (13.3%) and acromial stress fractures (6.5%). Cuff and colleagues [36, 37•] reported on the medium and long-term follow-up of a lateralized offset design and found 94% and 90% survivorship at 5 and 10 years, respectively. Moreover, scapular notching rates were significantly lower (9%) than those observed among Grammont-style prostheses [36, 37].

Glenosphere Position

Altering the cranio-caudal position of the glenosphere as a means of decreasing the rate of scapular notching and improving the impingement-free range of motion is an advantageous option as it does not affect the joint's lateral offset [13, 24]. Eccentric positioning of the glenosphere in a more caudal direction, resulting in inferior overhang, has been shown to significantly improve both adduction and abduction [15, 38–40]. In fact, biomechanical studies have reported approximately 11 to 39° of additional adduction with inferior overhang of the glenosphere [15, 38, 41]. Poon et al. [42] conducted a randomized controlled trial comparing concentric and eccentric glenospheres among 50 patients undergoing RTSA and found no statistically significant differences in scapular notching; however, they did note that inferior overhang of the glenosphere > 3.5 mm prevented notching, a finding consistent with previous reports [42, 43]. It is important to note that excessive inferior placement of the glenosphere can result in loss of glenoid fixation, excessive deltoid tension, the need for increased humeral resection, and potentially an inability to retain the humeral stem during a revision procedure [21].

Glenosphere Tilt

Based on biomechanical studies, inferior glenoid tilt of 10° provides the greatest arc of impingement-free motion while generating the most even distribution of force at the bone-implant interface [39, 44]. Despite these findings, clinical studies have yet to demonstrate an advantage to inferior inclination of the glenoid component. A retrospective review of 71 shoulders compared the rate of scapular notching among shoulders with neutrally placed glenosphere baseplates and those that were 10 to 15° inferiorly tilted and found no difference in notching between groups [45]. In addition, Edwards et al. [46] performed a randomized controlled trial to compare 10° of inferior tilt to neutral inclination of the glenoid component among 42 patients undergoing RTSA and found no significant difference in scapular notching or clinical outcomes at 1-year follow-up. Nyffeler and colleagues [15] conducted a cadaveric study directly comparing glenospheres placed in 15° of inferior tilt with those that there were placed in neutral with inferior overhang and found that the latter group had the greatest impingement-free range of motion. Although the optimal amount of glenoid tilt remains unclear, there is overwhelming evidence that superior inclination of the glenosphere can result in instability, early loosening, and ultimately failure [47, 48]. As such, aiming for slight inferior tilt may be beneficial in avoiding inadvertent superior inclination of the glenosphere.

Glenosphere Size

Large-diameter glenospheres have been shown to increase stability, provide a greater impingement-free arc of motion, and decrease scapular notching in biomechanical studies [38, 49, 50]. Mollon et al. [51] compared clinical outcomes among a cohort of 297 patients who underwent RTSA with a 38- or 42-mm diameter glenosphere and found that the larger glenospheres increased active forward elevation and external rotation by 15° and 6°, respectively. A recent prospective randomized study of 81 patients also compared 38- to 42-mm diameter glenospheres and noted a statistically significant decrease in scapular notching (48.8% vs. 12.1%) for the larger glenospheres [52•]. However, there were no statistically significant differences in functional outcomes between the groups [52•]. Despite the advantages associated with the use of larger glenospheres, it may not be possible to utilize them in all patients as they may not be appropriate for the anatomy of smaller individuals. They are also more technically challenging to implant and require excellent surgical exposure and patient positioning [5, 13]. Moreover, Haggart and colleagues [53••] recently compared the rate of polyethylene wear between 32- and 40-mm diameter glenospheres and found that larger glenospheres had significantly higher volumetric wear rates and experienced greater polyethylene volume loss. As a result, the surgeon must weigh the benefits of added stability and a greater arc of motion against the possibility of increased polyethylene wear when considering the use of a larger diameter glenosphere.

Humerus

Neck-Shaft Angle

The traditional Grammont reverse prosthesis was designed as a non-anatomic implant with a relative horizontal humeral neck inclination of 155°. Based on the work by Gutierrez and colleagues [39], the neck-shaft angle has the largest effect on inferior scapular impingement and adduction deficit. As the neck-shaft angle increases, the polyethylene cup is positioned in a more horizontal orientation, which results in mechanical abutment of the cup along the inferior scapular neck. To address the concern of scapular notching and increasing impingement-free motion, several authors have proposed decreasing the neck-shaft angle to a more vertical or anatomic inclination (i.e., 145° or 135°), which also effectively lateralizes the humerus [54, 55]. Using a three-dimensional computer model of RTSA, Ladermann et al. [56] compared the traditional inlay Grammont humeral stem with a short, curved onlay stem with varying humeral neck-shaft angles (155°, 145°, and 135°) and noted a dramatic improvement in adduction, extension, and external rotation with more varus neck-shaft angles (i.e., 145° and 135°) [56]. Findings from a cadaveric study suggest that although impingement-free range of motion is improved with varus neck-shaft angles, the 155° humeral inclination confers the greatest stability to anterior translation when the arm is in the internal rotation (i.e., position most likely to result in instability) [57]. A systematic review of 38 studies and 2222 shoulders compared scapular notching and dislocation rates of RTSA prostheses with a 135° and 155° humeral inclination and reported significantly higher rates of scapular notching in the 155° group (16.8% vs. 2.8%) with no difference in dislocation rates between groups [58]. Gobezie and colleagues [59•] recently published the results of a large randomized controlled trial comparing humeral inclination of 135° to 155° among patients undergoing primary RTSA with a neutral glenosphere and found no significant difference in forward flexion, external rotation, or functional outcomes. They did, however, demonstrate significantly lower rates of scapular notching in the 135° group (21% vs. 58%) [59•]. Therefore, although the rate of scapular notching is significantly reduced with a more anatomic neck-shaft angle, it still remains unclear whether a more varus humeral inclination results in a clinically meaningful improvement in motion.

Version

Traditionally, it had been recommended that the humeral component be placed in 0 to 30° of retroversion during a RTSA [2, 27]. However, these recommendations were primarily based on expert opinion. There is now a growing body of biomechanical and clinical evidence examining the effect of humeral version on both range of motion and clinical outcomes. Stephenson et al. [60] conducted a cadaveric study to examine the effect of humeral version on range of motion and noted 20 to 40° of retroversion most closely restored the functional arc of motion without impingement. Another study utilizing a three-dimensional model found for every 10° increase in retroversion, internal rotation behind the back decreased at least one vertebrae level [61]. Similar findings were noted by Berhouet and colleagues [62] who implanted 40 cadaveric shoulders with a RTSA at varying degrees of humeral retroversion and noted a statistically significant decrease in internal rotation and a concomitant increase in external rotation with greater humeral component retroversion. Despite biomechanical evidence to the contrary, clinical studies have not shown any significant difference in range of motion, strength, or functional outcome when comparing 0° and 20° of humeral retroversion [63–65]. However, Rhee et al. [64] did find patients with 0° of humeral retroversion performed significantly better on activities of daily living that required internal rotation.

Tray Offset

Lateralization of the humerus can improve rotator cuff torque and can be achieved using a humeral tray with variable offset options [66, 67]. Berhouet and colleagues [68] were the first to evaluate the effect of humeral tray offset positioning on impingement, moment arm, and the rotator cuff musculature. Using a three-dimensional shoulder model, they found that positioning the humeral tray with a lateral offset resulted in diminished superior impingement. However, a posterior offset not only decreased superior impingement but also increased the internal rotation moment arm of the subscapularis, without creating inferior impingement [68]. A more recent biomechanical study showed that impingement-free range of motion can be maximized using a posterolateral tray offset, while one can optimize the muscle moment arm using a medial offset which improves soft-tissue tension on the deltoid by effectively lateralizing the humerus [69]. Excessive lateralization of the humerus can result in increased soft tissue tension and higher forces generated by the deltoid for function. Ultimately, this can lead to deltoid-related pain and an increased risk of acromial stress fracture [66, 70, 71].

Stem Geometry

While the classic Grammont prosthesis featured a straight stem with an inlay humeral tray, many newer designs have a curved stem with an onlay humeral tray. The curved stem was created to preserve tuberosity bone stock, reduce the risk of greater tuberosity fracture, preserve the insertion of the rotator cuff (if present), improve the ease of implantation, and offer the ability to convert between TSA and RTSA, either intra- or post-operatively [56]. Similar to the variable offset humeral tray, both the curved stem and onlay system increase the offset of the humerus. They also decrease the acromiohumeral distance, which may lead to acromial impingement during abduction [56]. A recent retrospective review did report a trend towards a higher rate of acromial fractures among patients with an onlay (12%) as opposed to inlay (4%) system [72]. Merolla and colleagues [73•] compared the clinical and radiographic outcomes of patients who had undergone RTSA with the traditional Grammont humeral component versus those who had a short, curved stem onlay design with a 145° neck-shaft angle and found no differences in patient-reported outcomes. However, patients with the modern humeral component had significantly greater improvements in external rotation and lower rates of scapular notching, glenoid radiolucency, and humeral bone remodeling [73•].

Stem Length

Much like the other components of the traditional Grammont prosthesis, the length of the humeral stem has continued to evolve over time. Although cemented fixation of the humeral component was the gold standard for RTSA, the success of uncemented humeral fixation has allowed for the introduction of bone preserving short-stemmed [74, 75], and even stemless [76–78] components [79]. In fact, Moroder and colleagues [78] compared the clinical and radiological outcomes of stemless RTSA with a matched cohort of patients undergoing conventional uncemented stemmed RTSA for rotator cuff arthropathy and found no differences between groups. Considering the indication when selecting the stem length is crucial, as a stemless prosthesis may be appropriate in patients with primary cuff tear arthropathy, while a proximal humerus fracture will necessitate the use of a stemmed prosthesis [80]. Moreover, a stemless prosthesis can result in substantial variability in the neck-shaft angle.

Polyethylene Insert

The stability of the RTSA is dependent on the contact area between the glenosphere and polyethylene inlay, which can range from minimal (high mobility) to maximal (constrained or retentive) [5, 80, 81]. Retentive liners can afford additional implant stability; however, they do so with the risk of increased wear and possible polyethylene wear–induced aseptic loosening [82, 83]. In fact, Carpenter and colleagues [82] performed an in vitro wear simulation study and demonstrated that retentive liners undergo significantly greater volumetric loss and surface deviation compared with non-retentive liners. Conversely, reducing the depth of the polyethylene inlay increases range of motion and lowers the risk of notching. De Wilde et al. found that for every 3-mm decrease in depth of polyethylene cup, range of motion increased by 12° [41]. Lastly, increasing the thickness of the polyethylene insert can further stabilize the joint and lateralize the

Table 1 A summary of the implant design considerations when performing a RTSA

	Summary
Glenoid	
Lateral offset	Lateralization of the glenosphere using metal or bone augmentation to decrease scapular notching, increase range of motion and improve soft tissue tensioning
Inferior overhang	Placement of the glenosphere with > 3.5 mm beyond the inferior rim of the glenoid to prevent scapular notching and improve range of motion
Inferior tilt	Positioning of the baseplate in 10° of inferior inclination to prevent superior inclination and potentially decrease risk of scapular notching
Larger diameter	Large glenospheres (i.e., 40 mm or 42 mm) improve range of motion and may increase stability
Humerus	
Varus neck-shaft angle	Utilization of a 135° or 145° humeral neck inclination may result in increased range of motion and decreased scapular notching
Native retroversion	Increases in humeral retroversion lead to an increase in external rotation and a decrease in internal rotation
Tray offset	Use of a posterolateral tray offset may result in optimal range of motion while the moment arm of the deltoid may be most efficient with a medial offset tray
Short curved onlay stem	Both the curved and onlay features of the modern humeral short stem systems increase the lateral offset of the humeral
Polyethylene	Retentive polyethylene liners are associated with significant volumetric wear, which may result in aseptic loosening of the component

humerus; however, overstuffing the articulation must be avoided as it has unfavorable effects on the deltoid muscle and joint loading [84].

Conclusion

The Grammont reverse prosthesis revolutionized the treatment of shoulder disorders that previously had no easy solution. As our understanding of RTSA biomechanics has evolved so as the implants. We now know that there are multiple implant-related variables (Table 1) on both the humeral and glenoid side that play a role in maximizing joint efficiency, increasing impingement-free range of motion, decreasing scapular notching, improving stability, and preserving bone stock. The use of patient-specific instrumentation and navigation may be the next step in providing more accurate component positioning and improving our ability to better restore soft tissue balance in the shoulder. Despite the advances made thus far, there remains ample opportunity for continued improvement and innovation.

Compliance with Ethical Standards

Conflict of Interest Ujash Sheth declares that he has no conflict of interest.

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Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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