

Grammont reverse prosthesis: Design, rationale, and biomechanics

Pascal Boileau, MD, Duncan J. Watkinson, FRCS, Armodios M. Hatzidakis, MD, and Frederic Balg, MD, FRCSC, Nice, France

Combined destruction of the rotator cuff and the glenohumeral joint may lead to a painful and pseudo-paralyzed shoulder. In this situation a nonconstrained shoulder prosthesis yields a limited functional result or may even be contraindicated. Previous constrained prostheses (ball-and-socket or reverse ball-and-socket designs) have failed because their center of rotation remained lateral to the scapula, which limited motion and produced excessive torque on the glenoid component, leading to early loosening. The reverse prosthesis designed by Paul Grammont, unlike any previous reverse ball-and-socket design, has introduced 2 major innovations that have led to its success: (1) a large glenoid hemisphere with no neck and (2) a small humeral cup almost horizontally oriented with a nonanatomic inclination of 155°, covering less than half of the glenosphere. This design medializes and stabilizes the center of rotation, minimizes torque on the glenoid component, and helps in recruiting more fibers of the anterior and posterior deltoid to act as abductors. Furthermore, the humerus is lowered relative to the acromion, restoring and even increasing deltoid tension. The Grammont reverse prosthesis imposes a new biomechanical environment for the deltoid muscle to act, thus allowing it to compensate for the deficient rotator cuff muscles. The clinical experience does live up to the biomechanical concept: the reverse prosthesis restores active elevation above 90° in patients with a cuff-deficient shoulder. However, external rotation often remains limited, particularly in patients with an absent or fat-infiltrated teres minor. Internal rotation is also rarely restored after a reverse prosthesis. Failure

to restore sufficient tension in the deltoid may result in prosthetic instability. The design does appear to protect against early loosening of the glenoid component, but impingement of the humeral cup on the scapular neck can lead to scapular notching and polyethylene wear. This is a cause for concern, especially as the notch is often more extensive than can be explained by impingement alone. Bony lysis of the scapula may also be related to a polyethylene granuloma. Further follow-up is required to ensure that loosening does not become a problem in the long term, and it has been recommended to limit its use to elderly patients, arguably those aged over 70 years. Despite these concerns, the reverse prosthesis, based on the biomechanical Grammont concept, offers a true surgical option in several situations where only limited possibilities were previously available: cuff tear arthrosis, persistent shoulder pseudo-paralysis due to a massive and irreparable cuff tear, severe fracture sequelae, prosthetic revision in a cuff-deficient shoulder, and tumor surgery. Finally, surgeons must be aware that results are less predictable and complication/revision rates are higher in revision surgery. (*J Shoulder Elbow Surg* 2005;14:147S-161S.)

INTRODUCTION

Whereas the concept of anatomic unconstrained shoulder prostheses has been widely accepted, the concept of nonanatomic constrained or semiconstrained prostheses is more difficult for shoulder surgeons to accept because of failures experienced in the past.^{5,8,9,16,28,33}

In 1985, Paul Grammont designed a reverse prosthesis for arthritic shoulders with severe destruction of the cuff, in which standard anatomic prostheses could not solve the problem of restoring both joint stability and mobility.^{20,21} This prosthesis (Delta III total shoulder prosthesis; Depuy International Ltd, Leeds, England) has been used in France since 1991 and is now gaining increasing popularity throughout Europe.^{2,6,11,12,15,22,34,39} Despite the encouraging early

From the Department of Orthopaedic Surgery and Sports Traumatology, Hôpital de L'Archet, University of Nice.

Reprint requests: Pascal Boileau, MD, Professor and Chairman, Department of Orthopaedic Surgery & Sports Traumatology, Hôpital de L'Archet, University of Nice, 151, Route de St Antoine de Ginestière, 06202 Nice, France (E-mail: boileau.p@chu-nice.fr).

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Table I Published series for hemiarthroplasty in cuff-deficient shoulders

Author	Y	N	Follow-up (y)	Persistent postoperative pain (n)	Active elevation (preoperative/postoperative)
Pollock et al ³²	1992	19	3 (1-9)	2 (6%)	60°/112°
Arntz et al ¹	1993	18	3 (2-10)	7 (39%)	66°/112°
Williams and Rockwood ⁴¹	1996	21	4 (2-7)	3 (14%)	70°/120°
Field et al ¹⁷	1997	16	3 (2-5)	3 (19%)	60°/100°
Zuckerman et al ⁴³	2000	15	2 (1-15)	8 (53%)	69°/86°
Favard et al ¹⁵	2001	60	4 (2-10)	NA	57°/96°
Sanchez-Sotelo et al ³⁵	2001	33	5 (2-11)	9 (27%)	72°/91°

(NA: Non Available)

results in Europe, it has only recently acquired Food and Drug Administration approval in the United States.

The purpose of this report is to explain the rationale and biomechanics behind the design of the Grammont reverse prosthesis. On the basis of the literature and our own clinical experience, we will also try to evaluate whether the clinical results match the biomechanical concept. Finally, we will describe and summarize some of the unsolved problems with this prosthesis. It is hoped that this information will serve as a reference point for future work to be done in this area.

CUFF-DEFICIENT SHOULDER

Unconstrained shoulder arthroplasty has been a standard surgical option in the treatment of patients with massive unbalanced rotator cuff tears and arthritis.^{1,17,18,32,35,41,43} Total shoulder replacement, however, has been abandoned because the excessive shearing forces produce what is known as the "rocking-horse" phenomenon, leading to superior eccentric loading on the glenoid and glenoid loosening.^{18,32} Hemiarthroplasty has consequently become the recommended treatment option for the arthritic shoulder in patients with severe cuff deficiency, but the results in these patients have been less predictable, in terms of both mobility and pain relief (Table I). This is why Neer et al²⁹ proposed the term "limited-goal rehabilitation" for these hemiarthroplasties: they allow some improvement in shoulder pain and rotation but almost no improvement in active elevation or abduction in patients with preoperative pseudo-paralysis. Elevation occasionally exceeds the horizontal level but pain relief is often inconsistent, and early good results can deteriorate as a result of glenoid and/or acromial erosion (Figure 1).

Constrained and semiconstrained shoulder prostheses were adopted as a logical solution for the cuff-deficient arthritic shoulder. The idea was to provide a fixed center of rotation relative to the scapula and to try to convert the upward-directed force of the deltoid into a rotatory movement, making elevation possible. However, before development of the re-



Figure 1 Glenoid and acromial bone erosion after hemiarthroplasty for an arthritic, cuff-deficient shoulder may compromise initial good functional results.

verse prosthesis of Grammont, the clinical results of these prostheses were unsatisfactory because of poor motion and implant loosening, and they have all been abandoned.

The first constrained prostheses that were developed

Table II Published series for constrained ball-and-socket prostheses and bipolar prostheses

Prosthesis (author)	Y	N	Follow-up (y)	Persistent postoperative pain (n)	Active elevation (preoperative/postoperative)	Reoperation
Stanmore (Coughlin et al ¹⁰)	1979	16	3 (2–4)	6 (38%)	57/104	3 (19%)
Michael-Reese (Post et al ³³)	1980	43	2–6	3 (7%)	NA/NA	15 (35%)
Stanmore (Lettin et al ²⁶)	1982	50	2–10	12 (23%)	NA/70	9 (18%)
Macnab-English (McElwain and English ²⁷)	1987	13	3 (1–5)	2	57/85	2 (15%)
Swanson bipolar (Swanson et al ³⁸)	1989	35	5	4 (11%)	43/71	5 (14%)
Swanson bipolar (Lee and Niemann ²⁵)	1994	14	3 (2–4)	4 (29%)	35/55	4 (29%)
Worland bipolar (Worland et al ⁴²)	1997	33	2 (2–4)		NA/100	1 (3%)

(NA: Non Available)

in the 1970s were adapted from hip prostheses; based on a ball and socket (Bickel, Macnab-English, Stanmore, Michael-Reese, and Bipolar).^{10,25-28,33,38,42} Published results are summarized in Table II.

Subsequently, a number of prostheses were introduced based on a reverse ball-and-socket design (Fenlin, Gerard, Kessel, Kölbl, Liverpool, Neer, and Averyll).^{3,7,16,19,24,29} However, most remained essentially experimental, and the only 2 series published in the English-language literature, apart from the Delta, were on the Kessel prosthesis. Bayley and Kessel³ reported a series of 31 Kessel prostheses, of which 26 remained in situ and functioning at review (but the follow-up was not given). Of the prostheses, 5 (16%) were considered failures: 3 of 5 failed because of dislocation. Broström et al⁷ reported a series of 23 Kessel prostheses followed for 7 years; pain relief was good in over 90%, but mean active elevation was poor (35°) and the reoperation rate high (26%).

These previous constrained shoulder prostheses, other than the Grammont, tended to fail because their design resulted in excessive torque and shear forces at the glenoid component–bone interface (Figure 2). Furthermore, although they usually allowed some active elevation, this was in most cases less than 90° (ie, only scapulothoracic motion). Prosthetic instability was also a concern. Many never really went beyond the experimental stage, and most are no longer on the market today.

The question therefore arises: if all reverse prostheses have failed, why hasn't the Grammont reverse prosthesis? In other words, how is the Grammont prosthesis different?

DESIGN OF GRAMMONT REVERSE PROSTHESIS

The first model of reverse prosthesis, designed by Paul Grammont in 1985, had only 2 components (Figure 3). The glenoid component was a metallic or

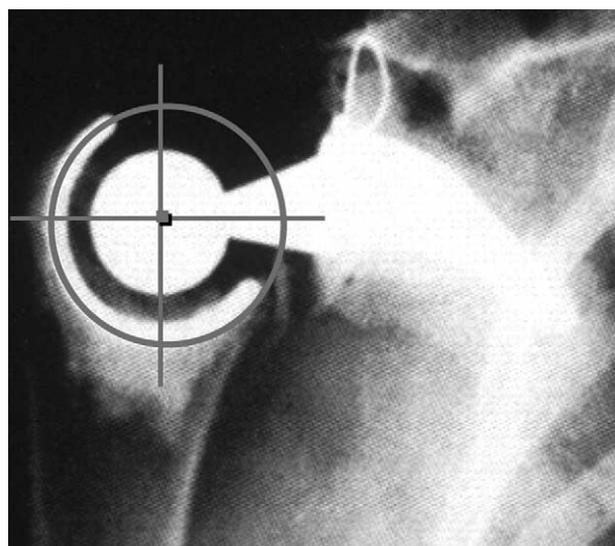


Figure 2 Previous reverse ball-and-socket prostheses tended to fail because their design resulted in excessive torque or shear forces on the glenoid component (notice the small head and neck, placing the center of rotation outside the scapula).

ceramic ball, initially two thirds of a sphere and 42 mm in diameter. It was designed to fit over the glenoid like a glove and was fixed with cement. The humeral component was a polyethylene socket. Its concave surface was one third of a sphere, and its stem was trumpet-shaped for cementing into the humeral medullary canal. A bell saw was used to prepare the glenoid, and 2 broaches were used to prepare the different parts of the humerus, 1 for the epiphysis and 1 for the diaphysis. The initial Grammont reverse prosthesis was cemented on both the humeral and glenoid sides.

The preliminary results were published (in French) in 1987.²⁰ There were 8 cases: 3 post-radiotherapy necrosis cases, 1 inflammatory osteoarthritis case, and 4

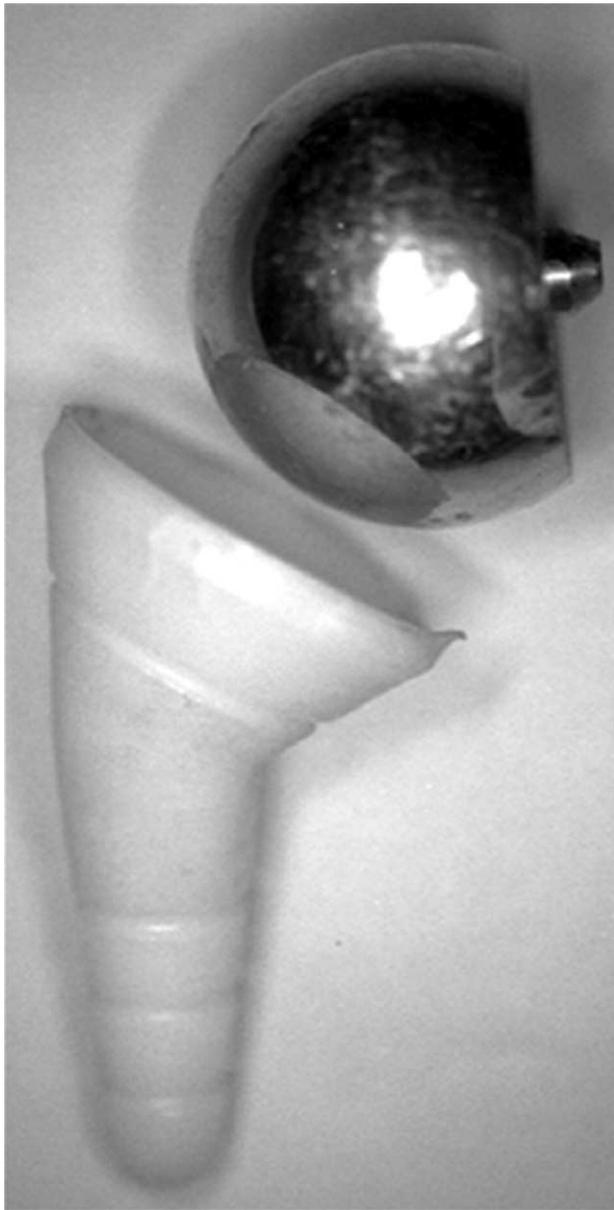


Figure 3 The first model of the Grammont reverse prosthesis, designed by Grammont in 1985, had only 2 components: the humeral component was all-polyethylene and trumpet-shaped and the glenoid component was a metallic or ceramic ball, initially two thirds of a sphere and 42 mm in diameter. It was designed to fit over the glenoid like a glove and fixed with cement. (Picture: Courtesy of Emmanuel Baulot, MD)

revisions of failed prostheses. The mean patient age was 70 years, and the cuff was absent or destroyed in all cases. Mean follow-up was only 6 months. A transacromial approach (with osteotomy of the lateral acromion) was used in all but 1 case. Revision osteosynthesis of acromial nonunion was required in 3 cases. All shoulders were pain-free, but mobility was variable. In 3

cases, active anterior elevation was 100° to 130°, but in the other 3 cases, it was less than 60°.

Unsatisfied with these results, Grammont made further modifications, evolving to the current design. Because he had several failures with the cemented glenoid component, he decided to change the glenoid to an uncemented system. His new concept was that the glenoid component should be fixed with a central peg and some screws of divergent direction to counteract the initial shearing forces.^{20,21} He also abandoned the idea of having two thirds of a sphere and opted for a design based on half of a sphere to place the center of rotation directly in contact with the glenoid surface, decreasing lateral offset at the glenohumeral articulation, thus decreasing shearing forces.

The second model was the Delta III reverse prosthesis (Depuy International Ltd), available in 1991, and still in use today. Grammont named this reverse prosthesis "Delta," as the concept was based on the sole deltoid for both function and stabilization. Fixation is now uncemented for the glenoid components and either cemented or uncemented in the humerus. The Delta III has 5 parts: the glenoid base plate (metaglenoid), the glenosphere, the polyethylene humeral cup, the humeral neck, and the humeral stem (Figure 4).

The glenoid component (metaglène) is a 29-mm disk, with a rough surface and hydroxyapatite coating. Initial fixation is ensured by a 29-mm-long central peg and 4 peripheral divergent screws (3.5 or 4.5 mm in diameter). The aim is to place 1 screw in the base of the coracoid and 1 screw into the inferior scapular pillar for maximum hold. The triangular and divergent assembly of the screws has been designed precisely to counteract the shearing forces during initial abduction (Figure 5).

The glenosphere is a cobalt-chrome sphere, available in 2 diameters: 36 and 42 mm, with a 19-mm offset. Initially, the fixation of the sphere on the metaglène was done by use of peripheral threads, but this mechanism had a tendency to unscrew, particularly in right shoulders. In 1996 glenosphere-metaglène fixation was changed to a peripheral Morse taper and reinforced by a central countersunk screw, after which no cases of disassociation have been reported.

The humeral stem is conical, and its surface is either polished or hydroxyapatite-coated for cemented or uncemented fixation, respectively. It is available in 3 lengths: 100 mm for the standard prosthesis and 150 and 180 mm for the revision prosthesis.

The humeral neck is screwed onto the humeral stem. It has a fin to control rotation, and there are holes to allow tuberosity osteosynthesis. Like the stem, it is available with a polished or a hydroxyapatite-coated surface. Three sizes are available: 36-1 and



Figure 4 Current design of the Grammont reverse prosthesis. The Delta III prosthesis has 5 parts: the glenoid base plate (metaglenoid), the glenosphere, the polyethylene cup, the humeral neck, and the humeral stem.

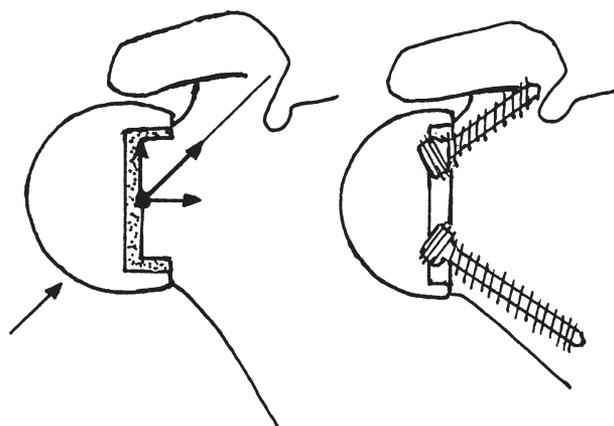


Figure 5 The change from a cemented to an uncemented glenoid with divergent screws to resist initial shear forces.

36-2 for a 36-mm-diameter cup and 42-2 for a 42-mm-diameter cup.

The humeral cup is made of polyethylene and has

2 diameters conforming the 36 and 42 mm glenospheres. It is 6-mm-thick and press-fitted onto the humeral neck component. A 9-mm metallic extension may be screwed onto the neck to increase the humeral offset. The humeral cup is also available in a more constrained form with a deeper cup.

The Delta I and II prostheses are "standard" unconstrained versions of the Delta III prosthesis. All 3 prostheses share the same stem and humeral neck. The Delta I is a hemiarthroplasty, which is easily converted from a Delta III by fixing a metal head onto the humeral neck, whereas the Delta II is a total shoulder prosthesis with a polyethylene glenoid component in place of the glenosphere.

POTENTIAL BIOMECHANICAL ADVANTAGES OF THE REVERSED PROSTHESIS, ACCORDING TO GRAMMONT'S CONCEPT

The Grammont reverse prosthesis, unlike any previous reverse ball-and-socket design, has introduced 2 major innovations:

1. In contrast to all previous reverse ball-and-socket prostheses, the Grammont glenoid component is third of a sphere with a large diameter of 36 or 42 mm and no neck. The back of the glenosphere is in direct contact with the prepared glenoid surface. This design has the advantage of placing the center of rotation of the joint in contact with the in the center of the humeral head and provides a fixed center of rotation. Furthermore, the large diameter allows greater range of movement before impingement of the components occurs and provides more stability.
2. The humeral component has a small cup, oriented with a nonanatomic inclination of 155°, that covers less than half of the glenosphere. This has the advantage of lowering the humerus resulting in overtensioning the deltoid. It allows a greater range of movement to occur before component-bone impingement.

In summary, the main biomechanical advantages of the reverse prosthesis according to Grammont's concept are as follows: (1) the large ball offers a greater potential arc of motion and more stability than a small ball, (2) the small lateral offset (absence of neck) places the center of rotation directly in contact with the glenoid surface and reduces the torque at the point of fixation of the glenoid component, (3) medializing the center of rotation recruits more of the deltoid fibers for elevation or abduction (Figure 6), and (4) lowering the humerus increases tension on the deltoid. These biomechanical properties lead to better functioning of the deltoid, compensating for the lack of a functional rotator cuff.

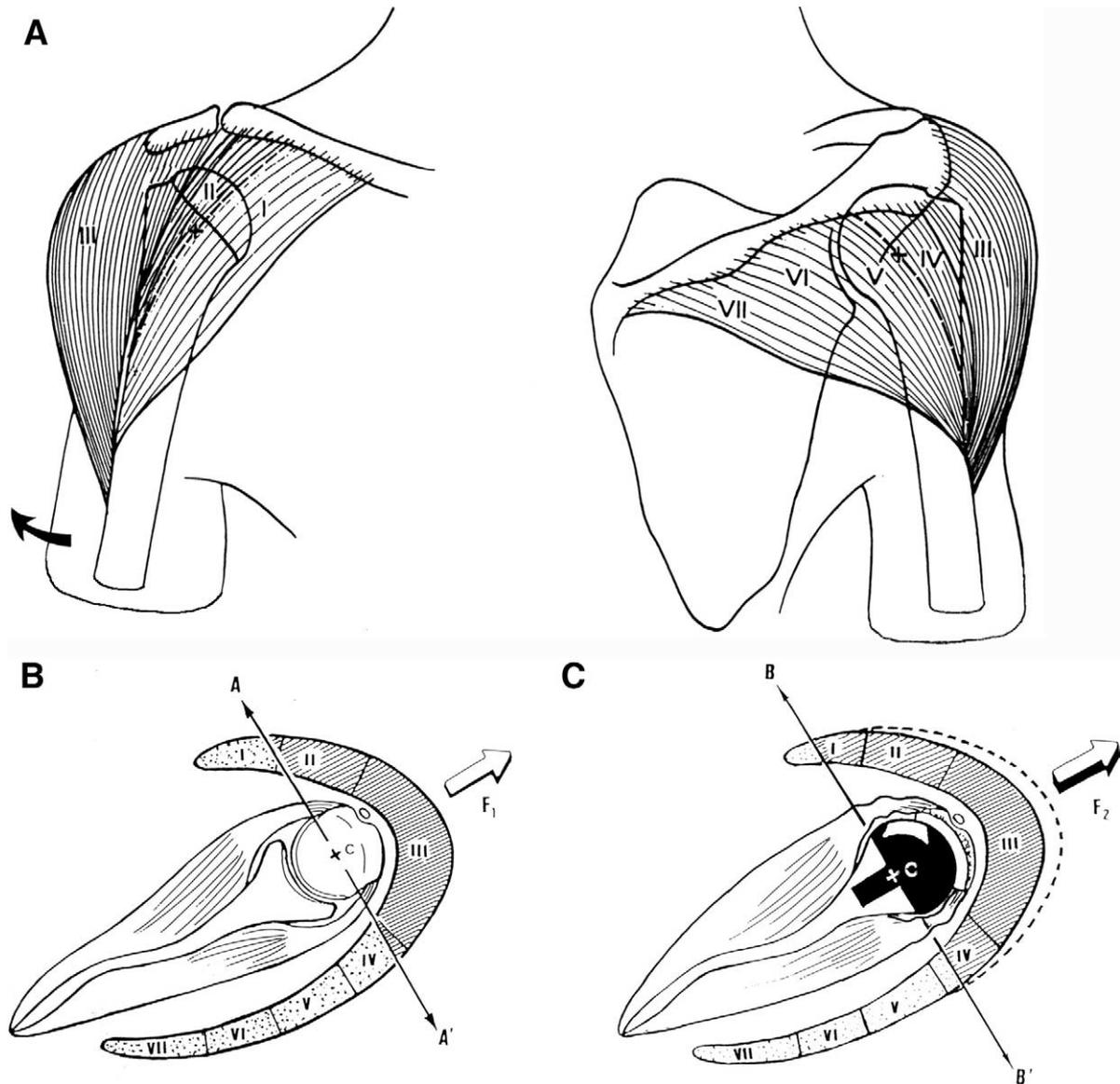


Figure 6 The 7 segments of the deltoid, according to Kapandji²³ (A); in a normal shoulder, only the middle deltoid (segment III) and part of the anterior deltoid segment (segment II) can participate to active elevation (B); after a reverse prosthesis, the medialization of the center of rotation recruits more of the deltoid fibers (segments I and IV) for active elevation (C).

CLINICAL EXPERIENCE WITH GRAMMONT REVERSE PROSTHESIS: DOES IT LIVE UP TO THE BIOMECHANICAL CONCEPT?

It remains to be seen whether the theoretic biomechanical benefits of the Grammont prosthesis will actually prevent the fate that has befallen other semi-constrained shoulder prostheses. The few published series of Delta prostheses are small but do show promising early results (Table III).

All series have mostly concentrated on cuff tear arthropathy, with follow-up ranging from 2 to 7 years,

postoperative elevation (when quoted) from 120° to 138°, postoperative Constant scores from 56.7 to 69, and a reoperation rate of 0% to 15%. Much higher reoperation rates (20%, 37.5%, and 60%) were seen in the 3 small series in which the Delta was used either for rheumatoid arthritis or for prosthetic revision.^{12,14,34} Rittmeister and Kerschbaumer³⁴ followed up 8 patients with Delta reverse prostheses implanted for severe rheumatoid arthritis with unreconstructible rotator cuff lesions. Three cases (37.5%) required revision: 2 because of glenoid loosening (1 septic and 1 aseptic) and 1

Table III Published series for Delta reverse prosthesis

Author, (y)	N	Pathology	Follow-up (mo)	Active elevation (preoperative/postoperative)	Constant (preoperative/postoperative)	Reoperation
Grammont et al ²⁰ (1987)	16	CTA	27	NA	14/69	13%
De Buttet et al ¹¹ (1997)	71	CTA	24	NA/120°	19.4/59.9	4.2%
De Wilde et al ¹² (2001)	5	Revision	30	"Fair"	14/62	20%
Rittmeister et al ³⁴ (2001)	8	RA	54	NA	17/63	37.5%
Jacobs et al ²² (2001)	7	CTA	16	NA	17.9/56.7	0%
Sirveaux et al ³⁶ (2001)	80	CTA	44	73°/138°	22.6/65.6	5%
Valenti et al ³⁹ (2001)	39	CTA	84	60°/120°	21/63	15%
Bouhahia et al ⁶ (2002)	16	CTA and SF	35	70°/138°	31/59	12.5%
Delloye et al ¹⁴ (2002)	5	Revision	81	NA/72°	NA/40	60%
De Wilde et al ¹³ (2002)	6	Tumors	12	NA/106°	NA	0%
Boileau et al (2005)	45	CTA, SF, and revision	40	55°/121°	17/59	13%

CTA, Cuff tear arthropathy; RA, rheumatoid arthritis; SF, sequelae of fracture.

because of acromial nonunion after a transacromial approach. De Wilde et al¹² had to perform revision in 1 of 5 patients after the reverse prosthesis was placed for failed hemiarthroplasty. The highest rate of revision has been reported by Delloye et al,¹⁴ who had to perform revision in 3 of 5 patients, also after the reverse prostheses were placed for failed hemiarthroplasty. Loosening of the glenosphere occurred in 2 cases, 6 years after surgery. On the basis of their series, they did not recommend further use of the prosthesis. In their opinion, loosening was clearly related to the progression of bone erosion in the scapula (notching).

In addition, it is important to note that results for this prosthesis have only been reported in older patients, with limited activity levels. One can only assume at present that the higher activity levels of younger patients will lead to higher failure rates.

THE NICE EXPERIENCE

We have reviewed our series of 45 Delta prostheses inserted for massive cuff tear arthritis (21 cases), fracture sequelae (5 cases), or failure of a previous arthroplasty (19 cases), with a mean follow-up of 40 months (range, 24 to 72 months).

Failures

To date, 10 patients (22%) have required revision surgery. Our experience confirms that the reverse prosthesis is a relatively safe operation in cuff tear arthritis whereas it is a risky operation in revision cases: 8 of 19 patients (42%) in the revision group needed to undergo reoperation, whereas only 1 of 21 patients (5%) in the cuff tear arthritis group underwent reoperation. The stem has been revised in 3 patients (1 periprosthetic fracture and 2 presumed cases of aseptic humeral loosening, although in 1 of

these cases *Staphylococcus epidermidis* was subsequently cultured). Two underwent resection arthroplasty for infection. Only 1 failure was related to the glenoid component, as a result of an intraoperative glenoid fracture. This shoulder was converted to a Delta I prosthesis (hemiarthroplasty). These 6 failures were excluded from the final clinical and radiologic analysis.

Range of motion and function

Our clinical experience is in keeping with the literature: the reverse prosthesis restores active elevation but not active rotation in patients with cuff-deficient shoulders. Mean active elevation improved from 55° preoperatively (SD, 25°; 95% confidence interval [CI], 47° to 63°) to 121° postoperatively (SD, 30°; 95% CI, 111° to 131°) ($P < .001$). There was no significant improvement in mean active external rotation, which was 7° preoperatively (SD, 19°; 95% CI, 1° to 13°) versus 11° postoperatively (SD, 15°; 95% CI, 5° to 16°) ($P = .46$). Internal rotation was not improved either: patients could only reach the first sacrum vertebra before and after the operation (S1 preoperatively and postoperatively). The Mean Constant score improved from 17 preoperatively (SD, 8; 95% CI, 14 to 20) to 59 postoperatively (SD, 19; 95% CI, 53 to 65) ($P < .001$). The mean postoperative age- and sex-adjusted Constant score was 87% (SD, 28%; 95% CI, 78% to 96%). The mean postoperative American Shoulder and Elbow Surgeons (ASES) shoulder score was 65 (SD, 24; 95% CI, 58 to 73). 78% of patients were satisfied or very satisfied with the result and 67% had no or slight pain. However, the postoperative Constant score, adjusted Constant score, and ASES shoulder score were all significantly higher in the massive cuff tear arthritis group compared with the revision prostheses group ($P =$

.01, .004, and .002, respectively). In our experience, patients with cuff-deficient shoulders regained better active elevation after a reverse prosthesis than after hemiarthroplasty. As one might expect, the functional results were not as good when the Delta was used in revision surgery. Both the Constant score and the ASES score were significantly lower in this group as compared with the cuff tear arthritis group.

Active external rotation and status of teres minor

We confirmed that the status of the teres minor affected the functional result: the Constant score improved to 66 ± 16 points when the teres minor was intact or hypertrophic but was only a mean of 46 ± 13 points when the muscle was torn or exhibited significant fatty infiltration ($P = .007$). The status of the teres minor also had a direct influence on the postoperative active external rotation: patients with an intact or hypertrophic teres minor had a mean of 15° of postoperative active external rotation, whereas those in whom the muscle was torn or exhibited fatty infiltration had no active external rotation at the last review ($P = .02$). A hornblower sign was evidence of this absent active external rotation.

Medialization and lowering of center of rotation

We also confirmed the displacement of the center of rotation using a radiologic method developed by Sirveaux et al.³⁴ The mean medialization was 19.0 mm (SD, 9.9 mm; 95% CI, 15.0 to 23.0 mm). The center of rotation was also lowered by a mean distance of 3.7 mm (SD, 9.2 mm; 95% CI, 0.5 to 6.9 mm), although this was relative to a high preoperative position in most cases.

Medialization of humerus

We measured the distance between the lateral border of the acromion and the intramedullary axis of the proximal humerus before and after the operation on an anteroposterior view with the arm at the side (Figure 7). The medialization of the humerus (medial translation of humerus) averaged 16 mm (95% CI, 13 to 19 mm).

Lowering of humerus and arm lengthening

We measured the length of the upper arm relative to the opposite side (with the elbow flexed) using a specially designed caliper (Figure 8). The distance between the acromion and olecranon increased by a mean of 15 mm (range, -5 to 40 mm; SD, 11 mm; 95% CI, 10 to 18 mm). Although downward displacement of the center of rotation is minimal, this increase in arm length does seem important for retensioning the deltoid. In practice, this means that the prosthesis should fit tightly when reduced, and our

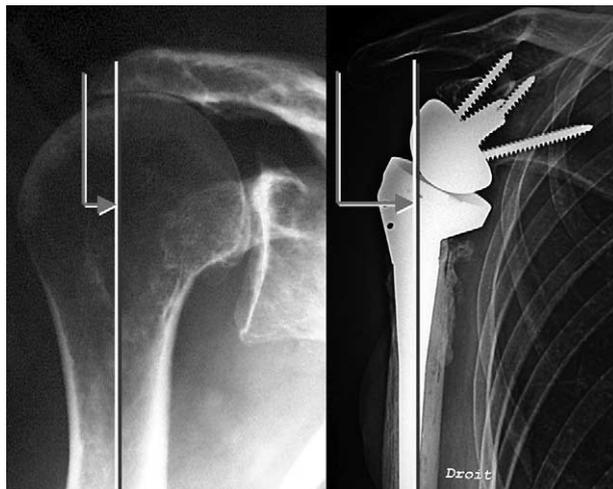


Figure 7 Medialization of the humerus leads to detensioning of the deltoid fibers unless the humerus is lowered in order to over-tension the deltoid.

experience has confirmed that when this is not achieved, instability can be a problem. Three cases were complicated by anterior instability, and in two cases, stability was restored by inserting an extension to the epiphyseal component to increase the offset. In the third case, however, the tension already appeared to be adequate, and stability was restored by changing a damaged polyethylene insert.

Glenoid fixation and scapular notching

Radiolucent lines were seen in 16 shoulders at the superior part of the metaglenoid plate, but these were less than 2 mm and none were progressive. In only 1 case the radiolucent line measured more than 2 mm. However, notching at the inferior aspect of the glenoid was present in 24 cases (74%), and this extended to or beyond the inferior screw in 10 cases. Fluoroscopic examination showed that this was a result of impingement of the medial aspect of the polyethylene humeral cup on the scapular neck inferiorly but also posteriorly. Neither the presence nor the size of the notch had any significant effect on the functional scores with our current follow-up. To date, there have been no revisions for glenoid loosening (even when the notch extended beyond the inferior screw) other than the 1 patient who sustained an intraoperative glenoid fracture.

Humeral fixation

Incomplete radiolucent lines were seen in 22 humeral components but in only 6 cases were they more than 2 mm wide and none were circumferential. Five patients did, however, require revision of the humeral



Figure 8 Lowering the humerus, after a reverse prosthesis, is demonstrated by the increased arm lengthening on the operative (right) side measured and compared with the opposite (left) side. Lowering of the humerus increases tension and strength of the deltoid.

component, although this was a result of infection in 2 and a fracture in 1.

UNSOLVED PROBLEMS WITH DELTA REVERSE PROSTHESIS

Deltoid tensioning and potential instability

According to Grammont et al,^{20,21} one should distinguish 2 different types of what they called “decoaptation” (Figure 9). This can be assessed on the postoperative anteroposterior view, with the arm at the side. Superior (asymmetric) decoaptation, which is considered “normal” by Grammont, is probably a result of impingement of the humeral cup on the inferior border of the scapular neck, the same mechanism that produces notching. It reduces with abduction or elevation when the middle deltoid contracts muscle. However, this impingement may in some cases participate in the prosthetic instability. Global decoaptation, which is abnormal, is a gap between the ball and the socket and is probably a result of insufficient tension in the deltoid muscle (Figure 10, A). The resulting instability should be addressed by increasing the offset to restore deltoid tension. As

seen above, this can be done by inserting a humeral neck extension under the polyethylene cup and/or by increasing the size of the glenosphere and the cup (42 mm instead of 36 mm).

Intraoperative determination of deltoid tension is difficult and guided mostly by surgical experience. The only guide one can really trust is that reduction should feel quite tight. We also have found that the conjoint tendon should feel tensioned after reduction with the arm at the side and the elbow extended. Although prosthetic instability is not a frequent problem, almost all series report some cases.^{6,11,12,34,36,39} We observed 3 prosthetic dislocations in our own series; all occurred approximately 1 to 3 months postoperatively. Two dislocations occurred in revision cases and were successfully treated by adding an extension to the humeral neck component in two and by changing the polyethylene humeral cup in one. The patients were immobilized in neutral rotation for 6 weeks and have sustained no additional dislocation since then.

Prosthetic instability may be related to insufficient tension of the deltoid and medial impingement but is also facilitated by medialization of the humerus and,

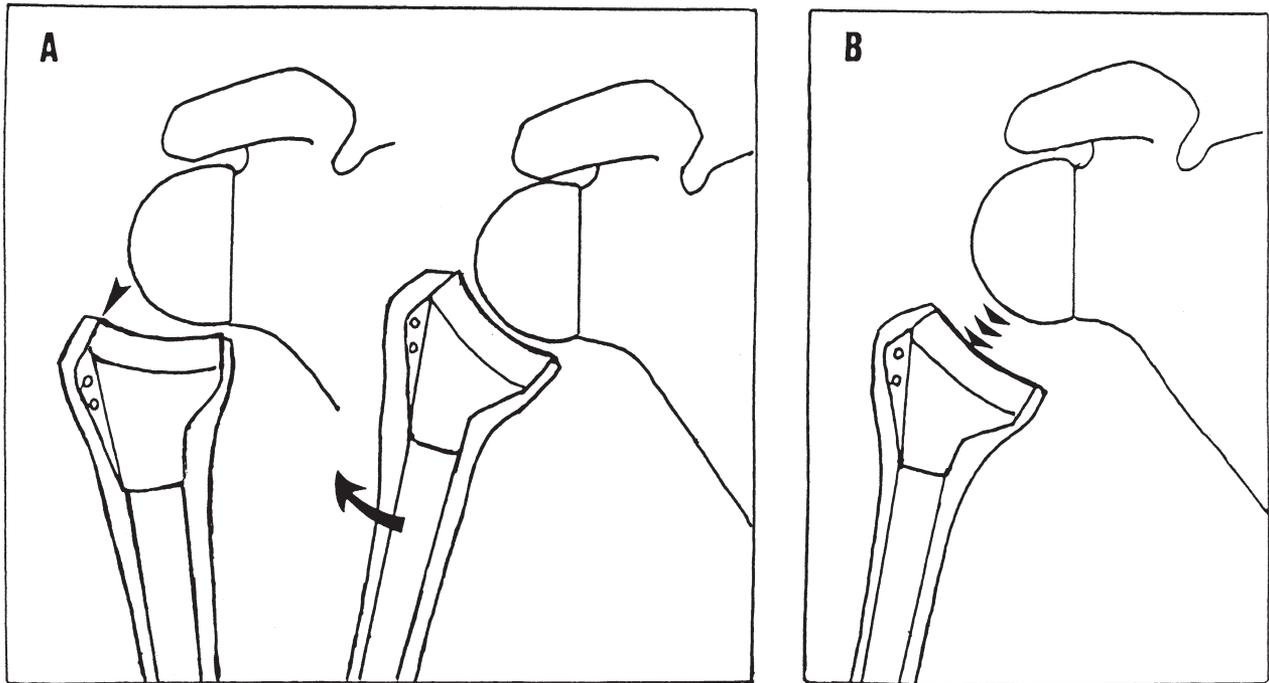


Figure 9 Superior decoaptation of the prosthesis can be normal and usually disappears with active elevation (**A**), whereas global decoaptation of the prosthesis is abnormal, leading to prosthetic instability (**B**).

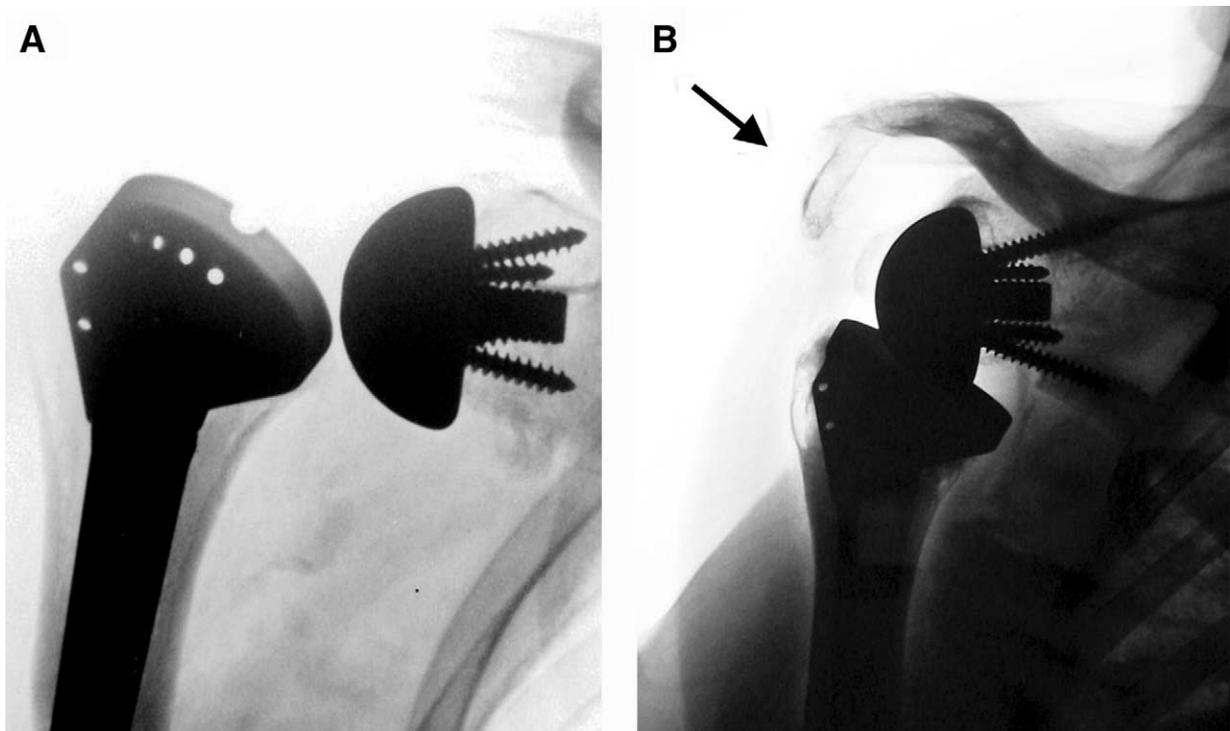


Figure 10 Undertensioning the deltoid may lead to prosthetic instability (**A**), whereas overtensioning the deltoid may lead to a fracture of the acromion (**B**).

consequently, the slackening of the remaining rotator cuff muscles (Figure 10, A). Prosthetic instability seems to be less frequent when the prosthesis has been inserted through an anterosuperior transdeltoid approach, probably because the remaining subscapularis is not detached. Another potential reason for prosthetic instability is the frequent formation of a hematoma in the dead space under the acromion after a reverse prosthesis. In 1 case, we observed that the liquid of the hematoma was interposed between the humeral cup and the glenosphere, contributing to the prosthetic dislocation. We have termed this the "piston mechanism." This is why we recommend inserting a drain after implanting a reverse prosthesis and we systematically place the patient in an abduction at 60° for 3 weeks to fill the dead space under the acromion and to avoid the collection of hematoma. Finally, prosthetic instability after a reverse prosthesis is more frequent in revision surgery because of the frequent atrophy or destruction of the anterior deltoid, and one should be even more prudent with postoperative rehabilitation in this case.

Overtensioning the deltoid may lead to a *fracture of the acromion*, especially in patients with severe osteoporosis and eroded acromial bone often seen in cuff tear arthritis. These can be considered as fatigue fractures (Figure 10, B). In our series we observed 2 acromial fractures that appeared as incidental findings on the 3-month postoperative radiographs. Neither patient could recall any trauma, both were completely asymptomatic, and there did not appear to be any detrimental effect on function. Overtensioning the deltoid muscle may also result in a slight and permanent abduction of the arm with impossibility for the patient to adduct the arm at the side. Elongation of the axillary nerve may also be a potential concern.

Humeral fixation

To date, the rate of glenoid component loosening in the Delta reverse prosthesis has been reported to be between 2% to 5%.^{11,12,15,22,34,37,39} One should keep in mind that the Grammont prosthesis is a semi-constrained prosthesis, which means that there is added constraints and torsional forces. If those constraints are potentially decreased on the glenoid side, then they may be increased on the humeral side. Our clinical experience has shown us that fixation may be more problematic on the humeral side than on the glenoid side. As mentioned above, we have not observed any glenoid loosening to date. Conversely, revision surgery was necessary at 12 to 18 months in 5 patients because of humeral loosening (though 4 were related to infection or fracture). The patients were aged 52 to 67 years, and all initially underwent implantation for prosthetic revision. Humeral radiolucent lines of more than 2 mm were seen in 4 addi-

tional cases. In a previous multicenter study, some cases of subsidence of the humeral component were observed when a noncemented humeral component was used.¹⁵ Finally, we have observed a late unscrewing between the humeral neck and stem in a patient from another center. In addition to compressive forces, rotational forces are also present on the humeral side.

Some of the potential reasons for such humeral subsidence, unscrewing or loosening are as follows: (1) the humeral stem of the Delta prosthesis is round and offers very little resistance to rotational torque; (2) the proximal epiphysis and metaphysis are often missing in fracture sequelae and revision cases (as a result of tuberosity migration and lysis), thus giving little or no bony support to the prosthetic stem; (3) the cortical bone of the humeral diaphysis is often very thin, particularly in revision and fracture sequelae cases; and (4) associated low-grade infection is often associated with revision cases or fracture sequelae. For all of these reasons, we recommend (1) the use of a cemented humeral stem or possibly a hybrid humeral component with the humeral neck part being uncemented and the stem being cemented, (2) the use of long stems in revision and fracture sequelae cases, and (3) the performance of a 2-step operation if there is any suspicion of infection (removal of the prosthesis, surgical debridement and cleaning of the joint, and implantation of a spacer with antibiotics, followed by prosthesis reimplantation 6 weeks later).

Scapular notching and polyethylene wear

In all series, scapular notching has been observed in more than 50% of cases (74% in our series); this is a common radiographic finding at early follow-up.^{6,11-13,15,34,36,37,39} We have performed fluoroscopic examinations which showed that scapular notching is a result of impingement of the medial aspect of the polyethylene humeral cup on the scapular neck inferiorly with the arm in the adducted position, but rotation may also play a role because the notch is often posterior. From a biomechanical standpoint, this impingement is logical, as it is the direct consequence of the absence of a prosthetic neck on the glenoid side and the lowering of the humerus (Figure 11, A). Polyethylene wear has been observed on some retrieved humeral cups (Figure 11, B). Impingement of the humeral cup on the scapular neck is a cause for some concern, especially if the notch is more extensive than what can be explained by impingement alone. The latter may be the initiating factor, with further osteolysis being triggered by polyethylene particles.³⁰ Favard et al¹⁵ have noted a negative effect of radiographic scapular notching on the clinical outcome: if the notch is large (extending beyond the inferior screw), the Constant score was

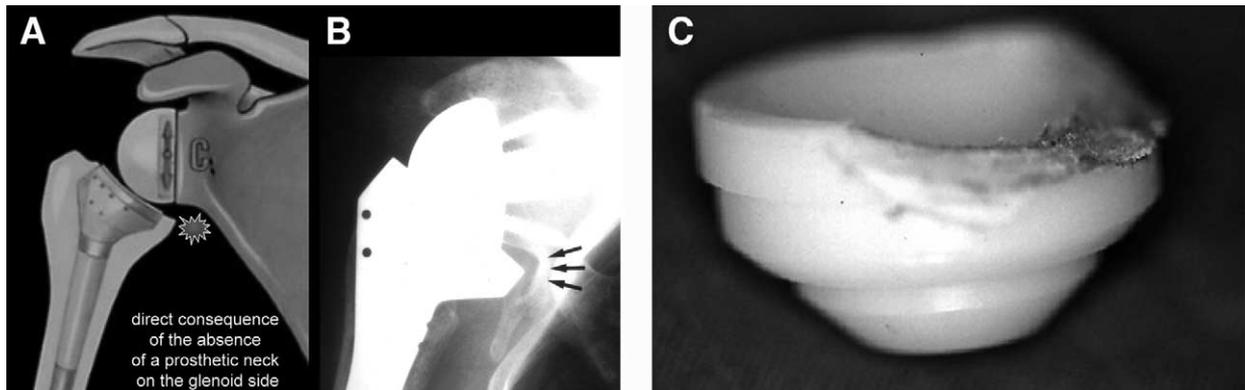


Figure 11 The scapular notching is a direct consequence of both the absence of a prosthetic neck of the glenosphere and the horizontal orientation of the humeral cup (**A**) an example of notching that reaches the inferior screw is shown (**B**). The retrieved glenoid component demonstrates polyethylene wear (**C**).

significantly lower and the risk for loosening was high in their series. To try to minimize this problem of scapular impingement and notching, our current surgical practice is to place the glenoid component as low (distal) as possible, with a slight inferior tilt of 15° to 20° after reaming more inferiorly³¹ (Figure 7).

In summary, medializing the center of rotation at the level of the glenoid surface and orienting the humeral cup almost horizontally have been biomechanical solutions found by Grammont to avoid excessive forces on the glenoid component and improve the power of the deltoid. In return, scapular notching and polyethylene wear seem to be part of "the price to pay." However, trying to escape from Grammont's concept by lateralizing the center of rotation outside the scapula (by increasing the offset of the glenosphere, for instance) may increase the risk of glenoid loosening (as was seen with previous reverse constrained prostheses). In the same way, decreasing inclination (neck-shaft angle) of the humeral component (to avoid scapular notching) could potentially increase the risk of prosthetic instability. Further biomechanical and clinical research is required to try to find a solution to these difficult problems.

Deficient or absent external rotation

As demonstrated in our series, the Grammont reverse prosthesis can effectively restore active elevation and abduction above the horizontal. However, it does not restore active external rotation. There are at least 4 major reasons that can explain the limited and weak external rotation after a Delta reverse prosthesis. The first one is related to the design of the prosthesis itself: the limited lateral offset of the glenosphere limits the possibility of rotation of the humeral cup around it with the arm at the side. The second reason for the limited and weak external rotation is biomechanical and is related to the medialization of

the center of rotation and of the humerus. The amount of posterior deltoid that can be used to compensate for the absent external rotators is decreased because of this humeral medialization (Figure 12). The remaining external rotators (ie, infraspinatus and teres minor) may also be slackened and less efficient because of this humeral medialization. However, the muscles insertions are also lowered, which, in theory, leads to keeping their tension unchanged. The only reason for these muscles to become less efficient is that their vectors become more oblique than horizontal because of the humeral lowering. The third reason for the lack of improvement in external rotation after a Delta reverse prosthesis is the status of the remaining teres minor, as already demonstrated in 2 previous studies.^{6,36} Our study confirms that active external rotation after a reverse prosthesis is significantly better when the teres minor is intact than when it is absent or has fatty infiltration. Finally, the fourth reason for the weak external rotation may be related to technique, as mentioned recently by Nyffeler et al³⁰: perforation of the posterior cortex of the scapula by the drill or the posterior screw may damage the suprascapular nerve at the base of the scapular spine. Therefore, if the infraspinatus is intact preoperatively, it should be protected during surgery to preserve the patient's active external rotation; the posterior screw must be either short convergent or directed inferiorly to avoid a lesion of the suprascapular nerve.

According to Grammont et al,^{20,21} there are 3 theoretic solutions to improve active external rotation when implanting a reverse prosthesis: (1) moving the deltoid V far forward, (2) performing an external derotation osteotomy of the humerus under the deltoid V, or (3) increasing retroversion at the time of implanting the humeral component. Obviously, only the latter could be used in daily surgical practice, but it would have the potential disadvantage of reducing internal

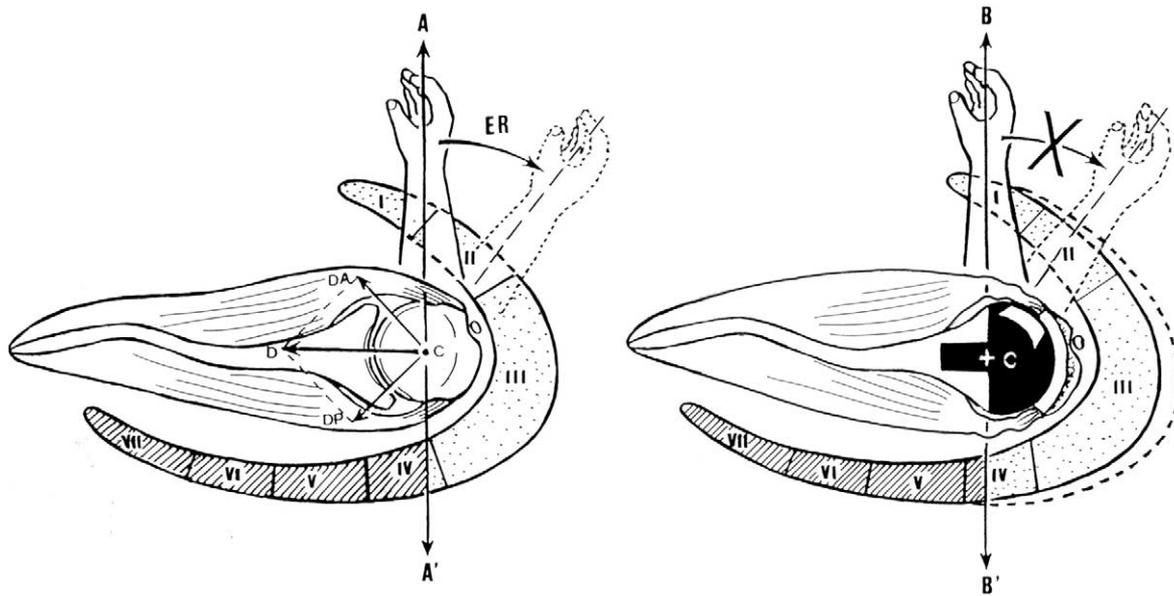


Figure 12 Deficient external rotation after a reverse prosthesis is a direct consequence of humeral medialization, which leads to a decreased amount of posterior deltoid that can be used for external rotation (ER). The slackening of the remaining rotator cuff muscles (infraspinatus and teres minor) may also play a role.

rotation, which may make it difficult for patients to reach behind the back. The only other logical solution to restore active external rotation is to perform a latissimus dorsi and teres major transfer at the same time as the reverse prosthesis. This is what we have started to do in patients with persistent pseudo-paralyzed shoulder and no active external rotation (preoperative lag and hornblower signs with severe muscle fatty infiltration of infraspinatus and teres minor).

Deficient or absent internal rotation

In our series we have found that the Delta reverse prosthesis rarely restores active internal rotation, making it difficult for patients to reach the back with the hand. Again, this is related to prosthetic design, which limits lateral offset and medializes the center of rotation leading to (1) limited excursion of the cup around the ball in the horizontal plane and (2) a decreased possibility to use the anterior deltoid to compensate for the absent internal rotators. The remaining subscapularis muscle, when present, may also be less efficient because of the lowering of the humerus, which makes its vector more oblique.

CONCLUSION

Shoulder arthroplasty in the arthritic, rotator cuff-deficient shoulder is a difficult surgical problem. The concept of the reverse prosthesis developed by Paul Grammont is another step forward in the field of shoulder arthroplasty. Unlike previous reverse ball-and-socket designs, he has introduced 2 major inno-

vations: (1) a large metal hemisphere with no neck on the glenoid side and (2) a small polyethylene cup (covering less than half of the hemisphere), oriented with a nonanatomic inclination of 155°, on the humeral side. This design provides a fixed and medialized center of rotation, minimizing torque on the glenoid component and improving the power of the anterior and posterior deltoid for abduction. Furthermore, the humerus is lowered relative to the acromion, restoring (and probably increasing) tension of the deltoid fibers. This retensioning of the deltoid, together with the improved lever arm for abduction of the anterior and posterior deltoid, allows the deltoid to compensate for the absent rotator cuff muscles (Figure 13). Our clinical experience is similar to that in the literature: the reverse prosthesis restores active elevation above 90° in patients with a cuff-deficient shoulder. However, external rotation often remains limited, especially in those patients with an absent or fat-infiltrated teres minor. The same is true for internal rotation, which is not improved after a reverse prosthesis. Failure to restore sufficient tension in the deltoid may result in prosthetic instability. The design does appear to protect against early loosening of the glenoid component, but impingement of the humeral cup on the scapular neck is a cause for concern because of bone lysis and polyethylene wear. Fixation of the humerus may be more of a concern than fixation of the glenoid, especially in revision and fracture sequelae cases, where the proximal epiphysis and metaphysis are often missing.

Despite these concerns, the Grammont reverse

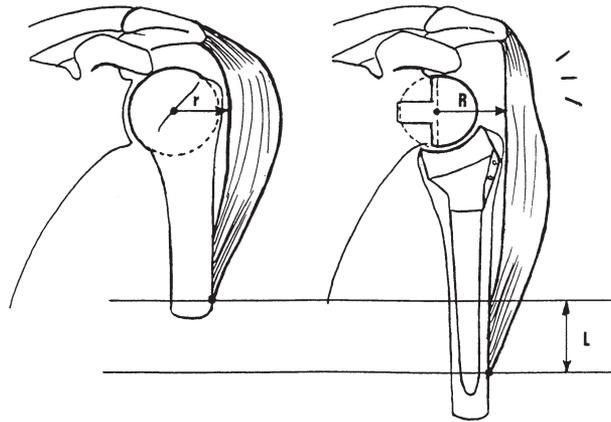


Figure 13 The lever arm across which the deltoid contracts to initiate elevation is greater with the reverse prosthesis because of the medialisation of the center of rotation ($R < r$). In addition, the strength of the deltoid is increased because of the lowering of the humerus (L) which lengthens the deltoid fibers. Both the medialisation and the lowering of the humerus are responsible for the modified contour of the shoulder after a reverse prosthesis.

prosthesis offers a potentially beneficial surgical option in situations where the rotator cuff and/or the proximal humerus are destroyed or absent. Such indications include shoulder stiffness or pseudo-paralysis due to osteoarthritis with massive and irreparable cuff tear^{2,11,19,20,22,32,34}; fracture sequelae (type 3 or 4) with proximal humerus distortion and tuberosity migration, nonunion, or osteolysis^{4,6}; prosthetic revision in a cuff-deficient shoulder^{12,14}; and tumor surgery.¹³ Conservative treatment and arthroscopic debridement with tenotomy of the long head of the biceps allow a regained function in many massive and irreparable rotator cuff ruptures. However, in some cases, the shoulder may remain unbalanced, leading to a persistent pseudo-paralyzed shoulder.⁴⁰ In this clinical situation, a reverse prosthesis may also be indicated, even in the absence of osteoarthritis. We emphasize that the reverse prosthesis is not a prosthesis designed to treat all irreparable rotator cuff tears without arthritis; nor is it a prosthesis to be used in situations in which nonconstrained shoulder arthroplasty (total shoulder arthroplasty or hemiarthroplasty) will yield a good result. Over-indications of this implant are a potential risk. There are 2 major contraindications to a reverse prosthesis: a history of previous infection and a nonfunctional deltoid muscle.

Finally, surgeons (and patients) must understand that the reverse prosthesis is still in its clinical trial phase. They must be aware that (1) results are less predictable and complication slash revision rates are high in revision surgery (dislocations, humeral fractures, loosening, low-grade infections) and (2) further follow-up is required to analyze loosening rates in the long term. At present, indications for a reverse prosthesis should be limited to elderly patients, arguably those aged over 70 years, with poor function and

severe pain related to cuff deficiency and osteoarthritis. A reverse prosthesis should not be offered to a young individual who desires to have a "normal shoulder" and will demand more than it is designed to do. The reverse prosthesis must be considered a salvage procedure, and surgeons should be aware that in case of failure, functional revision options are limited.

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REFERENCES

1. Arntz CT, Jackins S, Matsen FA III. Prosthetic replacement of the shoulder for the treatment of defects in the rotator cuff and the surface of the glenohumeral joint. *J Bone Joint Surg Am* 1993; 75:485-91.
2. Baulot E, Chabernaud D, Grammont PM. Results of Grammont's inverted prosthesis in omiarthritis associated with major cuff destruction. A propos of 16 cases [in France]. *Acta Orthop Belg* 1995;61(Suppl 1):112-9.
3. Bayley JJ, Kessel L. The Kessel total shoulder replacement. In: *Shoulder surgery*. New York: Springer Berlin Heidelberg; 1982.
4. Boileau P, Trojani C, Walch G, et al. Shoulder arthroplasty for the treatment of the sequelae of fractures of the proximal humerus. *J Shoulder Elbow Surg* 2001;10:299-308.
5. Boileau P, Walch G. The three-dimensional geometry of the proximal humerus. Implications for surgical technique and prosthetic design. *J Bone Joint Surg Br* 1997;79:857-65.
6. Boulahia A, Edwards TB, Walch G, Baratta RV. Early results of a reverse design prosthesis in the treatment of arthritis of the shoulder in elderly patients with a large rotator cuff tear. *Orthopedics* 2002;25:129-33.
7. Broström IA, Wallensten R, Olsson E, Anderson D. The Kessel prosthesis in total shoulder arthroplasty. A five-year experience. *Clin Orthop* 1992;277:155-60.
8. Burkhead WZ. History and development of shoulder arthroplasty. In: Friedman RJ, editor. *Arthroplasty of the shoulder*. New York: Thieme Medical, Inc; 1994. p. 1-26.

9. Cofield RH. Status of total shoulder arthroplasty. *Arch Surg* 1977; 112:1088-91.
10. Coughlin MJ, Morris JM, West WF. The semiconstrained total shoulder arthroplasty. *J Bone Joint Surg Am* 1979;61:574-81.
11. De Buttet A, Bouchon Y, Capon D, Delfosse J. Grammont shoulder arthroplasty for osteoarthritis with massive rotator cuff tears: report of 71 cases [abstract]. *J Shoulder Elbow Surg* 1997;6: 197.
12. De Wilde L, Mombert M, Van Petegem P, Verdonk R. Revision of shoulder replacement with a reversed shoulder prosthesis (Delta III): report of five cases. *Acta Orthop Belg* 2001; 67:348-53.
13. De Wilde LF, Van Ovost E, Uyttendaele D, Verdonk R. Results of an inverted shoulder prosthesis after resection for tumor of the proximal humerus[in French]. *Rev Chir Orthop Reparatrice Appar Mot* 2002;88:373-8.
14. Delloye C, Joris D, Colette A, Eudier A, Dubuc JE. Mechanical complications of total shoulder inverted prosthesis[in French]. *Rev Chir Orthop Reparatrice Appar Mot* 2002;88:410-4.
15. Favard L, Lautmann S, Sirveaux F, et al. Hemi arthroplasty versus reverse arthroplasty in the treatment of osteoarthritis with massive rotator cuff tear. In: Walch G, Boileau P, Mole D, editors. 2000 Shoulder prosthesis . . . two to ten year follow-up. Montpellier, France: Sauramps Medical; 2001. p. 261-8.
16. Fenlin JM Jr. Total glenohumeral joint replacement. *Orthop Clin North Am* 1975;6:565-83.
17. Field LD, Dines DM, Zabinski SJ, Warren RF. Hemiarthroplasty of the shoulder for rotator cuff arthropathy. *J Shoulder Elbow Surg* 1997;6:18-23.
18. Franklin JL, Barrett WP, Jackins SE, Matsen FA III. Glenoid loosening in total shoulder arthroplasty. Association with rotator cuff deficiency. *J Arthroplasty* 1988;3:39-46.
19. Gerard Y, Leblanc J, Rousseau B. A complete shoulder prosthesis[in French]. *Chirurgie* 1973;99:655-63.
20. Grammont PM, Trouilloud P, Laffay JP, Deries X. Etude et realisation d'une nouvelle prothese d'epaule. *Rhumatologie* 1987;39: 17-22.
21. Grammont PM, Baulot E. Delta shoulder prosthesis for rotator cuff rupture. *Orthopedics* 1993;16:65-8.
22. Jacobs R, Debeer P, De Smet L. Treatment of rotator cuff arthropathy with a reversed Delta shoulder prosthesis. *Acta Orthop Belg* 2001;67:344-7.
23. Kapankji, IA. The physiology of Joints, Vol 1, Baltimore. Williams & Wilkins, 1970.
24. Kolbel R, Friedebold G. Shoulder joint replacement[in German] . *Arch Orthop Unfallchir* 1973;76:31-9.
25. Lee DH, Niemann KM. Bipolar shoulder arthroplasty. *Clin Orthop* 1994;304:97-107.
26. Lettin AW, Copeland SA, Scales JT. The Stanmore total shoulder replacement. *J Bone Joint Surg Br* 1982;64:47-51.
27. McElwain JP, English E. The early results of porous-coated total shoulder arthroplasty. *Clin Orthop* 1987;218:217-24.
28. Morrey BF. Joint replacement arthroplasty. New York: Churchill Livingstone; 1991. p. 587.
29. Neer CS II, Craig EV, Fukuda H. Cuff-tear arthropathy. *J Bone Joint Surg Am* 1983;65:1232-44.
30. Nyffeler R, Werner CML, Simmen BR, Gerber C. Analysis of a retrieved Delta III total shoulder prosthesis. *J Bone Joint Surg.* 2004;86-B(8):1187-91.
31. Nyffeler RW, Werner CM, Gerber C. Biomechanical relevance of glenoid component positioning in the reversed Delta III total shoulder prosthesis. *J Shoulder Elbow Surg* 2004 (in press).
32. Pollock RG, Deliz ED, McIlveen SJ, Flatow EL, Bigliani L. Prosthetic replacement in rotator cuff deficient shoulders. *J Shoulder Elbow Surg* 1992;1:173-86.
33. Post M, Haskell SS, Jablon M. Total shoulder replacement with a constrained prosthesis. *J Bone Joint Surg Am* 1980;62:327-35.
34. Rittmeister M, Kerschbaumer F. Grammont reverse total shoulder arthroplasty in patients with rheumatoid arthritis and nonreconstructible rotator cuff lesions. *J Shoulder Elbow Surg* 2001;10: 17-22.
35. Sanchez-Sotelo J, Cofield RH, Rowland CM. Shoulder hemiarthroplasty for glenohumeral arthritis associated with severe rotator cuff deficiency. *J Bone Joint Surg Am* 2001;83:1814-22.
36. Sirveaux F, Favard L, Oudet D, Huguet D, Lautman S. Grammont inverted total shoulder arthroplasty in the treatment of glenohumeral osteoarthritis with massive and non repairable cuff rupture. In: Walch G, Boileau P, Mole D, editors. 2000 Shoulder prosthesis . . . two to ten year follow-up. Montpellier, France: Sauramps Medical; 2001. p. 247-52.
37. Sirveaux F, Favard L, Oudet D, et al. Grammont inverted total shoulder arthroplasty in the treatment of glenohumeral osteoarthritis with massive cuff rupture of the cuff. Results of a multicenter study of 80 shoulders. *J Bone Joint Surg Br* 2004; 86:388-95.
38. Swanson AB, de Groot Swanson G, Sattel AB, et al. Bipolar implant shoulder arthroplasty. Long-term results. *Clin Orthop* 1989;249:227-47.
39. Valenti P, Boutens D, Nerot C. Delta 3 reversed prosthesis for arthritis with massive rotator cuff tear: long term results (> 5 years). In: Walch G, Boileau P, Mole D, editors. 2000 Shoulder prosthesis . . . two to ten year follow-up. Montpellier, France: Sauramps Medical;2001. p. 253-9.
40. Walch G, Madonia G, Pozzi I, Riand N, Levigne C. Arthroscopic tenotomy of the tendon of the long head of the biceps in rotator cuff ruptures. In: Gazielly D, Gleyze P, Thomas T, editors. The cuff. Amsterdam: Elsevier; 1997. p. 350-5.
41. Williams GR Jr, Rockwood CA Jr. Hemiarthroplasty in rotator cuff-deficient shoulders. *J Shoulder Elbow Surg* 1996; 5:362-7.
42. Worland RL, Jessup DE, Arredondo J, Warburton KJ. Bipolar shoulder arthroplasty for rotator cuff arthropathy. *J Shoulder Elbow Surg* 1997;6:512-5.
43. Zuckerman JD, Scott AJ, Gallagher MA. Hemiarthroplasty for cuff tear arthropathy. *J Shoulder Elbow Surg* 2000;9:169-72.