J Shoulder Elbow Surg (2020) 29, S139–S148

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Early results of reverse total shoulder arthroplasty using a patient-matched glenoid implant for severe glenoid bone deficiency

Rajesh Rangarajan, MD[a,*], Collin K. Blout, BS[a], Vikas V. Patel, MD[a], Sevag A. Bastian, MD[b], Brian K. Lee, MD[a], John M. Itamura, MD[a]

[a]*Department of Shoulder and Elbow Reconstruction, Cedars-Sinai Kerlan-Jobe Institute at Adventist Health White Memorial, Los Angeles, CA, USA*
[b]*Orthopaedic Surgery Specialists, Adventist Health Glendale, Glendale, CA, USA*

Background: Reverse total shoulder arthroplasty (rTSA) in the presence of significant glenoid bone loss remains a challenge. This study presents preliminary clinical and radiographic outcomes of primary and revision rTSA using a patient-matched, 3-dimensionally printed custom metal glenoid implant to address severe glenoid bone deficiency.

Methods: Between September 2017 and November 2018, 19 patients with severe glenoid bone deficiency underwent primary (n = 9) or revision rTSA (n = 10) using the Comprehensive Vault Reconstruction System (VRS) (Zimmer Biomet, Warsaw, IN, USA) at a single institution. Preoperative and postoperative values for the Disabilities of the Arm, Shoulder and Hand score, Constant score, American Shoulder and Elbow Surgeons score, Simple Shoulder Test score, Single Assessment Numeric Evaluation score, and visual analog scale pain score and active range of motion were compared using the Wilcoxon signed rank test with the level of statistical significance set at $P < .05$.

Results: Complications occurred in 4 patients (21%), including a nondisplaced greater tuberosity fracture treated conservatively in 1, intraoperative cortical perforation during humeral cement removal treated with an allograft strut in 1, and recurrent instability and hematoma formation treated with humeral component revision in 1. One patient with an early periprosthetic infection was treated with component removal and antibiotic spacer placement at an outside facility and was subsequently lost to follow-up. Eighteen patients with 1-year minimum clinical and radiographic follow-up were evaluated (mean, 18.2 months; range, 12-27 months). Significant improvements were noted in the mean Disabilities of the Arm, Shoulder and Hand score (57.4 ± 16.5 vs. 29.4 ± 19.5, $P < .001$), mean Constant score (24.6 ± 10.2 vs. 60.4 ± 14.5, $P < .001$), mean American Shoulder and Elbow Surgeons score (32 ± 18.2 vs. 79 ± 15.6, $P < .001$), mean Simple Shoulder Test score (4.5 ± 2.6 vs. 9.3 ± 1.8, $P < .001$), mean Single Assessment Numeric Evaluation score (25.4 ± 13.7 vs. 72.2 ± 17.8, $P < .001$), mean visual analog scale pain score (6.2 ± 2.9 vs. 0.7 ± 1.3, $P < .001$), mean active forward flexion (53° ± 27° vs. 124° ± 23°, $P < .001$), and mean active abduction (42° ± 17° to 77° ± 15°, $P < .001$). Mean external rotation changed from 17° ± 19° to 32° ± 24° ($P = .06$). No radiographic evidence of component loosening, scapular notching, or hardware failure was observed at last follow-up in any patient.

Conclusion: The preliminary results of rTSA using the VRS to manage severe glenoid bone deficiency are promising, but longer follow-up is necessary to determine the longevity of this implant.

Cedars-Sinai Institutional Review Board approved this study (no. STUDY00000028).

*Reprint requests: Rajesh Rangarajan, MD, Department of Shoulder and Elbow Reconstruction, Cedars-Sinai Kerlan-Jobe Institute at Adventist Health White Memorial, 1700 E Cesar E. Chavez Ave, Ste 1400, Los Angeles, CA 90033, USA.

E-mail address: rajrangarajanmd@gmail.com (R. Rangarajan).

https://doi.org/10.1016/j.jse.2020.04.024

Level of evidence: Level IV; Case Series; Treatment Study

Keywords: Glenoid bone loss; glenoid deficiency; patient-matched glenoid implant; custom shoulder implant; reverse total shoulder arthroplasty; shoulder replacement; shoulder arthroplasty

Varying degrees of acquired glenoid bone loss have been reported in up to 50% of patients undergoing primary reverse total shoulder arthroplasty (rTSA),[12,24,55] but larger defects are more prevalent in revision procedures.[2,9,27,36] Glenoid bone deficiency in both primary rTSA and revision rTSA remains a challenging problem for even the most experienced surgeon because of the arduous task of properly positioning and securing the glenoid component in poor bone stock. Failure to obtain sufficient glenoid baseplate–bone contact, stable baseplate fixation, and adequate version and inclination correction will lead to increased baseplate stresses, micromotion, loosening, and early mechanical failure.[11,14,15,20,21,23,31,46,48] Although glenoid component loosening is uncommon with modern implants and techniques,[6,7,22,35,52] a recent meta-analysis found that osteoarthritis with bone loss is the most common pathology associated with aseptic baseplate loosening after primary rTSA,[52] and the incidence is higher still after revision rTSA.[6,52]

Several techniques are available to address this issue based on the severity of bone loss. Eccentric glenoid reaming can address asymmetrical erosion and correct retroversion up to 15°, albeit with the risks of joint medialization and poor bone quality support secondary to removal of subchondral bone.[13,26] Metal augmented baseplates are another option to address greater degrees of eccentric wear while preserving bone[1,3,25,33,40] but still require adequate baseplate-bone contact for stability, making them less suitable for large or uncontained defects. For more significant glenoid bone loss, a number of different bone grafting techniques have been described, with inconsistent clinical results, and these methods still carry the risks of graft subsidence, resorption, and nonunion.[6,8,19,39,41,44,45,47,49,51,53,56,57,61,28-30,32-34,38]

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technology and 3-dimensional (3D) printing are being increasingly used by orthopedic surgeons.[42] The successful use of patient-matched, 3-dimensionally printed custom acetabular components to address severe acetabular defects in total hip arthroplasty[5,43,58] prompted the development of patient-matched, 3D printed custom glenoid implants to address severe glenoid defects in shoulder arthroplasty, with multiple European studies reporting promising early results.[10,16-18,59,60]

The Comprehensive Vault Reconstruction System (VRS) (Zimmer Biomet, Warsaw, IN, USA) received US Food and Drug Administration 510(k) clearance in 2016 for use with rTSA in patients with significant bone loss.[18] The VRS is the only implant of this type commercially available in the United States, but published reports of its use are limited to case examples.[16,18] The purpose of this study was to present the 1-year minimum clinical and radiographic outcomes of a series of patients who underwent rTSA using the VRS to address severe glenoid bone deficiency.

Materials and methods

Study design

This was a retrospective study of all patients undergoing rTSA using the VRS performed by the senior author at a single institution with 1-year minimum clinical and radiographic follow-up. The indication to consider use of the VRS was severe glenoid bone deficiency with a failure to achieve at least 50% baseplate contact with native glenoid bone using the alternative scapular spine centerline[24] and a full-wedge augmentation during preoperative 3D planning (Blueprint software; Wright-Tornier, Memphis, TN, USA). In each case, after an extensive discussion of treatment options, a shared decision to use the VRS was made between the senior author and the patient. Between September 2017 and November 2018, 19 patients underwent rTSA using the VRS. One patient was lost to follow-up <3 months after surgery and was excluded from the final analysis. Thus, 18 patients (7 women and 11 men) with 1-year minimum clinical and radiographic follow-up were included in the study. The mean follow-up period was 18.2 months (range, 12-27 months). The group had a mean age of 66.6 years (range, 50-80 years) at the time of surgery. Patient demographic and preoperative data are listed in Table I. The VRS was used in 8 patients undergoing primary rTSA, 1 patient undergoing single-stage revision after a failed hemiarthroplasty, and 9 patients undergoing the second stage of a 2-stage revision for infection or failed rTSA.

Clinical and radiographic assessment

Preoperative clinical data collected included indication for surgery, number of previous arthroplasty procedures, active range of motion, Disabilities of the Arm, Shoulder and Hand (DASH) score, Constant score, American Shoulder and Elbow Surgeons (ASES) score, Simple Shoulder Test (SST) score, Single Assessment Numeric Evaluation (SANE) score, and visual analog scale (VAS) pain score. Postoperative clinical data collected at each visit included length of follow-up, any complications or revisions, active range of motion, DASH score, Constant score, ASES score, SST score, SANE score, and VAS pain score.

Table I Patient demographic and preoperative data

Patient No.	Age, yr	Sex	Follow-up, mo	Prior arthroplasty	Presence of implants	Indication for surgery	Defect classification[2,4,56,63]
1	65	M	27	2	Antibiotic cement spacer	Periprosthetic infection	Severe combined central and posterior
2	58	M	27	3	Antibiotic cement spacer	Periprosthetic infection	Severe combined central and posterior
3	73	M	27	3	Antibiotic cement spacer	Failed rTSA	Severe combined central and anterior
4	76	M	24	2	Antibiotic cement spacer	Periprosthetic infection	Severe combined central, anterior, and posterior
5	58	F	22	2	Antibiotic cement spacer	Periprosthetic infection	Severe combined central, anterior, and posterior
6	63	F	20	2	Antibiotic cement spacer	Failed rTSA	Severe combined central and posterior
7	50	M	19	1	Hemiarthroplasty	Failed hemiarthroplasty	Severe combined central, anterior, and posterior
8	57	M	18	0	None	Glenohumeral arthritis	C
9	64	M	18	3	Antibiotic cement spacer	Traumatic periprosthetic scapular fracture and periprosthetic infection	Severe combined central, anterior, and posterior
10	67	F	18	0	None	Glenohumeral arthritis	C
11	73	M	17	0	None	Cuff tear arthropathy	E3/B2
12	73	M	15	4	Antibiotic cement spacer	Periprosthetic infection	Severe combined central and posterior
13	77	M	14	0	None	Glenohumeral arthritis	B3
14	80	F	13	0	None	Glenohumeral arthritis	B3
15	71	F	13	0	None	Glenohumeral arthritis	B3
16	60	F	12	2	Antibiotic cement spacer	Periprosthetic infection	Severe combined central and posterior
17	72	F	12	0	None	Painful proximal humeral malunion and glenohumeral arthritis	A2
18	62	M	12	0	None	Capsulorrhaphy arthropathy	B3

M, male; *rTSA*, reverse total shoulder arthroplasty; *F*, female.

Radiographic evaluation included plain shoulder radiographs (true anteroposterior and axillary views) obtained preoperatively (Fig 1, *A*) and each postoperative visit. Fine-cut computed tomography (CT) scans with 3D reconstructions were obtained preoperatively and used to classify glenoid deficiency according to the Walch classification[4,62] in patients with glenohumeral arthritis, the Favard classification[55] for rotator cuff tear arthropathy, or the classification described by Antuna et al[2] for revision rTSA (Table I). All postoperative radiographs were reviewed in sequence for each patient to assess for humeral and glenoid component loosening, scapular notching, or other hardware failure.

Statistical analysis

The significance of the effect of the surgical procedure was measured using the Wilcoxon signed rank test comparing preoperative and postoperative values for range of motion and patient-reported outcome measures. The level of statistical significance was set at $P < .05$.

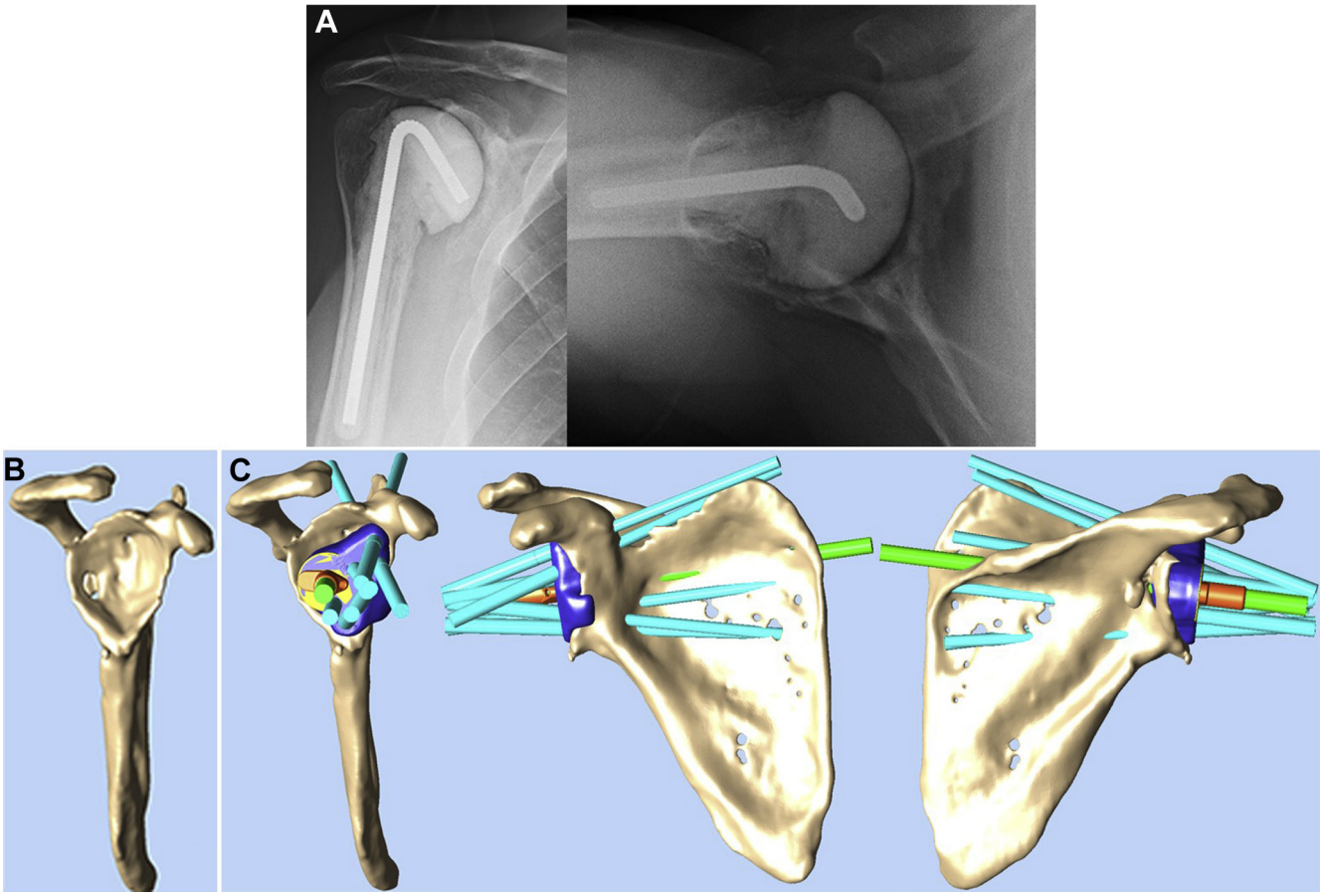

Figure 1 **(A)** Preoperative anteroposterior and axillary radiographs of patient 2 showing antibiotic spacer placement and severe glenoid bone deficiency. **(B)** Preoperative computed tomography–based 3-dimensional reconstruction showing severe combined central and posterior bone loss. **(C)** Preoperative Comprehensive Vault Reconstruction System *(VRS)* plan showing the implant, central and peripheral screw trajectories, planned custom boss, and built-in anterior lip to assist with positioning and orientation. The inferior glenoid osteophyte was removed to prevent scapular notching once the VRS was securely implanted.

To assess the ability of the data to detect a difference between the preoperative and postoperative measures, a post hoc power analysis was performed. The measure of statistical significance was set to an α of .05 and a β of .8.

Preoperative planning

In each case, using a 3D reconstruction of the scapula from a fine-cut preoperative CT scan (Fig. 1, *B)*, engineers worked with the senior author to design a proposal for the implant matched to fill the defect in the patient's anatomy (Fig. 1, *C*). This included implant size and positioning, screw trajectories, and any recommended bone removal for a custom boss if adequate bone stock was available. The final implant made of titanium with a porous plasma-spray coat was manufactured along with sterilizable high-fidelity models of the implant and scapular bone for intraoperative use (Fig. 2, *A* and *B*).

Surgical technique

All patients were positioned supine, and a deltopectoral approach was used. In primary rTSAs, a soft tissue tenodesis of the long head of the biceps was performed to the superior border of the pectoralis major tendon. The subscapularis tendon was tagged, peeled, and repaired at the end of the case whenever possible. The humeral head was then cut in primary cases. In revision cases, humeral implants were removed, and cement and soft tissues were removed from the intramedullary canal.

With the scapular bone model used as a guide, the entire glenoid face and the base of the coracoid process were completely exposed by releasing or removing all soft tissues until the implant model sat flush on bone. If any bony mismatch was discovered between the glenoid and the model, excess bone was meticulously contoured with a high-speed burr to ensure proper seating of the final implant.

If a custom boss was planned, the boss reaming guide was used to drill the central guide pin and ream the boss. In all cases, the final implant was then positioned using the built-in anterior lip to assist with seating and orientation (Fig. 1, *C*). Two drill bits were inserted in predetermined peripheral screw holes and left in place for provisional fixation (Fig. 2, *B*). The central 6.5-mm nonlocking screw was placed and achieved bony purchase and compression in all cases. All peripheral holes then received 4.75-mm fixed locking screws. Intraoperative fluoroscopy was used in all cases to confirm implant position and seating and to assess

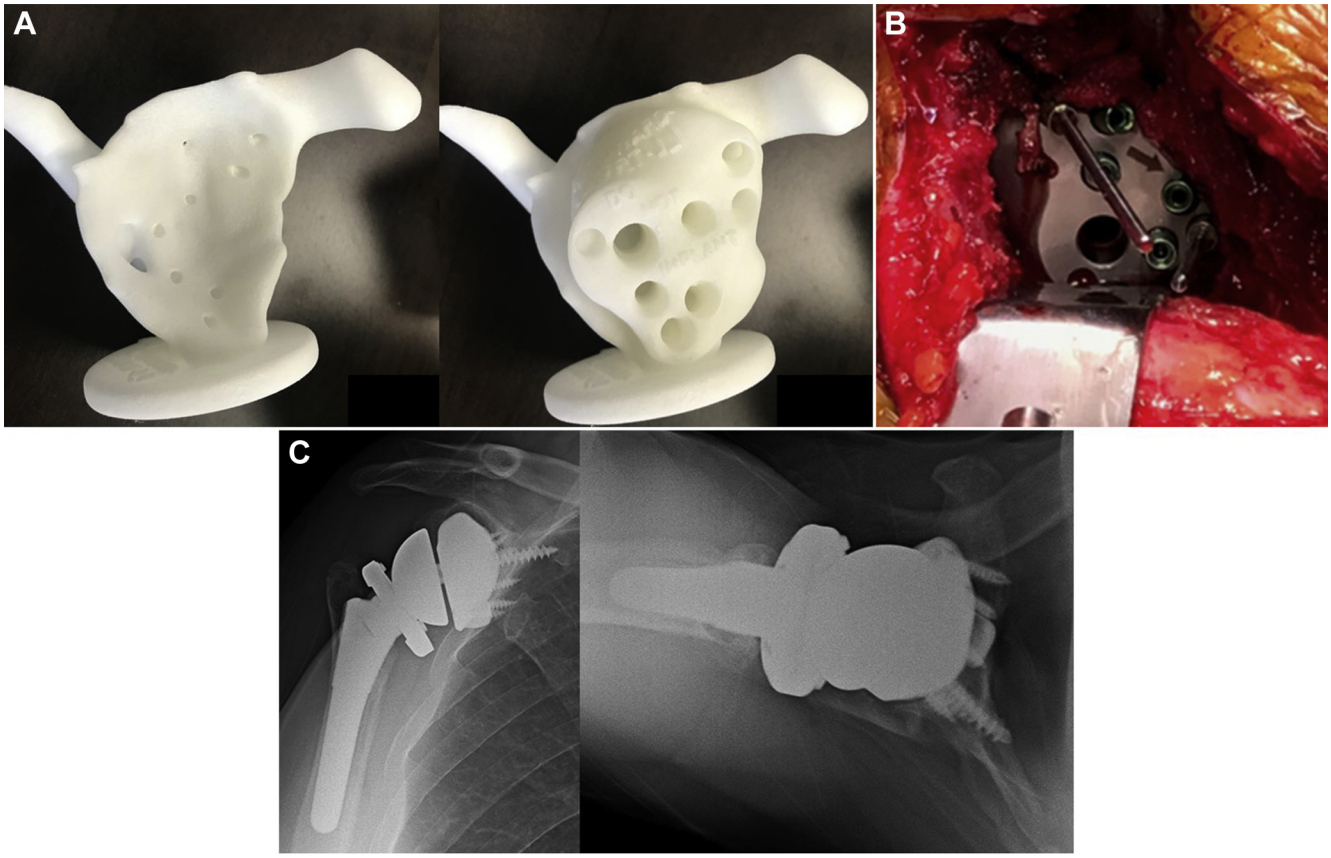

Figure 2 **(A)** Sterilizable polyamide models of the scapular bone and implant are used intraoperatively to guide exposure and ensure proper seating of the final implant. **(B)** Final Comprehensive Vault Reconstruction System *(VRS)* implant in situ with 2 drill bits inserted in predetermined peripheral holes for provisional fixation prior to central screw placement. **(C)** Postoperative anteroposterior and axillary radiographs of patient 2 at 27 months' follow-up. No change in implant position or evidence of loosening was observed after sequential review of all postoperative radiographs.

screw lengths and trajectories. At this point, on the basis of the preoperative plan, any excess bone or glenoid osteophytes that could lead to scapular notching or impingement were carefully removed.

Final glenosphere size, offset, and eccentricity were determined intraoperatively based on the preoperative plan, and the glenosphere was impacted into the built-in reverse Morse taper in the central screw hole of the implant. All humeral components were placed in 20° of retroversion, and all stems were press fit using the shortest length that could provide stable fixation. Humeral trays and bearings were chosen after trialing. All glenospheres and humeral components were standard implants from the Comprehensive Reverse Shoulder System.

Results

Clinical and radiographic assessment

Clinical assessment data for all patients collected preoperatively and at last follow-up visit are reported in Table II. Preoperative Constant, ASES, and SST scores were not available for 1 patient.

Mean active forward flexion (aFF) improved from 53° ± 27° to 124° ± 23° ($P < .001$), and mean active abduction (aABD) improved from 42° ± 17° to 77° ± 15° ($P < .001$). Mean active external rotation (aER) was 17° ± 19° preoperatively and 32° ± 24° at last follow-up ($P = .06$).

The mean DASH score improved from 57.4 ± 16.5 to 29.4 ± 19.5 ($P < .001$). The mean Constant score improved from 24.6 ± 10.2 to 60.4 ± 14.5 ($P < .001$). The mean ASES score improved from 32 ± 18.2 to 79 ± 15.6 ($P < .001$). The mean SST score improved from 4.5 ± 2.6 to 9.3 ± 1.8 ($P < .001$). The mean SANE score improved from 25.4 ± 13.7 to 72.2 ± 17.8 ($P < .001$). The mean VAS pain score improved from 6.2 ± 2.9 to 0.7 ± 1.3 ($P < .001$).

Subgroup analyses were performed of the 8 patients who underwent primary rTSA and the 10 patients who underwent revision rTSA. In the primary group, we observed significant improvements in all measured variables when comparing preoperative and last follow-up data ($P < .05$). Significant improvements in all clinical outcome metrics, as well as aFF and aABD, were also found in the revision group ($P < .05$); however, no significant change in aER was noted ($P = .51$).

Table II Range of motion and patient-reported outcome measures prior to surgery and at last follow-up

Patient No.	Follow-up, mo	aFF, °		aABD, °		aER, °		DASH score		Constant score		ASES score		SST score		SANE score		VAS pain score	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	27	45	110	45	85	30	45	76.7	29.2	45.0	54.9	50.0	71.7	10	10	50	55	6	0
2	27	100	120	70	90	45	50	39.2	10.8	38.0	68.5	66.7	96.7	7	12	30	85	2	0
3	27	10	117	10	88	10	52	67.5	18.3	20.0	61.4	56.7	75.0	3	9	10	70	1	0
4	24	45	90	45	75	0	35	46.7	21.7	25.7	56.3	50.0	78.3	6	10	25	65	2	0
5	22	45	90	45	45	10	45	62.5	23.3	22.0	44.8	11.7	81.7	2	8	30	80	8	0
6	20	45	135	40	90	0	30	24.2	9.2	13.0	70.1	45.0	83.3	2	11	20	80	3	0
7	19	0	120	0	90	0	−30	82.5	63.3	8.0	47.5	13.3	68.3	0	7	2	60	8	0
8	18	80	150	45	75	−20	45	33.3	16.7	25.7	71.2	33.3	95.0	7	9	20	85	6	0
9	18	45	90	45	45	30	10	72.5	62.5	13.0	28.8	11.7	55.0	3	8	10	60	9	3
10	18	80	150	45	70	0	40	69.2	30.0	27.0	84.0	8.3	98.3	3	12	10	99	10	0
11	17	45	128	45	67	20	25	52.5	12.5	NA	61.5	NA	91.7	NA	10	40	75	7	0
12	15	45	100	45	80	10	−20	42.5	35.8	25.0	41.0	41.7	51.7	6	6	25	60	5	3
13	14	70	135	70	60	40	30	56.5	20.0	20.0	74.0	21.7	93.3	7	10	50	65	9	0
14	13	60	130	30	75	20	40	70.0	67.0	17.0	57.8	13.3	55.0	3	6	30	70	9	4
15	13	45	160	45	100	0	60	55.0	2.5	22.0	85.0	16.7	100.0	3	12	20	100	9	0
16	12	45	165	45	85	50	30	64.7	49.2	23.0	69.5	43.3	78.3	2	10	15	75	3	0
17	12	45	120	30	80	25	30	42.5	20.0	29.0	56.3	33.3	85.0	7	9	30	90	6	0
18	12	110	120	60	80	30	50	75.8	36.7	44.0	55.4	26.7	63.3	6	9	40	25	8	2

aFF, active forward flexion; *aABD*, active abduction; *aER*, active external rotation; *DASH*, Disabilities of the Arm, Shoulder and Hand; *ASES*, American Shoulder and Elbow Surgeons; *SST*, Simple Shoulder Test; *SANE*, Single Assessment Numeric Evaluation; *VAS*, visual analog scale; *Pre*, preoperative; *Post*, last follow-up visit; *NA*, not available.

Post hoc power analysis indicated 100% power for aFF, aABD, the Constant score, the ASES score, the SST score, the SANE score, and the VAS pain score; 99.7% power for the DASH score; and 51.9% power for aER. Assuming a desired power of 0.8 to detect a difference in aER at an α level of .05, 43 patients would be required to reach significance.

No radiographic evidence of humeral or glenoid component loosening, scapular notching, or other hardware failure was noted in any patient. Postoperative advanced imaging was not indicated as all patients were doing well clinically.

Complications

Complications occurred in 4 of the 19 patients (21%). One patient with chronic hepatitis C lived in the Caribbean and presented to a local hospital with an infected prosthesis eroding through the skin. He underwent emergent component removal, irrigation and débridement, and antibiotic spacer placement <3 months after the surgical procedure and was lost to follow-up. In 1 patient with a history of chronic anticoagulation and multiple revision shoulder arthroplasty procedures, recurrent instability and hematoma formation developed. Three additional operations were performed within 2 months of revision rTSA using the VRS. Humeral component revision was performed in the first 2 procedures, and the third procedure was an isolated surgical wound hematoma evacuation. The glenosphere and VRS were not revised. This patient showed continued stability after the last procedure >2 years ago. One patient required an allograft strut graft to stabilize a cortical perforation of the humeral shaft that occurred during cement removal at the time of revision rTSA. One patient sustained a nondisplaced greater tuberosity fracture intraoperatively that was treated conservatively and healed.

Discussion

Glenoid bone loss is frequently encountered in both primary rTSA and revision rTSA.[2,9,12,24,27,36,55] The incidence of primary shoulder arthroplasty is increasing,[37,50,54,63,64] and a corresponding increase in the incidence of revision shoulder arthroplasty should be expected. Despite this knowledge, the best treatment option for severe glenoid bone deficiency in rTSA remains unknown. This study presents 1-year minimum clinical and radiographic outcomes of rTSA using the VRS and adds to the paucity of available literature reporting outcomes using patient-matched custom glenoid implants for severe glenoid bone deficiency.

The CAD-CAM total shoulder replacement (TSR) (Stanmore Implants Worldwide, Elstree, UK) is one type of

custom implant used for severe glenoid deficiency, which resembles a total hip arthroplasty and consists of a large glenoid shell fixed around the deficient glenoid bone to the scapula, a polyethylene liner, and a cobalt-chrome humeral stem and head.[10,59,60] Uri et al[59] first reported on its use as a revision implant for failed rTSA in 11 patients with a mean follow-up period of 35 months. Pain and functional outcome scores significantly improved. Four patients required reoperations unrelated to the glenoid component, and no glenoid loosening was noted.

The CAD-CAM TSR was also used as a revision implant in 21 patients with severe glenoid bone loss and a failed hemiarthroplasty for proximal humeral fractures or fracture sequelae.[60] Although pain and functional outcome scores significantly improved at 3 years' mean follow-up and no glenoid component loosening was noted, the complication rate was nearly 50%.

Chammaa et al[10] presented the outcomes of 37 patients with severe glenoid bone loss and rotator cuff deficiency who received the CAD-CAM TSR as a primary shoulder arthroplasty. At 5 years' follow-up, pain, functional outcome scores, and range of motion all showed statistically significant improvements. However, mean postoperative forward elevation was only 64°, and the authors attributed this to the constrained design of the implant. Reoperations occurred in 24% of patients, but glenoid loosening occurred in only 1 patient after a mechanical fall.

Debeer et al[17] recently described their series of 10 patients undergoing primary or revision rTSA using the Glenius Glenoid Reconstruction System (GGRS; Materialise, Leuven, Belgium) for severe glenoid deficiency. The GGRS is similar to the VRS in design, but the glenosphere is also a custom implant. No preoperative data were available for comparison, but at a mean of 30.5 months' follow-up, the mean VAS pain score was 3.3 (range, 0-7); Constant score, 41.3 (range, 18-75); QuickDASH (short version of DASH questionnaire) score, 35.8 (range, 2.3-70.5); and SST score, 5.7 (range, 1-11). Range of motion was not reported. One patient had postoperative instability treated with a larger polyethylene insert, and another patient had a brachial plexus injury that partially recovered but resulted in limited range of motion.

Published reports of rTSA using the VRS include just 4 brief case examples of patients undergoing revision rTSA using the VRS for significant glenoid bone loss.[16,18,] Three of these patients had undergone explant and antibiotic spacer placement for periprosthetic infection, and the fourth patient had a failed anatomic total shoulder arthroplasty with rotator cuff deficiency. The mean length of follow-up in these patients was 27.5 months (range, 18-48 months). Although only minimal range-of-motion data and no clinical outcome metrics were reported, satisfactory outcomes were described in all patients.

Our study is the most extensive case series of patients with severe glenoid bone deficiency undergoing rTSA using the VRS as either a primary or revision implant. At a mean follow-up of 18.2 months, the patients in our study showed significant improvements in range of motion, function, and pain relief. Comparison of our mean postoperative outcome measures with those of the GGRS series shows that the VRS cohort had a shorter follow-up period (18.2 months vs. 30.5 months), a lower VAS pain score (0.7 vs. 3.3), a higher Constant score (60.4 vs. 41.3), a similar DASH score (29.4 [DASH score] vs. 35.8 [QuickDASH score]), and a higher SST score (9.3 vs. 5.7).

The VRS does have a learning curve for surgeons. In patients treated earlier, the VRS implants were designed to be thick and wide, attempting to fill the entire defect, but these implants were cumbersome and difficult to maneuver and position. Because of this, we moved toward constructing implants using the least amount of metal necessary to restore version and inclination, prevent excessive medialization, and provide adequate bony contact for ingrowth.

Minimizing the time between the preoperative CT scan and surgery is also very important. In our experience, from the time the preoperative plan was approved, the implant could be manufactured and available for surgery a minimum of 8 weeks later. Even that duration may cause subtle changes to the glenoid anatomy if a hemiarthroplasty or cement spacer is present, leading to difficulty with seating the final implant at the time of surgery.

The VRS implant costs approximately $15,000, and this does not include glenosphere or humeral component costs. Facilities may not receive adequate reimbursement for these procedures, so cost remains an important consideration when deciding to use the VRS.

This study has several limitations. First, this is a retrospective study performed by a single surgeon at one institution, and although we had complete preoperative data for 17 of the 18 patients, there was no control group for comparison.

Second, we did not have an independent evaluator assess active or passive range of motion, and active range of motion was assessed clinically by the senior author at each visit. As shoulder range-of-motion evaluation solely based on chart review is highly unreliable, these results should be interpreted with caution.

Third, our radiographic assessment was based on a true anteroposterior view and an axillary view of the shoulder at each follow-up visit. The VRS has a complex 3D structure, and combined with inconsistent radiographic protocols, lucencies around the glenoid implant may have been missed. CT scans would have provided a more accurate assessment, but these were not performed in this study because of the added cost and radiation exposure for our patients.

Finally, although the primary impetus to use the VRS in patients with poor glenoid bone stock is to minimize the risk of glenoid loosening, the follow-up period in this study is too short to adequately assess for this potentially

devastating complication. However, this study is ongoing, and further follow-up of these patients will be performed.

Conclusion

The VRS is a patient-matched custom metal glenoid implant for use in rTSA with severe glenoid bone deficiency, and it is the only implant of this type commercially available for use in the United States. Preliminary results of this series of patients are promising, but longer follow-up is necessary to determine the longevity of this implant.

Disclaimer

Funding was provided by Adventist Health White Memorial.

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

References

1. Allred JJ, Flores-Hernandez C, Hoenecke HR, D'Lima DD. Posterior augmented glenoid implants require less bone removal and generate lower stresses: a finite element analysis. J Shoulder Elbow Surg 2016;25:823-30. https://doi.org/10.1016/j.jse.2015.10.003
2. Antuna SA, Sperling JW, Cofield RH, Rowland CM. Glenoid revision surgery after total shoulder arthroplasty. J Shoulder Elbow Surg 2001;10:217-24.
3. Bateman E, Donald SM. Reconstruction of massive uncontained glenoid defects using a combined autograft-allograft construct with reverse shoulder arthroplasty: preliminary results. J Shoulder Elbow Surg 2012;21:925-34. https://doi.org/10.1016/j.jse.2011.07.009
4. Bercik MJ, Kruse K, Yalizis M, Gauci MO, Chaoui J, Walch G. A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. J Shoulder Elbow Surg 2016;25:1601-6. https://doi.org/10.1016/j.jse.2016.03.010
5. Berend ME, Berend KR, Lombardi AV, Cates H, Faris P. The patient-specific Triflange acetabular implant for revision total hip arthroplasty in patients with severe acetabular defects: planning, implantation, and results. Bone Jt J 2018;100B:50-4. https://doi.org/10.1302/0301-620X.100B1.BJJ-2017-0362.R1
6. Bitzer A, Rojas J, Patten IS, Joseph J, McFarland EG. Incidence and risk factors for aseptic baseplate loosening of reverse total shoulder arthroplasty. J Shoulder Elbow Surg 2018;27:2145-52. https://doi.org/10.1016/j.jse.2018.05.034
7. Boileau P. Complications and revision of reverse total shoulder arthroplasty. Orthop Traumatol Surg Res 2016;102:S33-43. https://doi.org/10.1016/j.otsr.2015.06.031
8. Boileau P, Morin-Salvo N, Gauci MO, Seeto BL, Chalmers PN, Holzer N, et al. Angled BIO-RSA (bony-increased offset–reverse shoulder arthroplasty): a solution for the management of glenoid bone loss and erosion. J Shoulder Elbow Surg 2017;26:2133-42. https://doi.org/10.1016/j.jse.2017.05.024
9. Chalmers PN, Boileau P, Romeo AA, Tashjian RZ. Revision reverse shoulder arthroplasty. J Am Acad Orthop Surg 2019;27:426-36. https://doi.org/10.5435/JAAOS-D-17-00535
10. Chammaa R, Uri O, Lambert S. Primary shoulder arthroplasty using a custom-made hip-inspired implant for the treatment of advanced glenohumeral arthritis in the presence of severe glenoid bone loss. J Shoulder Elbow Surg 2017;26:101-7. https://doi.org/10.1016/j.jse.2016.05.027
11. Chebli C, Huber P, Watling J, Bertelsen A, Bicknell RT, Matsen F 3rd. Factors affecting fixation of the glenoid component of a reverse total shoulder prothesis. J Shoulder Elbow Surg 2008;17:323-7. https://doi.org/10.1016/j.jse.2007.07.015
12. Churchill RS, Spencer EE, Fehringer EV. Quantification of B2 glenoid morphology in total shoulder arthroplasty. J Shoulder Elbow Surg 2015;24:1212-7. https://doi.org/10.1016/j.jse.2015.01.007
13. Clavert P, Millett PJ, Warner JJP. Glenoid resurfacing: what are the limits to asymmetric reaming for posterior erosion? J Shoulder Elbow Surg 2007;16:843-8. https://doi.org/10.1016/j.jse.2007.03.015
14. Codsi MJ, Bennetts C, Powell K, Iannotti JP. Locations for screw fixation beyond the glenoid vault for fixation of glenoid implants into the scapula: an anatomic study. J Shoulder Elbow Surg 2007;16(Suppl):84-9. https://doi.org/10.1016/j.jse.2006.07.009
15. Codsi MJ, Iannotti JP. The effect of screw position on the initial fixation of a reverse total shoulder prosthesis in a glenoid with a cavitary bone defect. J Shoulder Elbow Surg 2008;17:479-86. https://doi.org/10.1016/j.jse.2007.09.002
16. Debeer P, Berghs B, Pouliart N, Van den Bogaert G, Verhaegen F, Nijs S. Treatment of severe glenoid deficiencies in reverse shoulder arthroplasty: the Glenius Glenoid Reconstruction System experience. J Shoulder Elbow Surg 2019;28:1601-8. https://doi.org/10.1016/j.jse.2018.11.061
17. Dines DM, Gulotta L, Craig EV, Dines JS. Novel solution for massive glenoid defects in shoulder arthroplasty: a patient-specific glenoid vault reconstruction system. Am J Orthop (Belle Mead NJ) 2017;46:104-8.
18. Ernstbrunner L, Werthel JD, Wagner E, Hatta T, Sperling JW, Cofield RH. Glenoid bone grafting in primary reverse total shoulder arthroplasty. J Shoulder Elbow Surg 2017;26:1441-7. https://doi.org/10.1016/j.jse.2017.01.011
19. Farron A, Terrier A, Büchler P. Risks of loosening of a prosthetic glenoid implanted in retroversion. J Shoulder Elbow Surg 2006;15:521-6. https://doi.org/10.1016/j.jse.2005.10.003
20. Favre P, Sussmann PS, Gerber C. The effect of component positioning on intrinsic stability of the reverse shoulder arthroplasty. J Shoulder Elbow Surg 2010;19:550-6. https://doi.org/10.1016/j.jse.2009.11.044
21. Flatow EL, Harrison AK. A history of reverse total shoulder arthroplasty. Clin Orthop Relat Res 2011;469:2432-9. https://doi.org/10.1007/s11999-010-1733-6
22. Formaini NT, Everding NG, Levy JC, Santoni BG, Nayak AN, Wilson C, et al. The effect of glenoid bone loss on reverse shoulder arthroplasty baseplate fixation. J Shoulder Elbow Surg 2015;24:e312-9. https://doi.org/10.1016/j.jse.2015.05.045
23. Frankle MA, Teramoto A, Luo ZP, Levy JC, Pupello D. Glenoid morphology in reverse shoulder arthroplasty: classification and surgical implications. J Shoulder Elbow Surg 2009;18:874-85. https://doi.org/10.1016/j.jse.2009.02.013
24. Friedman R, Stroud N, Glattke K, Flurin P-H, Wright TW, Zuckerman JD, et al. The impact of posterior wear on reverse shoulder glenoid fixation. Bull Hosp Jt Dis 2015;73(Suppl 1):S15-20.
25. Gillespie R, Lyons R, Lazarus M. Eccentric reaming in total shoulder arthroplasty: a cadaveric study. Orthopedics 2009;32:21-6. https://doi.org/10.3928/01477447-20090101-07
26. Hernandez-Ortiz EG, Christmas KN, Simon P, Diaz MA, Hess AV, O'Briain DE, et al. Improving preoperative planning of revision surgery after previous anatomic total shoulder arthroplasty. J Shoulder

Elbow Surg 2019;28:S168-74. https://doi.org/10.1016/j.jse.2019.04.005
27. Hill JM, Norris TR. Long-term results of total shoulder arthroplasty following bone-grafting of the glenoid. J Bone Joint Surg Am 2001;83:877-83.
28. Ho JC, Thakar O, Chan WW, Nicholson T, Williams GR, Namdari S. Early radiographic failure of reverse total shoulder arthroplasty with structural bone graft for glenoid bone loss. J Shoulder Elbow Surg 2020;29:550-60. https://doi.org/10.1016/j.jse.2019.07.035
29. Hoffelner T, Moroder P, Auffarth A, Tauber M, Resch H. Outcomes after shoulder arthroplasty revision with glenoid reconstruction and bone grafting. Int Orthop 2014;38:775-82. https://doi.org/10.1007/s00264-013-2191-z
30. Hopkins AR, Hansen UN, Bull AMJ, Emery R, Amis AA. Fixation of the reversed shoulder prosthesis. J Shoulder Elbow Surg 2008;17:974-80. https://doi.org/10.1016/j.jse.2008.04.012
31. Iannotti JP, Frangiamore SJ. Fate of large structural allograft for treatment of severe uncontained glenoid bone deficiency. J Shoulder Elbow Surg 2012;21:765-71. https://doi.org/10.1016/j.jse.2011.08.069
32. Jones RB, Wright TW, Roche CP. Bone grafting the glenoid versus use of augmented glenoid baseplates with reverse shoulder arthroplasty. Bull Hosp Joint Dis 2015;73:S129-35.
33. Jones RB, Wright TW, Zuckerman JD. Reverse total shoulder arthroplasty with structural bone grafting of large glenoid defects. J Shoulder Elbow Surg 2016;25:1425-32. https://doi.org/10.1016/j.jse.2016.01.016
34. Kang JR, Dubiel MJ, Cofield RH, Steinmann SP, Elhassan BT, Morrey ME, et al. Primary reverse shoulder arthroplasty using contemporary implants is associated with very low reoperation rates. J Shoulder Elbow Surg 2019;28:S175-80. https://doi.org/10.1016/j.jse.2019.01.026
35. Kelly JD, Zhao JX, Hobgood ER, Norris TR. Clinical results of revision shoulder arthroplasty using the reverse prosthesis. J Shoulder Elbow Surg 2012;21:1516-25. https://doi.org/10.1016/j.jse.2011.11.021
36. Kim SH, Wise BL, Zhang Y, Szabo RM. Increasing incidence of shoulder arthroplasty in the United States. J Bone Joint Surg Am 2011;93:2249-54. https://doi.org/10.2106/JBJS.J.01994
37. Klein SM, Dunning P, Mulieri P, Pupello D, Downes K, Frankle MA. Effects of acquired glenoid bone defects on surgical technique and clinical outcomes in reverse shoulder arthroplasty. J Bone Joint Surg Am 2010;92:1144-54. https://doi.org/10.2106/JBJS.I.00778
38. Klika BJ, Wooten CW, Sperling JW, Steinmann SP, Schleck CD, Harmsen WS, et al. Structural bone grafting for glenoid deficiency in primary total shoulder arthroplasty. J Shoulder Elbow Surg 2014;23:1066-72. https://doi.org/10.1016/j.jse.2013.09.017
39. Knowles NK, Ferreira LM, Athwal GS. Augmented glenoid component designs for type B2 erosions: a computational comparison by volume of bone removal and quality of remaining bone. J Shoulder Elbow Surg 2015;24:1218-26. https://doi.org/10.1016/j.jse.2014.12.018
40. Kyriacou S, Khan S, Falworth M. The management of glenoid bone loss in shoulder arthroplasty. J Arthrosc Jt Surg 2019;6:21-30. https://doi.org/10.1016/j.jajs.2018.12.001
41. Lal H, Patralekh MK. 3D printing and its applications in orthopaedic trauma: A technological marvel. J Clin Orthop Trauma 2018;9:260-8. https://doi.org/10.1016/j.jcot.2018.07.022
42. Li H, Qu X, Mao Y, Dai K, Zhu Z. Custom acetabular cages offer stable fixation and improved hip scores for revision THA with severe bone defects. Clin Orthop Relat Res 2016;474:731-40. https://doi.org/10.1007/s11999-015-4587-0
43. Lopiz Y, García-Fernández C, Arriaza A, Rizo B, Marcelo H, Marco F. Midterm outcomes of bone grafting in glenoid defects treated with reverse shoulder arthroplasty. J Shoulder Elbow Surg 2017;26:1581-8. https://doi.org/10.1016/j.jse.2017.01.017
44. Lorenzetti A, Streit JJ, Cabezas AF, Christmas KN, LaMartina J, Simon P, et al. Bone graft augmentation for severe glenoid bone loss in primary reverse total shoulder arthroplasty. JBJS Open Access 2017;2:e0015. https://doi.org/10.2106/JBJS.OA.17.00015
45. Lung TS, Cruickshank D, Grant HJ, Rainbow MJ, Bryant TJ, Bicknell RT. Factors contributing to glenoid baseplate micromotion in reverse shoulder arthroplasty: a biomechanical study. J Shoulder Elbow Surg 2019;28:648-53. https://doi.org/10.1016/j.jse.2018.09.012
46. Mahylis JM, Puzzitiello RN, Ho JC, Amini MH, Iannotti JP, Ricchetti ET. Comparison of radiographic and clinical outcomes of revision reverse total shoulder arthroplasty with structural versus nonstructural bone graft. J Shoulder Elbow Surg 2019;28:e1-9. https://doi.org/10.1016/j.jse.2018.06.026
47. Martin EJ, Duquin TR, Ehrensberger MT. Reverse total shoulder glenoid baseplate stability with superior glenoid bone loss. J Shoulder Elbow Surg 2017;26:1748-55. https://doi.org/10.1016/j.jse.2017.04.020
48. De Martino I, Dines DM, Warren RF, Craig EV, Gulotta LV. Patient-specific implants in severe glenoid bone loss. Am J Orthop (Belle Mead NJ) 2018;47. https://doi.org/10.12788/ajo.2018.0009
49. Neyton L, Boileau P, Nové-Josserand L, Edwards TB, Walch G. Glenoid bone grafting with a reverse design prosthesis. J Shoulder Elbow Surg 2007;16(Suppl):71-8. https://doi.org/10.1016/j.jse.2006.02.002
50. Palsis JA, Simpson KN, Matthews JH, Traven S, Eichinger JK, Friedman RJ. Current trends in the use of shoulder arthroplasty in the United States. Orthopedics 2018;41:e416-23. https://doi.org/10.3928/01477447-20180409-05
51. Paul RA, Maldonado-Rodriguez N, Docter S, Khan M, Veillette C, Verma N, et al. Glenoid bone grafting in primary reverse total shoulder arthroplasty: a systematic review. J Shoulder Elbow Surg 2019;28:2447-56. https://doi.org/10.1016/j.jse.2019.05.011
52. Rojas J, Choi K, Joseph J, Srikumaran U, McFarland EG. Aseptic glenoid baseplate loosening after reverse total shoulder arthroplasty: a systematic review and meta-analysis. JBJS Rev 2019;7:e7. https://doi.org/10.2106/JBJS.RVW.18.00132
53. Scalise JJ, Iannotti JP. Bone grafting severe glenoid defects in revision shoulder arthroplasty. Clin Orthop Relat Res 2008;466:139-45. https://doi.org/10.1007/s11999-007-0065-7
54. Schairer WW, Nwachukwu BU, Lyman S, Craig EV, Gulotta LV. National utilization of reverse total shoulder arthroplasty in the United States. J Shoulder Elbow Surg 2015;24:91-7. https://doi.org/10.1016/j.jse.2014.08.026
55. Sirveaux F, Favard L, Oudet D, Huquet D, Walch G, Molé D. Grammont inverted total shoulder arthroplasty in the treatment of glenohumeral osteoarthritis with massive rupture of the cuff. Results of a multicentre study of 80 shoulders. J Bone Joint Surg Br 2004;86:388-95. https://doi.org/10.1302/0301-620x.86b3.14024
56. Tashjian RZ, Broschinsky K, Stertz I, Chalmers PN. Structural glenoid allograft reconstruction during reverse total shoulder arthroplasty. J Shoulder Elbow Surg 2020;29:534-40. https://doi.org/10.1016/j.jse.2019.07.011
57. Tashjian RZ, Granger E, Chalmers PN. Structural glenoid grafting during primary reverse total shoulder arthroplasty using humeral head autograft. J Shoulder Elbow Surg 2018;27:e1-8. https://doi.org/10.1016/j.jse.2017.07.010
58. Taunton MJ, Fehring TK, Edwards P, Bernasek T, Holt GE, Christie MJ. Pelvic discontinuity treated with custom triflange component: a reliable option. Clin Orthop Relat Res 2012;470:428-34. https://doi.org/10.1007/s11999-011-2126-1
59. Uri O, Bayley I, Lambert S. Hip-inspired implant for revision of failed reverse shoulder arthroplasty with severe glenoid bone loss. Acta

Orthop 2014;85:171-6. https://doi.org/10.3109/17453674.2014.899850
60. Uri O, Beckles V, Falworth M, Higgs D, Lambert S. Revision arthroplasty with a hip-inspired computer-assisted design/computer-assisted manufacturing implant for glenoid-deficient shoulders. J Shoulder Elbow Surg 2014;23:205-13. https://doi.org/10.1016/j.jse.2013.05.004
61. Wagner E, Houdek MT, Griffith T, Elhassan BT, Sanchez-Sotelo J, Sperling JW, et al. Glenoid bone-grafting in revision to a reverse total shoulder arthroplasty. J Bone Joint Surg Am 2015;97:1653-60. https://doi.org/10.2106/JBJS.N.00732
62. Walch G, Badet R, Boulahia A, Khoury A. Morphologic study of the glenoid in primary glenohumeral osteoarthritis. J Arthroplasty 1999;14:756-60.
63. Westermann RW, Pugely AJ, Martin CT, Gao Y, Wolf BR, Hettrich CM. Reverse shoulder arthroplasty in the United States: a comparison of national volume, patient demographics, complications, and surgical indications. Iowa Orthop J 2015;35:1-7.
64. Zmistowski B, Padegimas EM, Howley M, Abboud J, Williams G, Namdari S. Trends and variability in the use of total shoulder arthroplasty for Medicare patients. J Am Acad Orthop Surg 2018;26:133-41. https://doi.org/10.5435/JAAOS-D-16-00720