ORIGINAL PAPER

Exposure of the brachial plexus in complex revisions to reverse total shoulder arthroplasty

Jorge Rojas[1] · Filippo Familiari[1] · Amrut U. Borade[1] · Jacob Joseph[1] · E. Gene Deune[2] · Jack V. Ingari[2] ·
Edward G. McFarland[1]

Abstract

Background Excision of extensive scar tissue (EEST) may be required in certain cases of revision reverse total shoulder arthroplasty (RTSA). Neurovascular structures are at a higher risk of iatrogenic direct injury in these cases. We describe a technique to expose and protect the musculocutaneous and axillary nerves in a series of revision RTSA cases that required EEST.
Methods Between 2004 and 2013, 83 revision RTSA procedures were identified in our database. Of these, 18 cases (22%) who underwent concomitant nerve exploration for EEST preventing glenoid exposure, preventing reduction of the humeral component, or causing instability of the implanted RTSA, were included. All patients were observed for a minimum of two years or until reoperation. Patient-reported outcome scores (PROMs), range of motion (ROM), and complication rates were analyzed.
Results Patients had significant pain relief and improvement in PROMs post-operatively. Two patients (11%) required another revision surgery because of infection (one patient with glenoid loosening; one patient with stem loosening). Two patients (11%) had instability successfully managed with closed reduction. Two patients (11%) had a clinically evident post-operative nerve injury. Both cases were neurapraxias (1 partial brachial plexopathy and 1 partial isolated axillary nerve injury) and experienced complete neurologic recovery at last follow-up.
Conclusions Complete permanent nerve injuries resulting from direct surgical trauma during revision RTSA requiring EEST can be avoided using the technique presented here. Despite proper exposition of the nerves, partial temporary neurapraxic injuries may occur. Patients who underwent this procedure experienced significant improvements in shoulder pain and function with complication rates consistent to those previously reported in revision RTSA.

Keywords Axillary nerve · Brachial plexus · Neurologic complications · Reverse total shoulder arthroplasty · Revision · Scar tissue

Introduction

Patients with failed shoulder arthroplasty or failed open reduction and internal fixation (ORIF) of proximal humerus fractures (PHF) suffer from pain in combination with a distinct loss of function. These problems are disabling for the patient and often require revision surgery. Reverse total shoulder arthroplasty (RTSA) is an attractive option for revision surgery and satisfactory outcomes have been reported after revision to RTSA for failed hemiarthroplasty (HA) [1–4], failed anatomic total shoulder arthroplasty (TSA) [5–11], failed RTSA [12–15], and failed ORIF [16–18]. Despite the satisfactory outcomes, revision arthroplasty is technically complex, requiring osteotomies for implant removal, reconstruction of soft tissue or osseous defects, and surgical dissection through abnormal scarred tissue planes. As a result, revision arthroplasty has a significantly higher risk of complications than primary shoulder arthroplasty [19], with reported complication rates as high as 69% (most frequently dislocation, infection, and nerve injury) [19–21].

Adequate management of soft tissue is essential during revision arthroplasty. Excision of scar and soft tissue releases

---

Level of evidence Level IV, Case Series, Treatment Study.

✉ Edward G. McFarland
   editorialservices@jhmi.edu

[1] Division of Shoulder Surgery, Department of Orthopaedic Surgery, The Johns Hopkins University, 10753 Falls Road, Suite 215, Pavilion II, Lutherville, Baltimore, MD 21093, USA

[2] Division of Hand Surgery, Department of Orthopaedic Surgery, The Johns Hopkins University, 601 N. Caroline, Baltimore, MD 21287, USA

Ⓐ Springer

are necessary to have an adequate exposure and to avoid having the soft tissue envelope as a hindrance to reduction of the implant. In addition, the release and removal of inferior soft tissues is important for implant stability, because a properly positioned implant may be unstable from inferior soft tissue impingement [22, 23]. In most revision cases, a glenoid-based release of the capsule with a limited excision of scar tissue is sufficient to allow safe and proper implantation of the components. However, in some revision cases, tissues around the glenohumeral joint may be so scarred that revision RTSA cannot be performed properly without excision of extensive scar tissue [19, 24]. In our experience, certain indications can require excision of extensive scar tissue to allow implantation of a revision RTSA: (1) when the glenoid is covered with scar that prevents safe exposure without exploration of the peripheral nerves, especially the axillary nerve; (2) when the humeral head or the prosthesis to be revised is displaced so medially into the glenoid that there is insufficient room in the joint for the RTSA components to be inserted or reduced without shortening the humerus (e.g., as when the prosthesis has been dislocated for substantial periods of time or in patients with failed, painful shoulder hemiarthroplasties that have worn away the glenoid bone posteriorly or superiorly); and (3) when, after reducing the humeral and glenoid components, positioning of the shoulder in adduction and external rotation results in instability of the prosthesis.

Excision of extensive scar tissue in the anterior and inferior glenoid without identification and isolation of the musculocutaneous and axillary nerves would put them at risk of iatrogenic direct injury due to the distortion of normal anatomical relationships. Therefore, the main goal of this study was to describe a surgical technique to expose and protect the musculocutaneous and axillary nerves that facilitates excision of extensive scar tissue during revision to RTSA for the three indications outlined above. Other aims were to determine the clinical outcomes and the rate of complications, especially the incidence and pattern of clinically evident nerve injury, when using this technique in this group of challenging patients.

Materials and methods

Patient group

Following Institutional Review Board approval, we retrospectively queried a prospectively collected shoulder arthroplasty research database for patients who underwent revision RTSA between January 1, 2004 and October 31, 2013 by one surgeon. A revision RTSA was defined as that performed after previous failed arthroplasty (resurfacing, hemiarthroplasty, TSA, or RTSA). RTSA cases performed for failed ORIF of PHF were considered as revision RTSA procedures for the purposes of this study considering that some of those cases

may require extensive excision of scar tissue. Of 83 revision cases identified in our institutional database, 18 cases (22%) who underwent concomitant nerve exploration for excision of extensive scar tissue were included. All patients were observed for a minimum of two years. The study included eight men and ten women. The mean patient age was 61 years (range, 40–82 years). The mean duration of follow-up was 45 months (range, 24–117 months). The median number of previous procedures was three (range, 1–9 procedures). Initial failed procedures included RTSA (nine patients), hemiarthroplasty (five patients), ORIF of PHF (three patients), and TSA (one patient). Primary indications for revision surgery included instability (seven patients), infection requiring a two-stage revision (four patients), rotator cuff insufficiency with anterosuperior scape (four patients), and symptomatic malunion/non-union (three patients). The decision to perform nerve exploration for excision of extensive scar tissue was made at the moment of surgery for any of the following indications: (1) inability to expose the glenoid because of scar tissue (six patients), (2) inability to reduce the newly inserted RTSA because of scar tissue in the glenoid (nine patients), and (3) instability of the newly inserted RTSA caused by soft tissue impingement in the posterior and inferior glenoid (three patients).

Surgical technique

All patients underwent general anesthesia either with or without a single-shot inter-scalene block or catheter. For all cases, a fellowship-trained hand or plastic surgeon was available if needed for exposure and neurolysis of the nerve structures during excision of scar. Patients underwent revision RTSA using a deltopectoral approach in a semi-sitting beach chair position with the arm placed on a Mayo stand. The Mayo stand was positioned so that the arm was in slight flexion, which took tension off of the brachial plexus, and peripheral nerves. We also found that slight flexion of the elbow contributed to reduce tension on the brachial plexus. The conjoint tendon was identified and an arthrotomy was performed lateral to this through the capsule or by release of the subscapularis tendon and capsule as a single unit. In some cases, there was such an extensive scar that the conjoint tendon could not be identified. In those cases, the deltoid insertion was identified first on the shaft and this allowed exposure of the interval between the deltoid and the proximal humerus to identify the capsule and perform the arthrotomy. The glenoid was inspected and the extent of scar tissue assessed. If there was no excessive scar preventing exposure of the glenoid, the baseplate was inserted using standard techniques. In cases where the glenoid was extensively covered with scar tissue (six patients), nerve exploration was performed at this point to perform an extensive excision of scar that allowed a safe implantation of the baseplate. Cases with severe bone loss and

excessive retroversion were treated by reaming the glenoid flat avoiding glenoid bone grafting.

Trial glenosphere and trial metaphyseal component were then placed to determine whether reduction of the components was possible and whether the components were stable. For two patients, an implant with a 155° neck-shaft angle and a less lateral-based (aka. "medialized") glenosphere (Aequalis Reversed Shoulder Prosthesis, Tornier, Edina, MN, USA) was used. For 13 patients, an implant with a more lateral-based glenosphere was used (RSP Reverse Shoulder Prosthesis, DJO, Austin, TX, USA). This prosthesis has a 135° neck-shaft angle, which has been shown to have less impingement than systems with a more vertical neck-shaft angle [25, 26] and it was preferred once it was available. One patient who underwent revision of a failed hemiarthroplasty had a well-fixed modular humeral stem and therefore was converted to RTSA using the same prosthetic system (Comprehensive Reverse Shoulder System, Zimmer-Biomet, Warsaw, IN). Two patients with chronically dislocated prosthesis who had undergone RTSA elsewhere (Aequalis Reversed Shoulder Prosthesis, Tornier, Edina, MN, USA (one patient); Delta III, DePuy, Warsaw, IN (one patient)) were treated with the use of metal spacers and thicker polyethylene to provide tension in the construct without the need of revising the baseplate or the humeral stem.

Since these shoulders were very tight, we utilized the smallest glenoid sphere in most cases. If the components could not be reduced, the proximal humerus was evaluated to see whether further bone removal would allow the humeral component to be lowered enough to achieve reduction. If this was not possible or unsuccessful, the trial components were removed, and we proceeded with nerve exploration for extensive excision of scar (nine patients). After excision of extensive scar tissue, the implants could be reduced without the need of shortening the humerus. After the shoulder was reduced, ROM of the implants was tested to verify stability. In three cases in which extensive scar excision and nerve exploration had not been required to this point, the implants were reduced but dislocated in adduction and external rotation, with inferior soft-tissue impingement as the cause of instability [22, 23]. As a result, nerve exploration was performed to facilitate a wider excision of scar in the inferior glenoid achieving a stable reduction of the shoulder. Once the trial components were placed in the shoulder and the shoulder was reduced, care was taken to assure that the nerves were safe and not entrapped by the components or not under any undue tension. The amount of scar removed was deemed satisfactory if the trial components could be reduced and remained stable when the shoulder was moved passively through a range of motion. Once the definitive implants were placed, the range of motion of the final construct was tested to verify stability of the shoulder. Figure 1 summarizes our approach to decision making of nerve exploration for excision of extensive scar tissue during complex revision RTSA cases.

Nerve exploration technique

Nerve exploration was performed in all cases by one of three surgeons who specialize in hand and nerve surgery. Musculocutaneous and axillary nerves could not be exposed in the anterior and inferior glenoid in any case because of the dense scar tissue. Therefore, the nerves had to be identified proximally where they branch off of the brachial plexus to be traced and neurolysed distally allowing to free them safely from the surrounding scar tissue. Magnification with loupes and a handheld nerve stimulator (VARI-STIM III Medtronic Inc., Jacksonville, FL) were used during nerve dissection. The interspace between the conjoint tendon and the lateral border of the pectoralis minor tendon was created to expose the fat pad covering the brachial plexus (Fig. 2). Using gentle scissor dissection, the musculocutaneous nerve was identified proximally, and this was confirmed electrically with the nerve stimulator (set at 0.5 mA). It was neurolysed distally with care taken to identify the branches as it went into the biceps. After this, the musculocutaneous nerve was dissected proximally to identify the axillary artery and the additional structures of the brachial plexus. The axillary artery served as the reference to identify the posterior cord of the brachial plexus. Gentle finger dissection was done to identify the posterior cord behind the axillary artery. The posterior cord was further dissected distally, and the axillary nerve was identified visually and confirmed electrically with the nerve stimulator (set at 0.5 mA). Further dissection was done of the axillary nerve to trace it behind the humerus and superiorly to the posterior capsule. In seven cases, distal dissection of the axillary nerve became very difficult given the small confines of the surgical bed and the firmness of the tissue due to scarring. Therefore, in those cases, the decision was made to release the conjoint tendon to allow for unfettered view of the surgical bed and to potentially decrease the chances of iatrogenic nerve injury. The conjoint tendon was released from the coracoid bone surface and no attempt was made to reattach it as in these cases, it was completely impossible to distinguish its fibers from the scar of the anterior capsule in the front of the shoulder. The pectoralis minor tendon was left intact in all cases. While protecting the exposed nerves, the thick scar tissue was excised in the anterior and inferior capsule en-bloc using cautery. In most cases, the scar tissue removed was 1- to 2-cm thick anteriorly and inferiorly (Fig. 3). Gradual removal of scar tissue as the axillary nerve was exposed from anterior to posterior allowed the axillary nerve to be exposed completely from the posterior cord to its terminal branches including the "blind spot" described by Maldonado et al. [27] (Fig. 4). We did not find a "tug test" [28] helpful in isolating the axillary nerve in any case. In cases in which scar tissue caused soft tissue impingement and instability of the components, additional care was taken to protect the
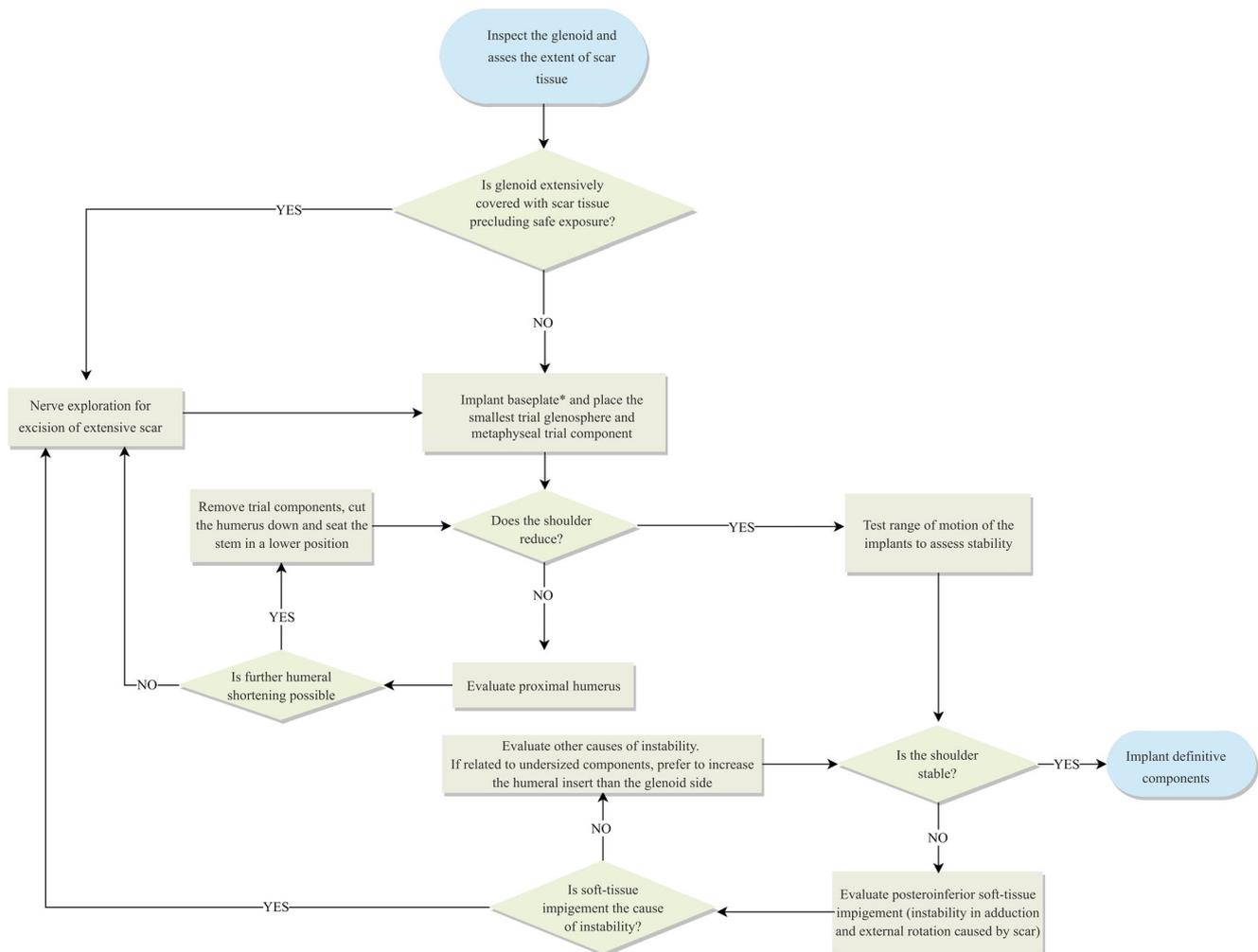
Fig. 1 Decision-making approach of nerve exploration for excision of extensive scar tissue during complex revision RTSA cases. If baseplate has been already implanted or does not require to be revised proceed to implant trial components

final branches of the axillary nerve when excising scar tissue in the inferior quadrants anterior and posterior to the glenoid.

## Clinical and complication assessment

Outcome measures that were evaluated included active range of motion (ROM) and patient-reported outcome measures (PROMs) collected in the prospective research database. Pre-operative and post-operative ROM testing was conducted using a handheld goniometer. ROM measures included abduction, forward flexion, external rotation (ER) with the arm at the side, and internal rotation (IR) with the arm at 90° of abduction. IR was also measured behind the back as the highest vertebral level reached by the patient with the thumb up the back. PROMs utilized were the American Shoulder and Elbow Society (ASES) score, the simple shoulder test (SST) score and a visual analog scale (VAS) for pain. All physical examinations were performed using a specific examination

protocol pre-operatively and post-operatively by the senior author. Pre-operative and post-operatively upper extremities were evaluated for sensation using light touch for the axillary, ulnar, radial and median nerves [29]. Sensation for all nerves were meticulously compared side to side and any changes are noted. The muscular examination includes muscles for the axillary, musculocutaneous, median, radial, and ulnar nerves. The muscles tested were rated using the modified Medical Research Council score for motor testing [30]. Medical records were reviewed for demographic information and complications including nerve injury, dislocation, periprosthetic fracture, infection, loosening, and reintervention/revision.

Statistical analysis

Baseline demographic variables, overall complication rate, and the pattern and rate of nerve injury were calculated. Pre-operative, post-operative, and change from pre-operative to post-operative outcome values (ROM, PROMs, and pain)

Fig. 2 Illustration of the neurovascular (NV) structures anterior to the shoulder with exposure of the musculocutaneous (MS) nerve. Nerve exploration begins in the interspace between the conjoint tendon and the lateral border of the pectoralis minor tendon (dashed circle)
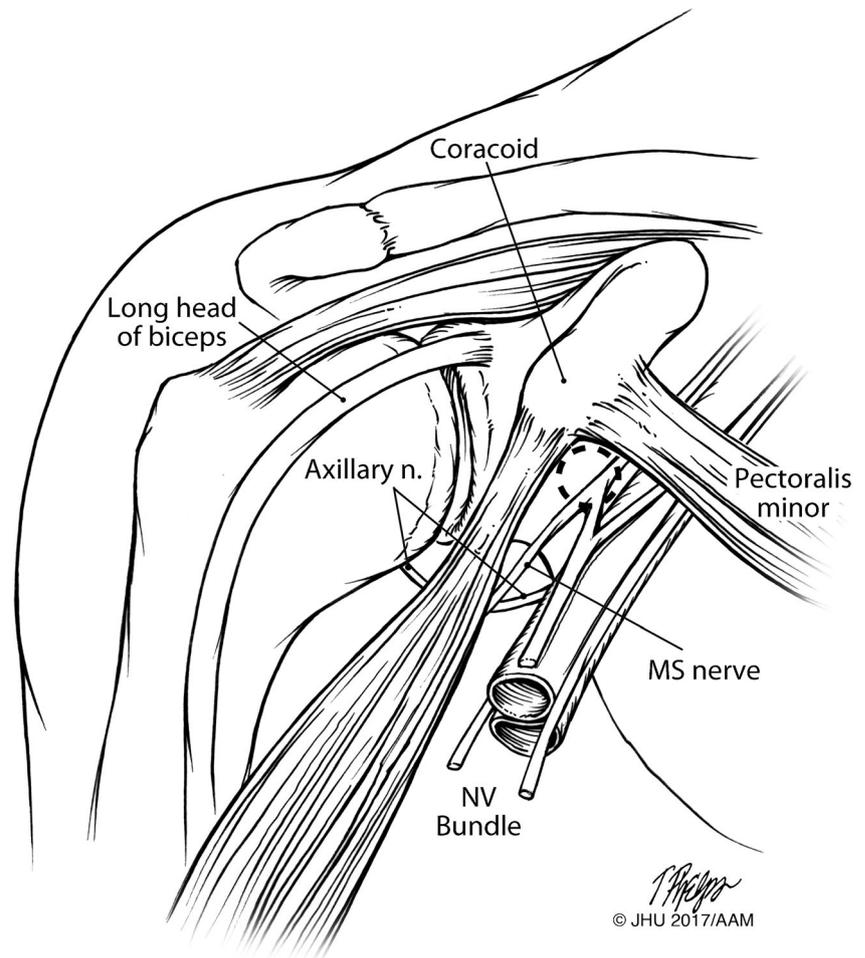
were calculated. Frequency and percentage of complications were calculated. To assess differences in clinical outcomes from pre-operative to post-operative, paired student t tests was used for continuous variables and Wilcoxon signed rank test was used for ordinal variables. Statistical significance was defined as $P < 0.05$. All statistical analyses were performed using Stata version 14 (StataCorp. 2015. Stata Statistical Software: Release 14. College Station, TX: StataCorp LP).

# Results

Clinical outcomes

Outcomes are summarized in Table 1. Pain level and PROMs had a statistically significant improvement after revision RTSA. Mean pre-operative ASES score and SST score significantly improved after revision RTSA. These improvements were above the MCID. Regarding range of motion, patients experienced a statistically and clinically significant improvement in the mean abduction and forward flexion after the procedure. However, the external rotation, internal rotation

at 90° and internal rotation at the back did not change after the procedure.

Complications

There were ten post-operative complications in six patients resulting in a 55% overall complication rate (10 of 18). Re-operation was required in four of these patients. One patient who underwent revision RTSA for failed ORIF sustained four complications (dislocation, periprosthetic fracture, infection, and stem loosening). Dislocation occurred two months after revision and was successfully treated with closed reduction and immobilization. The shoulder remained stable and the patient was satisfied with the result. However, one year later, this patient sustained a periprosthetic humerus fracture associated with stem loosening and infection that required removal of all components and antibiotic spacer placement. Another patient who underwent revision of a dislocated RTSA developed two complications (chronic periprosthetic joint infection and baseplate loosening). This patient had a history of alcohol abuse, cigarette smoking, kidney failure,

Fig. 3 **a** Illustration of extensive scar tissue in the anterior and inferior joint, which was necessary to remove to expose the axillary nerve and allow visualization of the inferior glenoid. The conjoined tendon was released in some cases to achieve adequate exposure. (MS, musculocutaneous; NV, neurovascular). **b** Photograph of the thick scar tissue resected en bloc after nerve exploration
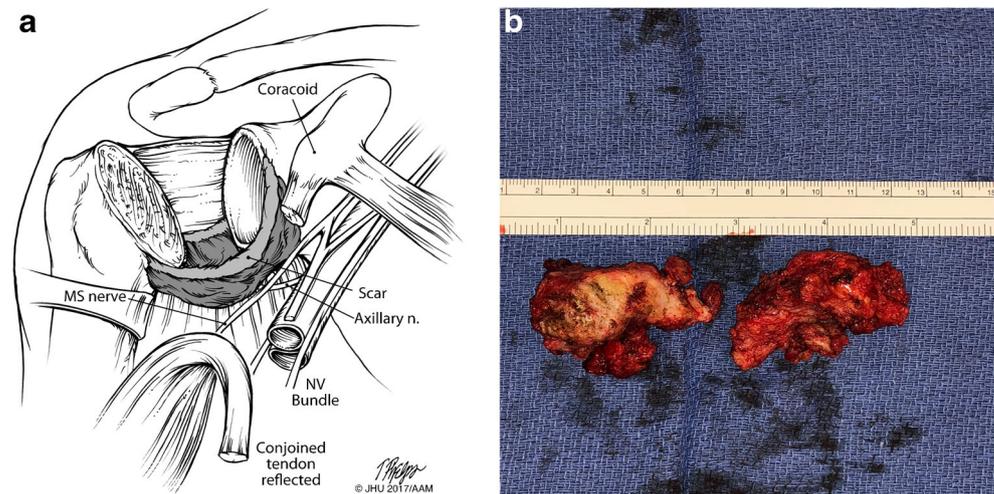
hepatitis C, cirrhosis, diabetes, and hypertension. This patient originally underwent RTSA as part of a two-stage revision for a chronic shoulder infection after multiple rotator cuff repairs. The original RTSA did not require excision of extensive scar tissue. Dislocation occurred two months after revision RTSA and instability recurred after two closed reductions. Therefore, this patient underwent the index revision procedure which included nerve exploration, excision of extensive scar, and replacement of the metaphyseal segment. He had no post-operative instability but developed a recurrent infection with baseplate loosening. The patient's poor health status made him susceptible

to further infections and unable to undergo further revision procedures. To control the infection, all the implants were removed, and the patient was left with a flail shoulder.

Two patients sustained a dislocation that were successfully treated with closed reduction under anaesthesia and immobilization with no new events of instability. Two patients had a post-operative clinically evident nerve injury, for an incidence of 11%. Both cases were neurapraxias without residual clinical sensory or motor changes at last follow-up. The characteristics and clinical course of nerve injuries are summarized in Table 2.

Discussion

We describe a useful technique to expose and protect the axillary and musculocutaneous nerves that facilitates excision of extensive scar tissue in complex revision cases to RTSA under the following specific indications: (1) glenoid extensively covered by scar tissue precluding safe exposure, (2) inability to reduce the trial humeral and glenoid components, and (3) instability of the trial components in adduction and external rotation secondary to inferior soft-tissue impingement.

Our findings indicate that this technique is effective to prevent direct complete injuries of the axillary and musculocutaneous nerves that may result in permanent sequelae when excision of extensive scar tissue is required for any of the indications outlined above. Despite exposing and directly observing the nerves, neurapraxic lesions were not entirely eliminated and it cannot be ruled out that these neurapraxic lesions were secondary to nerve manipulation during surgical dissection. However, the rate and pattern of nerve injuries found with the technique used here were similar to those previously reported in the literature of revision RTSA (0% to 9.5%) [5, 7–9, 14, 31–33]. Therefore, it is likely that neurapraxic lesions found in this study were more a result of indirect traction lesions due to positioning of the arm during
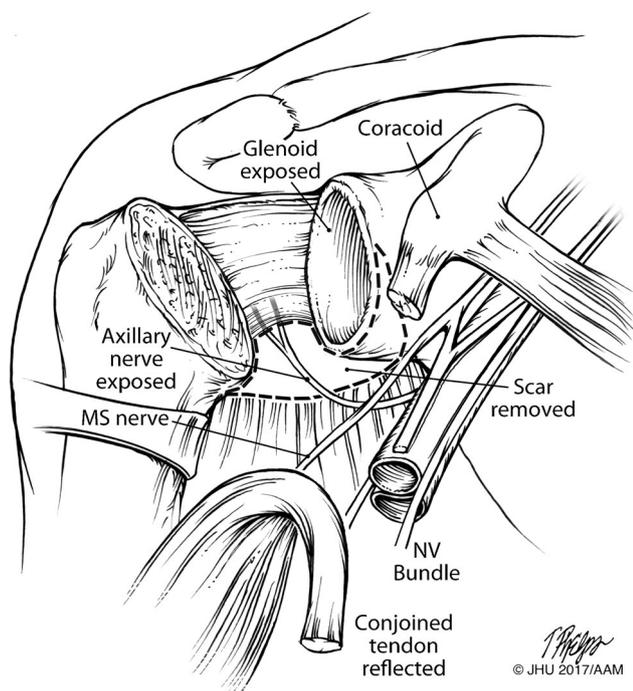

Fig. 4 Illustration of shoulder after scar tissue removal from around the glenoid with exposed axillary nerve to its terminal branches. (MS, musculocutaneous; NV, neurovascular)

Table 1 Comparison of clinical outcomes after revision RTSA with nerve exploration and extensive excision of scar tissue

	ASES	SST	VAS Pain	Abduction	Forward flexion	ER at side	IR at 90°	IR at the back (median level)
Pre-operative	34.7 ± 14.1	1.5 ± 0.8	73 ± 25	43.3 ± 19.7	38.8 ± 22.8	17.7 ± 19.5	23.2 ± 38.4	Lumbosacral junction
Post-operative	55.7 ± 11.9	4.2 ± 2.1	32 ± 16	85.5 ± 21.1	86.9 ± 19.6	16.8 ± 17.2	18.9 ± 34.2	Lumbosacral junction
Average improvement	21 ± 6.02	2.7 ± 2.2	41 ± 29.7	42.2 ± 5.7	48.8 ± 14.61	0.9 ± 25.9	4.3 ± 31.8	NA
P value	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	0.884	0.725	0.258

ASES American Shoulder and Elbow Surgeons score, *SST* Simple Shoulder Test Score, *VAS* Visual Analog Scale, *ER* External rotation, *IR* internal rotation

*Statistically significant value

the procedure [34, 35] or post-operative arm lengthening [36] than of nerve manipulation during surgical dissection.

Post-operative and change from pre-operative to post-operative values in ROM and PROMs of this group of patients were similar with those published in the literature of revision RTSA [2, 4, 7, 12, 13, 37, 38]. This is important because it is possible that extensive scar excision also remove some of the rotator cuff tendons needed for motion and in some cases during the nerve exploration it was necessary to release the conjoint tendon which might affect post-operative forward flexion.

This technique of nerve exploration and extensive excision of scar produced a 55% complication rate with a 22% reintervention rate. These rates are consistent with those reported in the literature ranging from 14% to 62% for complications and from 14% to 57% for reintervention [2, 4, 7, 10, 12, 13, 37, 38]. The post-operative instability rate in this group of patients was 16% (3/18). The three cases of instability were treated successfully with closed reduction and immobilization and could have been caused in part by a lack of soft tissue support after the surgery. Dislocation rates after revision RTSA reported in the literature differ based on the indication for revision, with lower reported rates for revision of failed ORIF (1.9%) [2] or failed TSA (3.8% to 6.6%) [14, 19] and higher rates for revision of failed RTSA (19% to 24%) [12, 37]. The group of patients included in this study had different indications for revision with 50% (9/18) of the patients undergoing revision of failed RTSA.

This study has some limitations that should be considered when interpreting the results. First, the retrospective method of data collection introduces the possibility of missing transient yet clinically significant nerve deficits that may not have been reported by the patient or that may not have been documented by the surgical team in patient records. Second, this group of patients represent a particular group of complex revision cases that required extensive excision of scar tissue (22% of all revision cases in our database) and therefore these results should not be generalized to the broad group of patients undergoing RTSA as a revision procedure. It would be unreasonable to compare this group to patients with primary RTSA or with revisions that did not meet the three criteria used in this study for implantation of RTSA. Similarly, a control group of patients requiring extensive excision of scar where nerve exploration had not been performed was not ethical or feasible. Third, the results reported here reflect those of a surgical team composed by hand surgeons with a high expertise in peripheral nerve surgery and one fellowship-trained shoulder and elbow surgeon who performs a high number of complex revision shoulder procedures yearly. Successful treatment of the soft-tissue challenges during revision arthroplasty depends on the skill of the surgeon in exposing the nerves, especially the axillary and musculocutaneous nerves. It is possible that less extensive dissection might have allowed enough scar tissue to be excised and exposure of the axillary nerve alone may have sufficed. However, visualization of the nerve was impossible

Table 2 Characteristics and clinical course of nerve injuries

Case	Sex	Age, years	Indication for revision RTSA	Type of neurologic deficit	Subjective findings	Objective findings	EMG findings	Months until complete recovery
1	F	65	Failed HA	Sensorimotor	Weakness, numbness	Altered sensation in the distribution of the radial nerve. Weakness in the extensor of the fingers. No ability to flex elbow	Partial brachial plexopathy affecting the lateral and posterior cords	6
2	M	40	Failed ORIF	Sensorimotor	Weakness, numbness	Decreased sensation; weakness for elevation; drop arm sign	Partial axillary nerve neuropathy	4

without extensive dissection, which involved exposing the brachial plexus, specifically the posterior cord. Similarly, shortening the humerus alone may have allowed reduction in some cases, but preservation of the anatomical length of the humerus and the greater tuberosity has been shown to contribute to RTSA stability [39–42]. The decision to use a second surgeon to explore the peripheral nerves and brachial plexus depends on the training, skill, and experience of the primary surgeon and is within the skill set of many orthopaedic surgeons. This study does not suggest that surgeons with special expertise in nerve surgery are routinely necessary for exposure of neurovascular structures during revision shoulder surgery.

Finally, our decision-making approach to perform nerve exploration for extensive excision of scar tissue is dynamic and depends on several factor that are assessed intra-operatively (Fig. 1). Therefore, it is difficult to predict which patients would require this approach before the revision procedure. Given the limited number of patients, we were unable to perform analyses of pre-operative factors that may be associated with the need of nerve exploration for extensive excision of scar tissue.

Conclusion

Complete permanent nerve injuries resulting from direct surgical trauma during revision RTSA requiring extensive excision of scar can be avoided using the technique presented here. Despite proper exposition of the nerves, partial temporary neurapraxic injuries may occur. Patients who underwent this procedure experienced significant improvements in shoulder pain and function with complication rates consistent to those previously reported in revision RTSA.

Compliance with ethical standards

References

1. Parnes N, Rolf RH, Zimmer ZR et al (2008) Management of failed hemiarthroplasty with reverse prosthesis. Tech Shoulder Elb Surg. https://doi.org/10.1097/BTE.0b013e31818d1f66

2. Merolla G, Wagner E, Sperling JW et al (2018) Revision of failed shoulder hemiarthroplasty to reverse total arthroplasty: analysis of 157 revision implants. J Shoulder Elb Surg 27:75–81. https://doi.org/10.1016/j.jse.2017.06.038

3. Randelli P, Randelli F, Compagnoni R et al (2015) Revision reverse shoulder arthroplasty in failed shoulder arthroplasties for rotator cuff deficiency. Joints 3:31–37. https://doi.org/10.11138/jts/2015.3.1.031

4. Levy JC, Virani N, Pupello D, Frankle M (2007) Use of the reverse shoulder prosthesis for the treatment of failed hemiarthroplasty in patients with glenohumeral arthritis and rotator cuff deficiency. J Bone Jt Surg Br 89–B:189–195. https://doi.org/10.1302/0301-620X.89B2.18161

5. Walker M, Willis MP, Brooks JP et al (2012) The use of the reverse shoulder arthroplasty for treatment of failed total shoulder arthroplasty. J Shoulder Elb Surg 21:514–522. https://doi.org/10.1016/j.jse.2011.03.006

6. Werner BS, Abdelkawi AF, Boehm D et al (2017) Long-term analysis of revision reverse shoulder arthroplasty using cemented long stems. J Shoulder Elb Surg 26:273–278. https://doi.org/10.1016/j.jse.2016.05.015

7. Flury MP, Frey P, Goldhahn J et al (2011) Reverse shoulder arthroplasty as a salvage procedure for failed conventional shoulder replacement due to cuff failure—midterm results. Int Orthop 35:53–60. https://doi.org/10.1007/s00264-010-0990-z

8. Melis B, Bonnevialle N, Neyton L et al (2012) Glenoid loosening and failure in anatomical total shoulder arthroplasty: is revision with a reverse shoulder arthroplasty a reliable option? J Shoulder Elb Surg 21:342–349. https://doi.org/10.1016/j.jse.2011.05.021

9. Ortmaier R, Resch H, Matis N et al (2013) Reverse shoulder arthroplasty in revision of failed shoulder arthroplasty-outcome and follow-up. Int Orthop 37:67–75. https://doi.org/10.1007/s00264-012-1742-z

10. Shields EJ, Wiater JM (2018) Patient outcomes after revision of anatomic total shoulder arthroplasty to reverse shoulder arthroplasty for rotator cuff failure or component loosening: a matched cohort study. J Am Acad Orthop Surg submitted:1–6. https://doi.org/10.5435/JAAOS-D-17-00350

11. Chacon A, Virani N, Shannon R et al (2009) Revision arthroplasty with use of a reverse shoulder prosthesis-allograft composite. J Bone Jt Surg - Ser A 91:119–127. https://doi.org/10.2106/JBJS.H.00094

12. Black EM, Roberts SM, Siegel E et al (2015) Failure after reverse total shoulder arthroplasty: what is the success of component revision? J Shoulder Elb Surg 24:1908–1914. https://doi.org/10.1016/j.jse.2015.05.029

13. Werner BS, Boehm D, Gohlke F (2013) Revision to reverse shoulder arthroplasty with retention of the humeral component. Acta Orthop 84:473–478. https://doi.org/10.3109/17453674.2013.842433

14. Valenti P, Kilinc AS, Sauzieres P et al (2014) Results of 30 reverse shoulder prostheses for revision of failed hemi- or total shoulder arthroplasty. Eur J Orthop Surg Traumatol 24:1375–1382. https://doi.org/10.1007/s00590-013-1332-9

15. Garver J, Mata-Fink A, Zhu D et al (2017) Revision strategies in reverse total shoulder arthroplasty. J Shoulder Elb Arthroplast 1:247154921769525. https://doi.org/10.1177/2471549217695259

16. Grubhofer F, Wieser K, Meyer DC et al (2017) Reverse total shoulder arthroplasty for failed open reduction and internal fixation of fractures of the proximal humerus. J Shoulder Elb Surg 26:92–100. https://doi.org/10.1016/j.jse.2016.05.020

17. Maier MW, Zeifang F, Caspers M et al (2015) Can reverse shoulder arthroplasty in post-traumatic revision surgery restore the ability to perform activities of daily living? Orthop Traumatol Surg Res 101:191–196. https://doi.org/10.1016/j.otsr.2014.12.007

18. García-Fernández C, Lopiz Y, Rizo B et al (2018) Reverse total shoulder arhroplasty for the treatment of failed fixation in proximal

humeral fractures. Injury 49:S22–S26. https://doi.org/10.1016/j.injury.2018.06.042

19. Saltzman BM, Chalmers PN, Gupta AK et al (2014) Complication rates comparing primary with revision reverse total shoulder arthroplasty. J Shoulder Elb Surg 23:1647–1654. https://doi.org/10.1016/j.jse.2014.04.015

20. Wall B, Nove-Josserand L, O'Connor DP et al (2007) Reverse total shoulder arthroplasty: a review of results according to etiology. J Bone Joint Surg Am 89:1476–1485. https://doi.org/10.2106/JBJS.F.00666

21. Rittmeister M, Kerschbaumer F (2001) Grammont reverse total shoulder arthroplasty in patients with rheumatoid arthritis and nonreconstructible rotator cuff lesions. J Shoulder Elb Surg 10:17–22. https://doi.org/10.1067/mse.2001.110515

22. Chae J, Siljander M, Wiater JM (2018) Instability in reverse total shoulder arthroplasty. J Am Acad Orthop Surg 26:587–596. https://doi.org/10.5435/JAAOS-D-16-00408

23. Chalmers PN, Rahman Z, Romeo AA, Nicholson GP (2014) Early dislocation after reverse total shoulder arthroplasty. J Shoulder Elb Surg 23:737–744. https://doi.org/10.1016/j.jse.2013.08.015

24. Kelly JD, Zhao JX, Hobgood ER, Norris TR (2012) Clinical results of revision shoulder arthroplasty using the reverse prosthesis. J Shoulder Elb Surg 21:1516–1525. https://doi.org/10.1016/j.jse.2011.11.021

25. Werner BS, Chaoui J, Walch G (2017) The influence of humeral neck shaft angle and glenoid lateralization on range of motion in reverse shoulder arthroplasty. J Shoulder Elb Surg 26:1726–1731. https://doi.org/10.1016/j.jse.2017.03.032

26. Huri G, Familiari F, Salari N et al (2016) Prosthetic design of reverse shoulder arthroplasty contributes to scapular notching and instability. World J Orthop 7:738–745. https://doi.org/10.5312/wjo.v7.i11.738

27. Maldonado AA, Spinner RJ, Bishop AT et al (2016) Effectiveness of the extended surgical approach to visualize the axillary nerve in the blind zone in an arthroscopic axillary nerve injury model. J Plast Reconstr Aesthetic Surg 69:1697–1703. https://doi.org/10.1016/j.bjps.2016.09.016

28. Flatow EL, Bigliani LU (1992) Tips of the trade. Locating and protecting the axillary nerve in shoulder surgery: the tug test. Orthop Rev 21:503–505

29. Tan EW, Ting BL, Jia X et al (2013) Diagnostic errors in orthopedic surgery. Am J Med Qual 28:60–68. https://doi.org/10.1177/1062860612447856

30. Medical Research Council (1981) Aids to the examination of the peripheral nervous system, Memorandum no. 45, Her Majesty's Stationery Office. London

31. Patel DN, Young B, Onyekwelu I et al (2012) Reverse total shoulder arthroplasty for failed shoulder arthroplasty. J Shoulder Elb Surg 21:1478–1483. https://doi.org/10.1016/j.jse.2011.11.004

32. Boileau P, Melis B, Duperron D et al (2013) Revision surgery of reverse shoulder arthroplasty. J Shoulder Elb Surg 22:1359–1370. https://doi.org/10.1016/j.jse.2013.02.004

33. Holcomb JO, Cuff D, Petersen SA et al (2009) Revision reverse shoulder arthroplasty for glenoid baseplate failure after primary reverse shoulder arthroplasty. J Shoulder Elb Surg 18:717–723. https://doi.org/10.1016/j.jse.2008.11.017

34. Kam AW, Lam PH, Murrell GAC (2014) Brachial plexus injuries during shoulder arthroplasty: what causes them and how to prevent them. Tech Shoulder Elb Surg 15:109–114. https://doi.org/10.1097/BTE.0000000000000030

35. Van Hoof T, Gomes GT, Audenaert E et al (2008) 3D computerized model for measuring strain and displacement of the brachial plexus following placement of reverse shoulder prosthesis. Anat Rec (Hoboken) 291:1173–1185. https://doi.org/10.1002/ar.20735

36. Lädermann A, Lübbeke A, Mélis B et al (2011) Prevalence of neurologic lesions after total shoulder arthroplasty. J Bone Jt Surg - Ser A 93:1288–1293. https://doi.org/10.2106/JBJS.J.00369

37. Farshad M, Grögli M, Catanzaro S, Gerber C (2012) Revision of reversed total shoulder arthroplasty. Indications and outcome. BMC Musculoskelet Disord 13. https://doi.org/10.1186/1471-2474-13-160

38. Black EM, Roberts SM, Siegel E et al (2014) Reverse shoulder arthroplasty as salvage for failed prior arthroplasty in patients 65 years of age or younger. J Shoulder Elb Surg 23:1036–1042. https://doi.org/10.1016/j.jse.2014.02.019

39. Sperling JW, Cofield RH (2005) Humeral windows in revision shoulder arthroplasty. J Shoulder Elb Surg 14:258–263. https://doi.org/10.1016/j.jse.2004.09.004

40. Johnston PS, Creighton RA, Romeo AA et al (2012) Humeral component revision arthroplasty: outcomes of a split osteotomy technique. J Shoulder Elb Surg 21:502–506. https://doi.org/10.1016/j.jse.2011.02.001

41. Gohlke F, Rolf O (2007) [Revision of failed fracture hemiarthroplasties to reverse total shoulder prosthesis through the transhumeral approach: method incorporating a pectoralis-major-pedicled bone window]. Oper Orthop Traumatol 19:185–208. https://doi.org/10.1007/s00064-007-1202-x

42. Budge MD, Moravek JE, Zimel MN et al (2013) Reverse total shoulder arthroplasty for the management of failed shoulder arthroplasty with proximal humeral bone loss: is allograft augmentation necessary? J Shoulder Elb Surg 22:739–744. https://doi.org/10.1016/j.jse.2012.08.008