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Intraoperative neuromonitoring during reverse shoulder arthroplasty

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Background: The aim of this study was to evaluate the risk of nerve injury with neuromonitoring during reverse total shoulder arthroplasty.

Materials: This study included 15 shoulders of 15 patients (11 females and 4 males) who underwent reverse total shoulder arthroplasty. The mean age was 74.8 ± 4.4 years. Nine shoulders had cuff tear arthropathy, 4 had massive rotator cuff tears, 2 had osteoarthritis, and 1 had rheumatoid arthritis. The somatosensory evoked potentials of the median nerve, transcranial motor evoked potentials, and free-electromyograms from 6 upper-extremity muscles were measured intraoperatively. We defined a nerve alert as 50% amplitude attenuation or 10% latency prolongation of the somatosensory evoked potentials and transcranial motor evoked potentials and sustained neurotonic discharge on free-electromyogram.

Results: Thirty-one alerts were recorded in 11 patients. The axillary nerve was associated with 17 alerts. Eleven alerts occurred during the glenoid procedure and 5 alerts occurred during the humeral procedure. One patient who did not recover from the alert of the axillary nerve had clinically incomplete paralysis of the deltoid muscle.

Conclusion: The present findings suggest that the axillary nerve was the nerve most frequently exposed to the risk of injury, especially during glenoid and humeral implantation.

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

Keywords: Intraoperative neuromonitoring; reverse shoulder arthroplasty; nerve injury

This study was approved by the Institutional Review Board of Gunma University Hospital (14-51).

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Reverse total shoulder arthroplasty (RSA) has been practiced as an effective surgery for massive rotator cuff tears and rotator cuff dysfunction for cases in which results were insufficient with anatomical total shoulder arthroplasty (TSA).[10] One of the main complications of RSA is nerve injury, with a frequency of 0.5% to 4%.[2,5,10,30] Some studies reported that RSA carries a higher risk of nerve injury than TSA.[15,25]

To avoid nerve injuries during orthopedic surgeries, neuromonitoring has been used intraoperatively in shoulder surgery, including TSA,[24] the Latarjet procedure for instability,[8] fracture fixation,[28] and arthroscopy.[9] Only 1 intraoperative neuromonitoring study[25] for RSA has compared the incidence and patterns of intraoperative nerve alerts between anatomic TSA and RSA, with results showing that RSA has a higher incidence of intraoperative nerve alerts than TSA during the postreduction stage due to arm lengthening. In the study,[25] each procedure was divided into 4 stages (surgical approach, humeral preparation, glenoid preparation, and postreduction), which are common procedures between TSA and RSA. That study set the threshold of nerve alerts at 80% amplitude attenuation although previous intraoperative neuromonitoring studies for shoulder surgeries, such as TSA,[24] the Latarjet procedure for instability,[8] and fracture fixation,[28] applied a threshold of 50% amplitude attenuation. Which stage of the RSA procedure carries the highest risk of nerve injury and which procedures should be performed most carefully to avoid nerve injuries remain unclear.

To clarify the nerve injury risks for each nerve as well as in each stage during Grammont-design RSA using an appropriate threshold of intraoperative neuromonitoring, we evaluated the nerve injury risks using a threshold of 50% amplitude attenuation with the RSA procedure divided into 6 stages: (1) approach, (2) dislocation, (3) glenoid exposure and implantation, (4) humeral implantation, (5) reduction, and (6) skin closure.

Materials and methods

Subjects

All patients provided their informed consent before participation. Intraoperative neuromonitoring was conducted on 15 shoulders of 15 patients who had undergone RSA at a single institution between January 2015 and March 2016.

Inclusion and exclusion criteria

The inclusion and exclusion criteria were defined on the basis of the previous study.[25] No patients were excluded. For enrollment in the study, all patients had to have (1) undergone an RSA procedure and (2) been evaluated at a postoperative clinical neurologic examination by the attending surgeon in the postanesthesia care unit immediately after surgery. All patients were included, regardless of the comorbid profile, history of rheumatoid arthritis (RA), cervical spine disease, previous rotator cuff surgery, fracture sequelae, previous failed arthroplasty, and current or prior prescription of steroids.

Surgical procedures

All RSAs were performed in the beach chair position through a deltopectoral approach and a subscapularis tenotomy by a senior orthopedic surgeon (A.Y.) with more than 14 years' experience performing shoulder surgery. An Aequalis Reversed II (Tornier Inc., Bloomington, MN, USA) was used for all RSAs. The humeral cut was made at the anatomic neck as outlined in the original version, with additional reaming of the metaphysis included for the placement of the inlaid humeral prosthesis, which has a 155° neck angle. The glenosphere baseplate was placed as low as possible on the glenoid with slight (approximately 10°) inferior inclination. The diameter of the glenosphere was 36 mm in all patients. Trial reduction was used to determine the optimum tension of the prosthesis. The size of the implant spacer was selected by confirming the moderate gap by pulling the upper limb, and the excessive tension was not exerted on the conjoined tendon and brachial plexus. After prosthesis placement and reduction, the subscapularis was repaired.

Intraoperative neuromonitoring

The RSA procedure was divided into 6 stages as mentioned above: (1) approach, (2) dislocation, (3) glenoid exposure and implantation, (4) humeral implantation, (5) reduction, and (6) skin closure (Fig. 1, *a-c*).

Intraoperative neuromonitoring was performed according to previous studies.[8,24,28] The neuromaster MEE-1200 (Nihon Kohden, Tokyo, Japan) was used for monitoring in this study. After patients' positioning, the stimulating and recording leads were set on the head and both upper limbs. The parameters used for the neuromonitoring were somatosensory evoked potentials (SSEPs), transcranial motor evoked potentials (TcMEPs), and free electromyogram (free-EMG). The median nerves of bilateral sides were monitored for SSEPs. Considering the innervation patterns according to Kendall and McCreary,[13] TcMEPs and free-EMG were recorded from 6 bilateral upper-extremity muscles: the deltoid (DEL), biceps brachii (BB), extensor carpi radialis longus (ECRL), triceps brachii (TB), abductor pollicis brevis (APB), and abductor digiti minimi (ADM) (Fig. 2, Table I). The controls of SSEPs and TcMEPs were measured more than 30 minutes after anesthetic induction, before incision. If the attenuation of parameters on the healthy side appeared because of anesthetic depth progression intraoperatively, the stimulating strength was increased within the safe stimulating range of SSEPs (10-20 mA) and TcMEPs (100-200 mA).

To prevent false-negative alerts of neuromonitoring, based on previous studies for TSA,[24] the Latarjet procedure for instability,[8] and fracture fixation,[28] a significant nerve alert was defined as 50% attenuation and 10% prolongation of latency in SSEPs and TcMEPs or sustained neurotonic discharge on free-EMG. Of note, this was a lower threshold than was used in a previous neuromonitoring study for TSA and RSA.[25] When an alert occurred, the monitoring parameters were re-examined immediately. If the alert occurred reproducibly, we recorded it

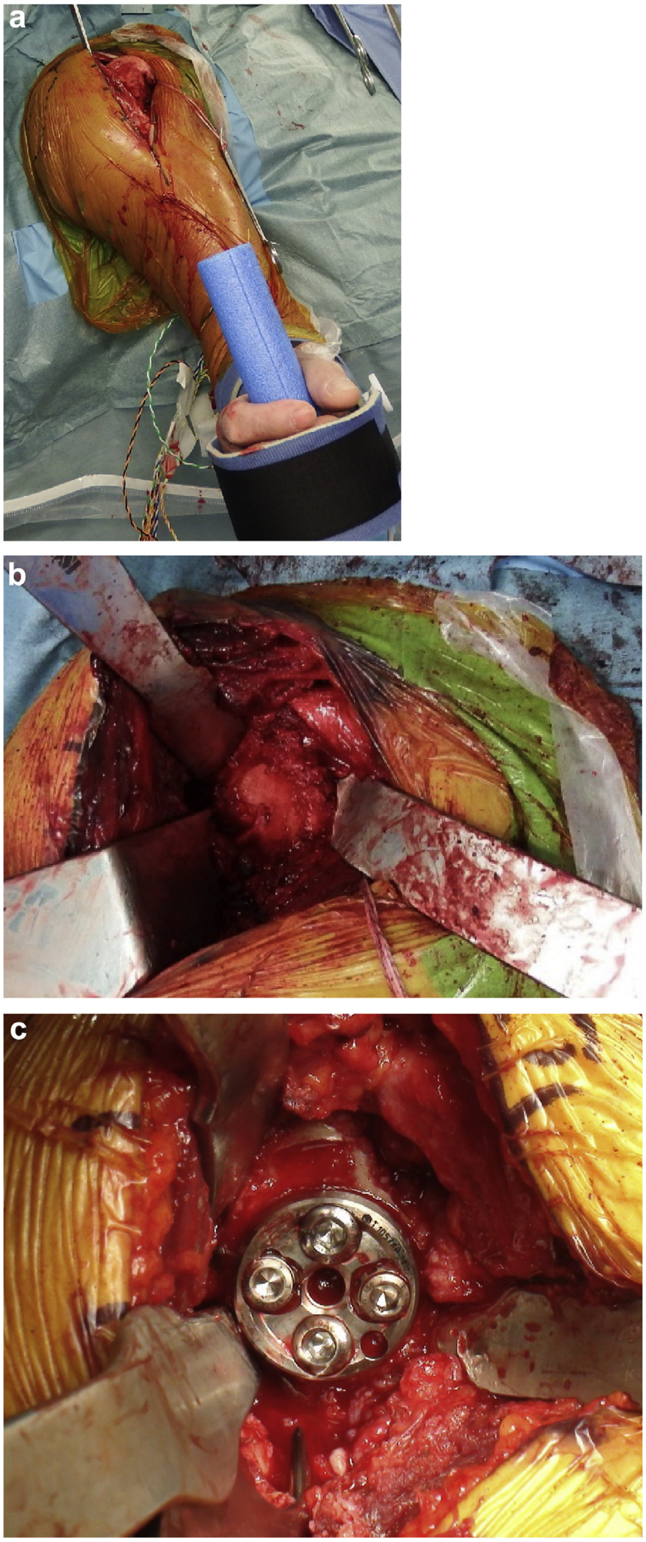

Figure 1 Procedures during the operation. (**a**) The dislocation stage. The arm position involved shoulder external rotation and extension. (**b**) Glenoid exposure during the stage of glenoid implantation. (**c**) The baseplate was set during the stage of glenoid implantation.

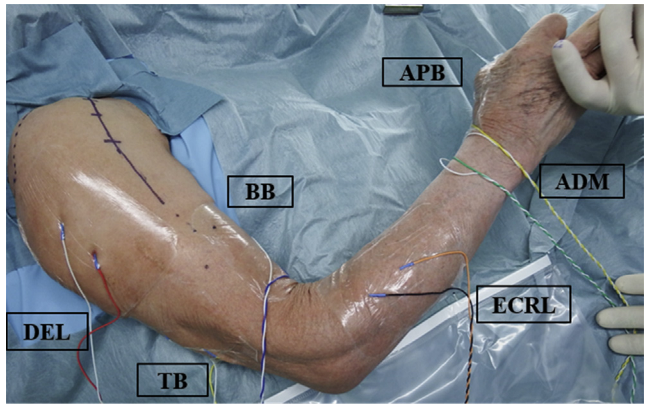

Figure 2 Recording from 6 upper-extremity muscles on TcMEPs and free-EMG. *TcMEP*, transcranial motor evoked potentials; *EMG*, electromyography; *DEL*, deltoid; *BB*, biceps brachii; *ECRL*, extensor carpi radialis longus; *TB*, triceps brachii; *APB*, abductor pollicis brevis; *ADM*, abductor digiti minimi.

as a nerve alert. The retractors were then first removed. If the alert continued, the upper limbs were returned to the neutral position to relieve the tension exerted on the nerves. If the alert went unresolved for 5 minutes after repositioning of the arm, we investigated whether or not the nerve was directly injured by removing the implants. Even if the alert persisted, the surgery progressed to the next procedure after confirming no direct injury of the nerve. The alerts were recorded by an orthopedic surgeon (S.S.) who had been well trained by a neurologist. The procedure, position of the operative arm, and whether or not the nerve alert was resolved were also recorded.

Counting nerve alerts

Attenuation recorded as a nerve alert was counted as 1 when the alert persisted and did not improve despite carefully checking nerve injury as described below. Nerve alerts were counted in each nerve and at each stage of the RSA procedure. If the alert persisted at the nerve and did not improve within the threshold despite confirmation of no direct injury of the nerve, the nerve alert was counted as 1 for that stage of the RSA procedure only; we did not count it for the next stage because the nerve alert had occurred at the previous stage.

To investigate the risk of the nerve injury at each stage, a combined nerve alert was counted as 1 alert at a stage, even if the alert came from more than 1 nerve. On the other hand, to investigate the risk of nerve injury in each nerve during the entire operation, a combined nerve alert was separately counted as 1 alert in each nerve. For example, if a combined alert comprised 2 nerve alerts—for an axillary and a radial nerve—we counted it as 2 nerve alerts (an axillary and a radial nerve alert).

Anesthesia during and after RSA

Total intravenous anesthesia was administered by giving propofol and remifentanil continuously. A muscle relaxant (rocuronium)

Table I Pattern of brachial plexus and peripheral nerve monitoring[13]

Region assessed	C5 and C6	C5 and C6	C5, C6, C7, C8	C6, C7, C8, T1	C6, C7, C8, T1	C8 and T1
Trunk	Upper	Upper	Upper and middle	Middle and lower	Upper, middle, and lower	Lower
Cord	Posterior	Lateral	Posterior	Posterior	Lateral and medial	Medial
Nerve	Axillary	Musculocutaneous	Radial	Radial	Median	Ulnar
Muscle	Deltoid	Biceps brachii	ECRL	Triceps brachii	APB	ADM

ECRL, extensor carpi radialis longus; *APB*, abductor policis brevis; *ADM*, abductor digiti minimi.

was used only when anesthesia was introduced. To confirm whether or not muscle relaxation remained, we checked the train-of-four electrical stimulation of the ulnar nerve on the healthy side. If the effect of the muscle relaxant persistent, an antagonistic drug (sugammadex) was administered. The operation was started after confirming that no muscle relaxation effect remained. The tube of the continuous brachial plexus block was placed using saline through the interscalene with an ultrasound system before the introduction of anesthesia. After the operation, the continuous administration of local anesthetic (popschine) was started. It was removed 2 days after the operation.

The postoperative neurological examination

The patients were examined for the contraction of the muscles in question as early as possible postoperatively. Dysesthesia was checked when the effect of the brachial plexus block had disappeared. If the patient had a neurologic deficit, we carefully observed the patients and investigated the relationship between the intraoperative alerts and the duration until the recovery of nerve injury.

Statistical analyses

The Mann-Whitney *U* test, χ^2 test, and Fisher's exact test were used for comparisons between the demographic data of 2 groups with and without the nerve alert. To determine the difference in the body mass index (BMI) between the subjects in the previous study and those in the present study, a 1-sample *t*-test was used to evaluate the null hypothesis of the mean BMI in the previous study[5] ($H_0 = 29.8$). To determine the nerve injury risks for each nerve and at each stage compared with risk zero, a 1-sample *t*-test was performed to evaluate the null hypothesis of no risk during surgery (H_0: number of alerts is 0). Then, to determine the presence of any differences among nerves or stages, a 1-way repeated measures analysis of variance and Tukey's multiple comparison test as a post hoc analysis were performed. To identify the interaction of nerve injury risks between nerves and procedure stages, the distribution was analyzed with a χ^2 test. To determine the difference in the total number of nerve alerts per surgery between the previous study[5] and present study, a sample *t*-test was used to evaluate the null hypothesis of the mean total number of nerve alerts per surgery in the previous study[5] ($H_0 = 8.1$). SPSS version 25 (IBM, Armonk, NY, USA) was used for all statistical analyses, and a value of $P < .05$ was considered statistically significant.

Results

This study evaluated 15 shoulders, including 9 cuff tear arthropathys (CTAs), 3 massive rotator cuff tears (with 1 osteonecrosis), 2 with osteoarthritis, and 1 with RA. No patients underwent RSA for fracture sequelae, previous failed cuff surgery or arthroplasty. There were 11 females and 4 males. There were 3 patients with diabetes, 4 smokers, and 3 alcohol drinkers. The mean age, height, and weight were 74.8 ± 4.4 years, 149.3 ± 6.2 cm, and 56.1 ± 8.8 kg, respectively. One patient has taken steroids because of RA. Nerve alerts occurred in 11 of the 15 shoulders (73.3%). Between patients with and without nerve alerts, there were no significant differences in the demographic data, diagnoses, preoperative active and under anesthesia range of motion, constant score, and total operation time (Table II).

BMI

In the present study, the mean BMI was 25.2 ± 2.9 kg/m^2. There were no significant differences in the BMI between patients with and without nerve alerts. The 1-sample *t*-test showed that the BMI in the present study was significantly smaller than in the previous study[18] ($P < .0001$).

Nerve alerts

Twenty nerve alerts were recorded in 11 shoulders. Eighteen alerts were related to TcMEPs, and the other 2 were based on sustained neurotonic free-EMG activity. Eight alerts were combined alerts involving multiple nerves. Dividing the 8 combined alerts into alerts for each nerve resulted in a total of 19 individual-nerve alerts. The total number of alerts by nerve was 31. The mean value of 29 TcMEP alerts was 30% ± 15% (range, 3%-50%). The distribution of those values was as follows: 5 alerts in 0% to 5%, 1 in 11% to 20%, 6 in 21% to 30%, 7 in 31% to 40%, 9 in 41% to 50%.

Twenty-nine of 31 nerve alerts recovered to the same stage as when it occurred. One nerve alert recovered after removing the retractors, 26 recovered after the arm placed

Table II A comparison between the shoulders with and without nerve alerts

	With alerts (11 shoulders)	Without alerts (4 shoulders)	P value
Sex (male/female) (n)	4/7	0/4	.516
Diagnosis (n) (CTA/MRCT/OA/RA)	8/2/1/0	1/1/1/1	.213
Age (yr)	73.5 ± 4.0	78.5 ± 4.5	.077
Body mass index (kg/m^2)	24.6 ± 3.0	26.6 ± 3.1	.361
Diabetes mellitus (n)	2	1	1.000
Smoking (n)	4	0	.516
Alcohol drinking (n)	3	0	.516
Steroid treatment (n)	0	1	.333
Range of shoulder motion			
Preoperative			
Active flexion (°)	45 ± 18	51 ± 25	.692
Active abduction (°)	48 ± 18	50 ± 14	.894
Active external rotation (°)	8 ± 14	6 ± 33	.597
Under anesthesia			
Flexion (°)	139 ± 20	143 ± 12	.743
Abduction (°)	128 ± 35	130 ± 25	.895
External rotation (°)	58 ± 24	40 ± 28	.168
Constant score	23.3 ± 5.8	20.1 ± 9.0	.768
Operation time (min)	153 ± 35	136 ± 15	.859

CTA, cuff tear arthropathy; *MRCT*, massive rotator cuff tear; *OA*, osteoarthritis; *RA*, rheumatoid arthritis.

in neutral position, and 2 recovered spontaneously regardless of retractors and arm position. The remaining 2 alerts involving the axillary nerve were unresolved, and their values were 6% and 48% at the end of the operation. In the former case, we temporarily removed the glenosphere implant for a sustained nerve alert. We will explain this approach in detail later.

Alerts in each nerve

Seventeen of 31 alerts involved the axillary nerve, 7 involved the radial nerve, 4 involved the musculocutaneous nerve, 2 involved the median nerve, and 1 involved the ulnar nerve. The mean numbers of alerts in each nerve per stage are shown in Table III. The 1-sample *t*-test showed that the axillary nerve (P = .001) and radial nerve (P = 0.014) carried significantly higher risks of alert than zero risk. Furthermore, the axillary nerve had a significantly higher risk than the musculocutaneous nerve (P = .008), the median nerve (P = .001), and the ulnar nerve ($P < .001$) (Fig. 3, *a*).

Table III The mean numbers of alerts in each nerve

Number of alerts in each nerve		P value
Axillary	1.1 ± 0.3	.001*
Radial	0.5 ± 0.2	.014*
Musculocutaneous	0.3 ± 0.2	.104
Median	0.1 ± 0.1	.334
Ulnar	0.1 ± 0.1	.334

Data are presented as mean ± SEM. The axillary nerve (P = .001) and radial nerve (P = .014) carried significantly higher risks of alert than zero risk.
* $P < .05$.

Alerts in each stage of the surgical procedure

All nerve alerts were recorded at the stages from dislocation to reduction. There were 20 nerve alerts during 15 RSA procedure stages, and the mean of total alerts per surgery was 1.3 ± 1.0. There were 11 alerts during the glenoid procedure, 5 during the humeral procedure, 3 during dislocation, and 1 during reduction. The glenoid (P = .003) and humeral (P = .027) procedures had significantly higher risks of alert than zero risk (Table IV).

The mean number of alerts during the glenoid procedure was significantly higher than during exposure (P = .003), reduction (P = .006), and skin closure (P = .003) (Fig. 3, *b*). The 1-sample *t*-test showed that the total number of alerts per stage in the present study was significantly smaller than in the previous study[5] ($P < .0001$).

Interaction of nerve injury risks between nerves and procedures

To determine the interaction of nerve injury risks between the nerves and procedures, the distribution of each nerve and procedure was analyzed using a χ^2 test. There was no interaction of nerve injury between the nerves and procedures (P = .862).

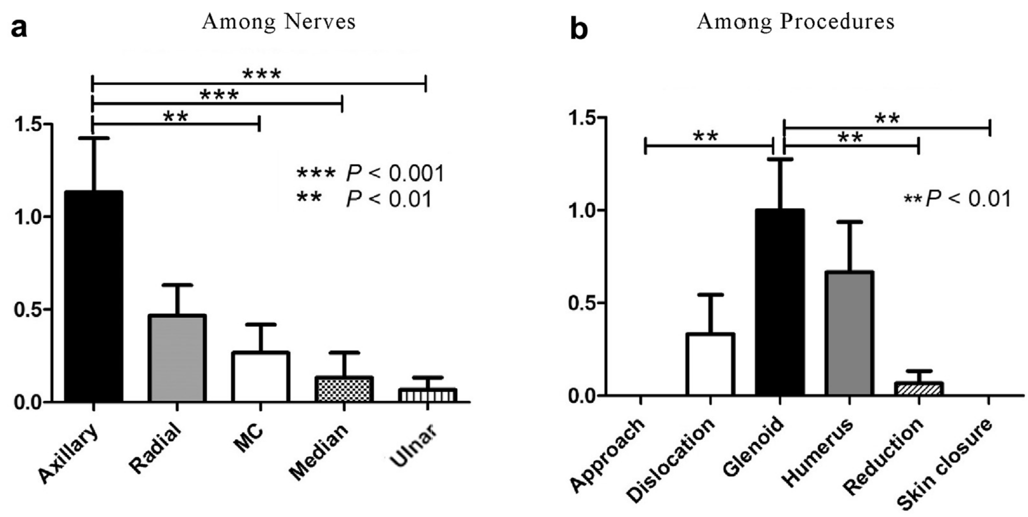

Figure 3 The mean numbers of nerve alerts per surgery by the nerve and stage. A 1-way analysis of variance and Tukey's multiple comparison test as a post hoc analysis were used for the comparisons among the nerves and stages. (**a**) Mean numbers of alerts for each nerve. The axillary nerve had a significantly higher risk than other nerves (musculocutaneous nerve [MC] nerve: $P = .008$, median nerve: $P = .001$, ulnar nerve: $P < .001$) except for the radial nerve ($P = .071$). (**b**) Mean numbers of alerts for each stage. The mean number of alerts during the glenoid procedure was significantly higher than during the exposure ($P = .003$), reduction ($P = .006$), and skin closure ($P = .003$). The differences between the glenoid procedure and the other procedures were not statistically significant (the dislocation: $P = .110$, the humeral procedure: $P = .786$).

The postoperative evaluation

Postoperatively, a clinical neurological disorder was found in 2 patients. One patient was a 71-year-old woman with CTA who had suffered from cervical canal stenosis (C3/4–5/6) before surgery. The axillary nerve alert was recorded on TcMEP as 4% of the control amplitude after placing the baseplate on the glenoid. The alert did not resolve even when the retractors were removed, and the upper limbs were returned to a neutral position. Although the implant was removed, no direct axillary nerve injury was observed, and the surgery was resumed with caution. The alert was unresolved during the surgery (final TcMEPs: 6%), and postoperatively, she had partial deltoid muscle paralysis. We believe that there may have been some involvement of cervical canal stenosis. Another patient was a 75-year-old woman with CTA. The nerve alert (TcMEPs: 41% in the glenoid procedure) involved the axillary nerve and was resolved after returning the arm to a neutral position. However, she reported feeling mild numbness in the median nerve area of the thumb postoperatively. This numbness recovered by 2 weeks after surgery. The brachial plexus block may have caused the symptom.

There were no clinical neurological disorders in any of the 4 patients without intraoperative nerve alerts. No other complications or neurological monitoring complications were observed intraoperatively or postoperatively.

Table IV The mean numbers of alerts at each stage per stage

Number of alerts in each stage		*P* value
Exposure	0.0 ± 0.0	–
Dislocation	0.3 ± 0.2	.136
Glenoid	1.0 ± 0.3	.003*
Humerus	0.7 ± 0.3	.027*
Reduction	0.1 ± 0.1	.334
Skin closure	0.0 ± 0.0	–

Data are presented as mean ± SEM. The glenoid ($P = .003$) and humeral ($P = .027$) procedures had significantly higher risks of alert than zero risk.

* $P < .05$.

Discussion

The most important finding of the present study is that the axillary nerve and glenoid procedure carry the highest risks of nerve injury during RSA.

Postoperative neurological disorders in shoulder surgery

Postoperative neurological disorders in shoulder surgery are reportedly caused not only by direct nerve injury but also by pressure exerted on the nerve with retractors and hematoma, vascular injury, humeral shaft fractures, cement extrusion, and interscalene block.[7,24,27] Postoperative nerve disorder occurs in 1% to 4% of the cases[4,22] and 3.1% of cases of reconstruction for anterior instability.[11] However, in studies conducted with intraoperative neuromonitoring in shoulder surgery,[8,24] 56.7% to 76.5% of patients triggered an electrophysiological alert, which is considered to indicate a risk of nerve injury. In addition, it has also been reported that 16.7% showed abnormalities based on EMG after TSA.[24] If potential neurological disorders not detected as clinical issues are taken into account, then intraoperative neurological injuries during shoulder surgery may occur at a very high rate. The rate of postoperative neurological disorder is reported to range from 0.5% to 4% in RSA.[2,5,10,30] In the present study, 73.3% of the patients triggered nerve alerts, although only 1 (0.7%) clinical neurological disorder was deemed potentially related to this intraoperative alert. The findings from a study with intraoperative neuromonitoring for RSA and TSA suggest that RSA carries an approximately 5 times greater risk of postoperative neurological disorder than TSA.[25]

Preoperative risk factors of neurological disorders on RSA

Parisien et al[25] reported that the number of nerve alerts was significantly correlated with preoperative forward flexion limitation and that the preoperative diagnosis was rotator cuff arthropathy. Lopiz et al[21] showed that there were no significant differences in preoperative range of motion (ROM) and constant score between patients with and without neurologic lesions. In the present study, no predictive factors for nerve alerts were detected among the demographic data, the range of motion, constant score, or operation time similar to the latter. However, 1 patient who suffered from cervical canal stenosis had incomplete paralysis of the axillary nerve postoperatively. The fragility of the nervous system, such as in cases of cervical radiculopathy, might be a risk factor.

The BMI and the total number of nerve alerts per surgery

No intraoperative neuromonitoring study for RSA has been performed before in an Asian population, who are expected to be smaller in size than the subjects in the previous study[25] conducted in the United States. Body size differences might affect the risk of nerve injury during RSA as the RSA implants are mainly developed in European countries and the United States and might, therefore, be targeted for patients in those countries. However, although a smaller body size might be expected to carry an increased risk of nerve injury during RSA, in the present study, the total number of nerve alerts per procedure was significantly smaller than in the previous study[25] despite the patients having a significantly smaller BMI.

We found no previous reports regarding the association between the incidence of nerve injury and body size. We suspect that patients with a small body size might have a higher risk of nerve injury because of the excessive tension on the soft tissue induced by the relatively large implant. However, in this study including subjects with relatively small body size, the incidence of alerts was actually less frequent than in a study including subjects with a relatively large body size.[25] Although the precise reason remains a matter of speculation, this higher incidence in the United States seems to be due to excessive tension on the nerve induced by the thickness of the soft tissue.

A comparison with TSA

Nagda et al[24] performed intraoperative neuromonitoring for 30 patients (20 TSAs, 3 hemiarthroplasties, and 7 revision TSAs). They reported 30 nerve alerts, including 15 during the glenoid procedure (50.0%) and 10 during the humeral procedure (33.3%). Parisien et al[25] performed 24 TSAs and reported 106 nerve alerts including 46 alerts during the humeral preparation (43.4%) and 31 during the glenoid preparation (29.2%). Similar to these studies on TSA, the nerve alerts in this study tended to occur during the glenoid and humeral procedures and with the arm in the dislocated position.

A comparison with RSA

In the investigation of 12 patients who underwent intraoperative neuromonitoring during RSA,[25] 97 nerve alerts were recorded. There were more alerts on the axillary nerve and the radial nerve than the other nerves. The incidence of alerts in each procedure was almost homogeneous, differing from our results in that most of the nerve alerts occurred during the glenoid and humeral implantation. Nerve alerts were recorded second most frequently during the postreduction stage. Differences in not only the implant model and size but also the tension due to implantation may underlie these discrepant results. The difference in the number of alerts might have been caused by the way the nerve alerts were counted. The number of alerts in our study was relatively small because we counted nerve alerts only once, even if they were not resolved in the same stage of the procedure.

Intraoperative risk factors of neurological disorders on RSA

With a nonanatomical design, such as arm lengthening and rotation center of the shoulder joint is internal lower, RSA allows the upper limb to be lifted with a small amount of force because nonanatomical design enables to increase the lever arm and tension in the deltoid. However, arm lengthening in RSA is cited as the cause of neurological injury,[12,15,23,25,29] due to increased tension on the brachial plexus and axillary nerve. Postoperative arm lengthening is reported to be 2 cm on average in RSA.[14] Although the threshold of the arm lengthening remains unclear, Lädermann et al[14] suggested that arm lengthening should be kept within 2 cm to avoid postoperative neurologic disorders. Given that we did not conduct such measurements in the present study, caution must be taken to avoid excessive arm lengthening. Similar to our findings, the high-risk operative stages were found in previous studies[24,25] to include the procedures of the glenoid fossa and humeral head, wherein the upper limb position often assumes an external rotation position for dislocation. The external rotation position increases stress on the nerve, causing neurological injury.[8,24,25,28] In addition, according to an anatomical study,[18] when the arm position emphasizes not only external rotation but also extension, the stress exerted on the brachial plexus (especially the axillary and radial nerves) increases. This corresponds with our finding that the nerve alerts were recorded most frequently on the axillary nerve and second most frequently on the radial nerve during dislocation.

In addition, we believe that the backward retraction of the humeral head due to dislocation and the ensuing loss of support may pull or stress the axillary nerve and cause a neurological disorder. Another anatomic cadaveric study[16] suggested that the anterior branch of the axillary nerve might run within 2 mm from the humeral implant. The need for increased glenoid exposure and prolonged retraction for the larger glenosphere implant in RSA may also increase the risk of nerve injury.[3,6] To prevent neurological injury, when the upper limb position is prolonged during extension and external rotation, the upper limb should be returned to the neutral position to relieve the tension, or the angle of the beach chair position should be increased to avoid excessive shoulder extension.[18,25]

Interaction between the nerves and procedure

No significant interaction between the nerves and procedures was found in our study. However, we believe that this is because of the small number of alerts. In several anatomic studies, it was reported that the mean distance between the inferior rim of the glenoid and the axillary nerve was 3.2 to 13.6 mm.[1,19,20,26] RSA requires an increased glenoid exposure and long duration of retraction for the implantation of the glenosphere. This implantation and the inferior placement of the glenoid baseplate may increase the risk of injury of the axillary nerve.[15,24] In addition, the distance between the axillary nerve and the lesser edge of the humeral head has been reported to range from 5.2 to 8.1 mm, and the only structure separating the nerve from the humeral implant is the thin capsule.[16,19] Leschinger et al[19] suggested caution be practiced to avoid damaging the posterior humeral cortex when reaming the metaphysis, as the humeral implantation might place the axillary nerve at risk. We must be careful to minimize the risk of axillary nerve injury during the implantation of the glenoid and humerus.

Threshold of neuromonitoring

A higher threshold value might include false negatives. Therefore, to avoid nerve injuries, a lower threshold should be applied. Regarding the neuromonitoring parameters, Nagda et al[24] reported that 97% of nerve alerts in TSA occurred on TcMEPs. In the present study, the incidence of nerve alerts on TcMEPs was 94%, still a relatively high rate. The performance of TcMEPs may be recommended for intraoperative neuromonitoring.

The threshold of TcMEPs was set as an attenuation above 50% in this study, according to past studies.[8,24,28] Two patients were not intraoperatively resolved nerve alert on TcMEPs of the axillary nerve. One of the 2 patients investigated in this study had a continuously lower amplitude that was less than 10% that of the control observed during the previous surgery, and the patient thereafter suffered from incomplete paralysis of the axillary nerve postoperatively. The amplitude in another patient gradually recovered to 48% eventually, and she had no clinical deficit postoperatively.

During spine surgery, a threshold of 70% to 80% is used as the standard, with 0 false negatives.[17] Parisien et al[25] also use 80% as the threshold in RSA and TSA. If the cutoff of our study had been set at 80%, 6 of the 31 alerts would still be applicable, including the event of postoperative incomplete paralysis of the axillary nerve. An 80% cutoff may be sufficient and acceptable only for detecting clinical nerve injury. However, from the perspective of prevention, we feel that using a 50% threshold may be better for detecting nerve injury as early as possible or avoiding it altogether. Unfortunately, few studies have described intraoperative neuromonitoring for RSA, so further investigations are necessary.

Limitations

The present study has several limitations. First, the sample size was small, and we did not exclude patients with preoperative neurological disorders. Second, we must consider the possibility of injury due to the interscalene brachial plexus block. To avoid such injury, a well-trained anesthesiologist performed the tubing and used a blunt needle and ultrasonography. Furthermore, the patients were still awake during tubing. After confirming no clinical nerve injury due to the tubing, the anesthesiologist started the induction.

Conclusions

Our study with intraoperative neuromonitoring suggested that the axillary nerve was at particularly high risk of injury during glenoid implantation in RSA. Furthermore, risks of nerve injury were noted when the arm was in the dislocation position, external rotation, and shoulder extension. We should avoid keeping the patient in that position longer than necessary to prevent nerve damage.

Disclaimer

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