



Identifying the axillary nerve during shoulder surgery: an anatomic study using advanced imaging

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ARTICLE INFO

Keywords:

Shoulder
axillary
nerve
arthroplasty
Latarjet
arthroscopy
injury

Level of evidence: Anatomy Study; Imaging

Background: The axillary nerve (AXN) is one of the more commonly injured nerves during shoulder surgery. Prior anatomic studies of the AXN in adults were performed using cadaveric specimens with small sample sizes. Our research observes a larger cohort of magnetic resonance imaging (MRI) studies in order to gain a more representative sample of the course of the AXN and aid surgeons intraoperatively.

Methods: High-resolution 3T MRI studies performed at our institution from January 2010 to June 2019 were reviewed. Four blinded reviewers with musculoskeletal radiology or orthopedic surgery training measured the distance of the AXN to the surgical neck of the humerus (SNH), the lateral tip of the acromion (LTA), and the inferior glenoid rim (IGR). Intraclass correlation coefficient was calculated to assess reliability between reviewers. The nerve location was assessed relative to rotator cuff tear status.

Results: A total of 257 shoulder MRIs were included. Intraclass correlation coefficient was excellent at 0.80 for the SNH, 0.90 for the LTA, and 0.94 for the IGR. All intraobserver reliabilities were above 0.80. The mean distance from the AXN to SNH was 1.7 cm (range, 0.7–3.1 cm; interquartile range, 1.38–2.00) and that from the AXN to IGR was 1.6 cm (range, 0.6–2.6 cm; interquartile range, 1.33–1.88). The mean AXN to LTA distance was 7.1 cm, with a range of 5.2–9.0 cm across patient heights; there was a large effect size related to the LTA to AXN distance and patient height with a correlation of $r = 0.603$ ($P < .001$). Rotator cuff pathology appears to affect nerve location by increasing the distance between the AXN and SNH ($P = .027$).

Discussion/Conclusion: The AXN is vulnerable to injury during both open and arthroscopic shoulder procedures. This injury can be either a result of direct trauma to the nerve or secondary to traction placed on the nerve with reconstructive procedures that distalize the humerus. Our study demonstrates that the AXN can be found as little as 5.6 mm from the IGR and 6.9 mm from the SNH. In addition, we illustrate the relationship between patient height and the LTA to AXN distance and complete rotator cuff tears and the SNH to AXN distance. Our study is the first to demonstrate the nerve's proximity to important surgical landmarks of the shoulder using a large sample size of high-resolution images in living human shoulders.

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The axillary nerve (AXN) is an important peripheral somato-sensory nerve that is prone to injury during both arthroscopic and open shoulder surgery.^{2,3,6,8,9,11,15,18–21,28} The AXN originates from the posterior cord of the brachial plexus and runs inferolaterally along the anterior aspect of the subscapularis muscle. On

encountering the inferior border of the subscapularis muscle, the nerve courses posterolaterally to go through the quadrilateral space. Here, it divides into 2 major trunks, which have significant anatomic variability.^{7,17,32} Most commonly, the AXN gives off an anterior circumflex trunk and a posterior trunk. The posterior trunk supplies a branch to the teres minor muscle as well as a branch to the posterior aspect of the deltoid muscle before terminating as the superior lateral brachial cutaneous nerve. The anterior circumflex trunk courses around the surgical neck of the humerus before giving branches that supply the middle and anterior aspects of the deltoid muscle.^{1,4,5,7,10,21,24,32}

Approval for this study was received from the UCSD Human Research Protection Program (Project #191168X).

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<https://doi.org/10.1016/j.jseint.2020.06.011>

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The course of the AXN places it at particular risk during both arthroscopic and open shoulder surgery.^{2,3,6,8,9,11,15,18–21,28} Specific arthroscopic procedures are associated with higher rates of AXN injury. For example, arthroscopic Latarjet, capsular repair, and humeral avulsion of the glenohumeral ligament repair have shown rates of clinically detectable nerve injury ranging from 1.2% to 2.1%.^{2,11}

Neurologic injury has been shown to occur at an even higher frequency with open shoulder surgery. Studies evaluating neurologic injury sustained in open Latarjet procedures report rates ranging from 3.1% to 10%.^{8,23} The incidence of clinical neurologic injury after shoulder arthroplasty has been described to range from 0.4% to 4.3%.^{3,18,21} Because these analyses are dependent on physical examination detecting a frank neurologic deficit, it is possible that rates of neurologic injury are even higher if accounting for subclinical injuries.^{3,20} Further research using perioperative electromyography (EMG) and nerve conduction studies (NCS), as well as intraoperative nerve monitoring, has suggested that the rate of neurologic injury may be significantly higher.^{6,22,24}

These findings highlight the importance of intraoperative identification and protection of the AXN. Prior studies have attempted to define the position of the AXN relative to anatomic landmarks using the dissection of cadaveric shoulder specimens.^{4,10,29} However, these studies have been limited in sample size, and the effects of specimen sectioning, embalming, and surgical dissection on distortion of anatomy are unclear.^{10,29} Magnetic resonance imaging (MRI) measurements offer an opportunity to evaluate anatomy in vivo, without the need for dissection or cadaver preparation. One study in the pediatric population used MRI to evaluate the relationships between anatomic landmarks and humeral length.²⁵ No study to date has used MRI to conduct systematic measurements of the AXN relative to important surgical landmarks in the adult population.

This study seeks to build on prior analyses to further assess the course of the AXN using high-resolution, 3 Tesla (3T) MRI in a large sample size ($n > 250$) of living patients. It is anticipated that with a larger sample size, there would be a greater degree of deviation than previous studies. We sought to identify characteristics in our patient population that would estimate the location of the AXN within a narrower range. A secondary goal of the analysis was to determine the effect of patient height or rotator cuff (RTC) tears on the AXN position.

Materials and methods

The institutional review board approved this retrospective review of electronic medical records and MRI examinations. Four blinded reviewers, including 1 musculoskeletal radiologist and 3 orthopedic surgeons, measured the distance of the AXN to areas of surgical interest, including the lateral tip or aspect of the acromion (LTA), the inferior glenoid rim (IGR), and the surgical neck of the humerus (SNH).

High-resolution 3T shoulder MRIs performed at our institution between January 2010 and June 2019 were included. Studies of lower resolution (non-3T) and studies with excessive motion artifact were excluded, as well as studies with tumors or other pathology that distorted the normal shoulder anatomy. Patients who were less than 18 years of age were also excluded.

Consecutive images were reviewed, and all measurements were made using a radiology information system IMPAX (Agfa Healthcare, Greenville, South Carolina, USA). All measurements were made in the coronal plane using T1-weighted images. The AXN was identified in the quadrilateral space and followed proximally. The coronal MRI slice that best depicted the LTA was used for the LTA to AXN measurements. The coronal slice that best depicted the IGR was used for the IGR to AXN measurement. The coronal slice that

best demonstrated the most medial aspect of the SNH was used for the SNH to AXN measurement. Examples of these measurements are illustrated in Fig. 1. In some scenarios, all 3 measurements were made on the same coronal slice of the MRI; however, different measurements were frequently made on different coronal slices of the same MRI sequence. A subset of 20 MRI studies was measured on 2 separate instances by all raters to determine reliability. RTC tear grade was determined from the radiology report created by our academic institution's fellowship-trained musculoskeletal radiologists and was designated as no tear, low-grade partial thickness, moderate-grade partial thickness, high-grade partial thickness, or complete or full thickness.

Statistical analysis was performed using SPSS software v.26 (SPSS Statistics for Windows, Version 26.0; IBM, Armonk, NY, USA). The Pearson correlation coefficient was used to determine the existence of linear correlations. Analysis of variance was performed to assess for differences in the aforementioned linear distances depending on grade of RTC tear. Alpha was set to $P < .05$ to declare significance. Intraclass correlation coefficient (ICC) was calculated to assess for reliability between reviewers.

Results

Two hundred and fifty-seven shoulder MRIs met inclusion criteria and were analyzed. This analysis included 144 (56%) studies of male patients and 113 (44%) studies of female patients. There were 138 (54%) studies of the right shoulder and 119 (46%) of the left shoulder that were analyzed. Descriptive statistics for the AXN to surgical landmark measurements made are presented in Table I.

Pearson correlation of $r = 0.603$ ($P < .001$) was found for the correlation between patient height and the distance from the LTA to the AXN, which equated to a large effect size based on Cohen's (1988) description. The correlation between patient height and the distance from the SNH to the AXN was $r = 0.350$ ($P < .001$), which corresponded to a small to medium effect size. The correlation

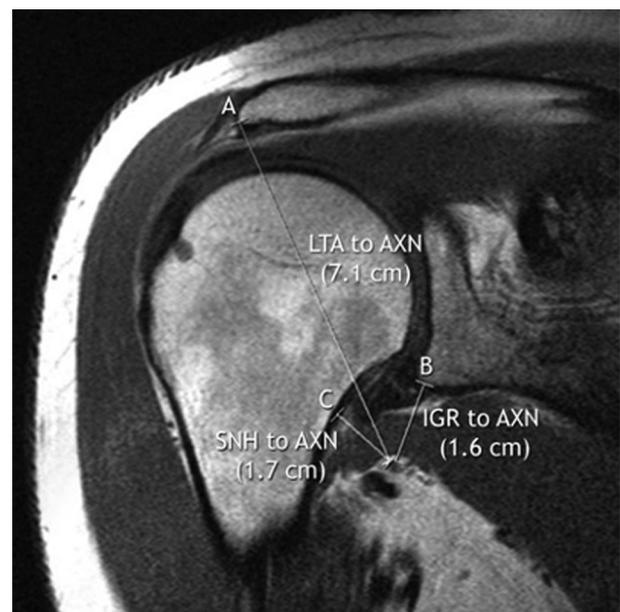


Figure 1 Example of measurements completed in each magnetic resonance imaging study. Line A represents the distance between the lateral tip of the acromion process and the axillary nerve (LTA to AXN). Line B represents the distance between the inferior glenoid rim and the axillary nerve (IGR to AXN). Line C represents the distance between the surgical neck of the humerus and the axillary nerve (SNH to AXN). Average measurements derived from this study are labeled in parentheses.

Table I

Mean distances with 95% CI, minimum measurement, maximum measurement, and standard deviations for each measurement made. LTA to AXN: Lateral tip of the acromion to axillary nerve. SNH to AXN: Surgical neck of the humerus to axillary nerve. IGR to AXN: Inferior glenoid rim to axillary nerve

	Mean (95% CI) (cm)	Minimum (cm)	Maximum (cm)	Standard deviation
LTA to AXN	7.1 (7.03-7.22)	5.2	9.0	0.77
SNH to AXN	1.7 (1.64-1.78)	0.7	3.1	0.44
IGR to AXN	1.6 (1.57-1.67)	0.6	2.6	0.38

LTA, lateral tip of the acromion; AXN, axillary nerve; SNH, surgical neck of the humerus; IGR, inferior glenoid rim; CI, confidence interval.

between patient height and the distance from the IGR to the AXN was $r = 0.328$ ($P < .001$), which corresponded to a small to medium effect size. The relationship between patient height and the LTA to AXN distance is presented in Fig. 2. Regression modeling was performed to further delineate the relationship between patient height and the LTA to AXN distance (Fig. 2). The linear regression of Fig. 2 was used to create Table II, a series of predicted AXN to LTA distances for patients of various heights.

When broken down by the specific tendon injured, a significant difference was seen with the tendons of the supraspinatus (1.6 cm vs. 1.9 cm, $P = .003$) and subscapularis (1.7 cm vs. 2.1 cm, $P = .006$), but there was no significant difference for the infraspinatus tendon (1.7 cm vs. 2.0 cm, $P = .067$), with the longer values corresponding to the AXN to SNH distance with a positive RTC tear.

There was a significantly shorter distance of the SNH to AXN in those without any full-thickness tears of the RTC (including those with intact RTC or a partial thickness tear of the RTC) (mean = 1.65 cm; 95% confidence interval, 1.59-1.71 cm) compared with those with at least 1 full-thickness RTC tear (mean = 1.87 cm; 95% confidence interval, 1.77-1.97 cm), as demonstrated in Table III. This difference was not significant when evaluated for the LTA or IGR.

Intraclass correlates

All ICCs were excellent with values >0.80 (Table IV).

Discussion

This study used high-resolution 3T MRI to evaluate the course of the AXN in a large cohort of living patients with the aim of helping

surgeons identify and protect the AXN during both arthroscopic and open shoulder surgery. Patient height and associated RTC pathology were assessed and found to have an effect on the nerve position relative to important surgical landmarks.

Prior studies have attempted to define the course of the AXN in cadaveric shoulder specimens.^{1,7,10,29} There have been multiple cadaveric studies that have reported the distance from the posterolateral corner of the acromion process to the AXN as it moves through the quadrilateral space.^{10,29} Uz et al²⁹ used 30 shoulder specimens to record the mean distance of 7.8 cm from the posterolateral corner of the acromion process to the AXN and its branches. A subsequent study by Gurushantappa et al¹⁰ of 50 cadaveric specimens showed a mean distance of the AXN from the posterolateral aspect of the acromion process of 7.46 cm. This current study identified the AXN to be located a mean 7.12 cm from the LTA, slightly closer than reported by Gurushantappa and Uz.^{10,29} This slight discrepancy could be secondary to differences in bony landmark used (posterolateral vs. lateral acromion) or possibly a result of anatomic distortion during cadaveric dissection. Our mean measurement does not vary greatly from those performed on cadavers; however, this value was obtained using a larger sample size with a wider distribution in patient age. In the current study, we also demonstrated a strong correlation between patient height and the AXN to LTA distance. This has important clinical implications for soft tissue dissection in shoulder surgery, as height is a frequent variable among patients.

RTC tendon pathology is frequent in patients being evaluated for shoulder arthroplasty. Consequently, this study sought to determine the effects of RTC tears on the anatomic course of the AXN. Our analysis identified a statistically significant increase in the

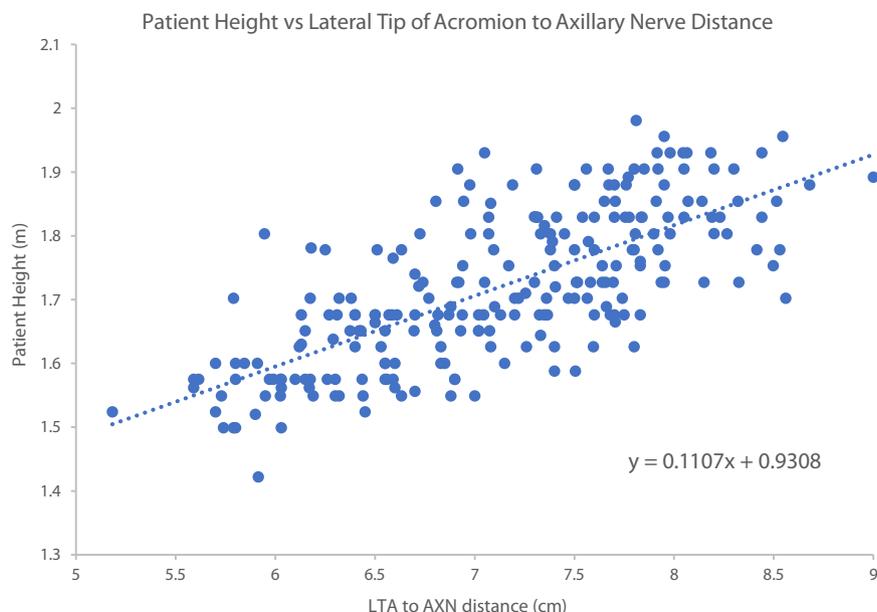


Figure 2 A scatter plot with a best-fit line was used to demonstrate the relationship between patient height and the lateral tip of acromion to axillary nerve (LTA to AXN) distance.

Table II
For each given height shown in imperial and metric measurements, the estimated lateral tip of acromion to axillary nerve distance (LTA to AXN)

Patient height (feet/inches)	Patient height (m)	LTA to AXN distance (cm)
4'11"	1.5	5.14
5'3"	1.6	6.04
5'7"	1.7	6.94
5'11"	1.8	7.85
6'3"	1.9	8.75
6'7"	2.0	9.65

The values were generated using the linear regression equation from the patient height vs. LTA to AXN scatter plot (Fig. 2).

distance from the AXN to the SNH in the presence of RTC tears. This difference in distance between those with and without RTC tears was not noted for the AXN to LTA or the AXN to IGR. This increase in the distance from the AXN to SNH is likely the sequelae of superior humeral migration that occurs with RTC tears.¹² Conversely, the nerve's static position relative to the scapula preserves its relationships with the glenoid and acromion, even in the presence of RTC pathology.

A recent large study by Hamada et al¹¹ of 2027 different arthroscopic shoulder stabilization procedures showed a rate of AXN injury of only 0.2%. A majority of these procedures were soft Bankart repairs. Further investigation found that the rate of AXN injury was relatively higher in humeral avulsion of the glenohumeral ligament repair (2.0%) and capsular repair (1.25%).¹¹ The authors of this study suggested that the increased suture passing being performed on the avulsed aspect of the shoulder capsule or glenohumeral ligament led to higher risk of injury to the nearby AXN. Another study of arthroscopic Latarjet procedures demonstrated a similar incidence of AXN injury in 1.2% in its cohort.²

Injury to the AXN has been well studied with regard to the open Latarjet as well. There is evidence to suggest that the incidence of AXN injury during open Latarjet is between 1.7% and 4.0%.^{8,28} Interestingly, Shah et al²⁸ found that only the lesions to the AXN did not resolve at the time of final follow-up, further emphasizing the importance of avoiding them at the outset. Delaney et al⁶ used intraoperative nerve monitoring to detect intraoperative nerve insults. The AXN was involved in 35 of 45 separate nerve alert episodes. The most common stages of the procedure in which nerve alerts occurred were during glenoid exposure and graft insertion.⁶ The IGR to AXN distance had a mean of 1.6 cm in our sample and is the first reported reference in the literature to the knowledge of our authors. We believe establishing this distance is relevant and has the potential to minimize AXN injury during this procedure.

There are large studies that estimate the incidence of neurologic injury from 0.4% to 4.3% during total shoulder arthroplasty (TSA) and reverse total shoulder arthroplasty (RSA).^{3,20} A limitation of these studies is that only clinically obvious motor or sensory deficits were used as endpoints for retrospective detection of a neuropraxia, and it

Table III
Difference in distances measured in those with a full-thickness RTC tear (+Full-thickness RTC tear) vs. those without a full-thickness tear of at least 1 RTC tendon (–Full-thickness RTC tear) with 95% confidence intervals in parentheses and corresponding *P* values

Distance measured	+Full-thickness RTC tear (n = 51) (cm)	–Full-thickness RTC tear (n = 206) (cm)	<i>P</i> value
LTA to AXN	7.32 (7.14-7.52)	7.06 (6.9-7.17)	.035
SNH to AXN	1.87 (1.77-1.97)	1.65 (1.59-1.71)	<.001
IGR to AXN	1.69 (1.61-1.77)	1.60 (1.55-1.66)	.064

RTC, rotator cuff; LTA, lateral tip of the acromion; AXN, axillary nerve; SNH, surgical neck of the humerus; IGR, inferior glenoid rim.

Table IV
Intra- and interobserver reliability was calculated to assess for reliability within and between raters

Intraobserver ICC	To the lateral tip of the acromion	To the surgical neck of the humerus	To the inferior glenoid rim
Measurer 1	0.90	0.91	0.90
Measurer 2	0.98	0.98	0.90
Measurer 3	0.96	0.93	0.93
Measurer 4	0.96	0.80	0.83
Interobserver	0.90	0.80	0.94

ICC, intraclass correlation coefficient.

was theorized that subclinical lesions might have been missed because they were never reported or documented. A prospective study by Lädermann et al¹⁸ sought to detect neurologic lesions using pre- and postoperative EMG/NCS in patients undergoing TSA or RSA. This study reported that 23% of patients developed a new nerve lesion on EMG/NCS at a mean of 3.6 weeks postoperatively, suggesting a much higher incidence compared with previous retrospective studies. Of these nerve lesions, those involving the AXN were found to be the most common. Even more interesting was that the relative risk of neurologic injury in RSA compared with TSA was 10.9. We hypothesize that a fundamental anatomical difference between these 2 patient populations, that is the absence of a functional RTC, would influence the position of the AXN, thus creating a more likely scenario for injury during RSA. Our results, however, demonstrated that the AXN was further from the SNH in those with RTC tears compared with those with intact RTCs. More recent research by Kim et al¹⁶ shows that AXN deficits were the most common nerve deficit after RSA in their sample. They identified that those with postoperative nerve deficits had undergone, on average, a greater amount of humeral distalization relative to those without nerve deficits. In addition to this, many of the postoperative deficits recovered spontaneously without any additional intervention. These findings suggest that nerve traction may account for a larger proportion of nerve injuries than previously believed.

In a study by Nagda et al,²⁴ intraoperative nerve monitoring during shoulder arthroplasty showed 57% of their patients to have a significant intraoperative “nerve alert.” Their group reported that 16.7% of these nerve alerts were from the AXN. Additional studies have suggested that intraoperative nerve injuries during RSA and TSA are most commonly caused by traction on the individual nerve or brachial plexus.^{14,30} Studies using intraoperative nerve monitoring found that excessive time with the operative arm in external rotation and extension, especially during glenoid and humeral preparation, increased the risk of nerve injury.^{21,24,26} Interestingly, in each of the 30 nerve alert episodes, none of the nerve alerts returned to baseline with retractor removal alone.²⁴ Other possible causes of intraoperative nerve injury included peripheral nerve block, cement extrusion, and arm lengthening.^{1,3,7,31}

To our knowledge, this is the first study to date with a large sample size using high-resolution 3T MRI to evaluate the anatomic relationship of the AXN to surgical landmarks in adults and to correlate those measurements with patient height and the presence of RTC tears. One prior study in the pediatric population using MRI demonstrated a linear relationship of the LTA to AXN distance when compared with the longitudinal length of the humerus.²⁵ There are multiple studies in adult cadavers that correlate the LTA to AXN distance to cadaver height or humeral length; however, they were performed on samples of 20 and 70 cadaver specimens.^{13,27} Prior studies using cadaveric specimens are limited by small sample sizes and changes in anatomy introduced by dissection and embalming.

Our study is not without limitations. The study used MRI to make measurements regarding the AXN in 3-dimensional space. The alignment of the coronal plane by the various MRI technologists may have been inconsistently applied relative to the anatomic axis of the scapula. This error would potentially introduce variability in the plane by which measurements were performed. Despite potential heterogeneity of the measurements from the 4 different observers, intraobserver and interobserver reliability measures were excellent ($ICC \geq 0.80$). Although our measurements were highly reproducible and we demonstrated an association between patient height and RTC pathology to the location of the AXN, we are still unable to confirm any particular etiology of nerve injury during surgery, as detailed in the discussion above.

Conclusion

The AXN is vulnerable to injury during both open and arthroscopic shoulder procedures. This injury can be either a result of direct trauma to the nerve or secondary to traction placed on the nerve with reconstructive procedures that distalize the humerus. Although there is no replacement for careful surgical dissection and soft-tissue handling, the knowledge of anatomy and its variability based on patient characteristics can be a valuable tool with potential to influence patient outcomes. The AXN is of critical importance in patients undergoing both open and arthroscopic shoulder procedures and permanent injury to this nerve can be catastrophic. Our findings suggest that given patient height and knowledge of existing RTC pathology, we can formulate a more accurate estimate of the location of the AXN, which could be useful in identifying and protecting this structure intraoperatively.

Disclaimer

Eric W. Edmonds received honorarium from Arthrex, Inc., which is unrelated to the subject of this work. He also serves on the Board of Directors or Committees for the Pediatric Orthopedic Society of North America and the American Academy of Orthopedic Surgeons.

The other 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.

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