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MRI evaluation of axillary neurovascular bundle: Implications for minimally invasive proximal humerus fracture fixation

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Background: Percutaneous fixation of proximal humeral fractures places the axillary nerve and posterior humeral circumflex artery at risk for injury. Safe operative zones for the axillary nerve are described based on external measurements from anatomic landmarks, but no study to date has incorporated advanced imaging to help guide surgical procedures in the region of the axillary neurovascular bundle (ANVB). We sought to define the location and trajectory of the ANVB in relation to osseous landmarks using magnetic resonance imaging (MRI) measurements.

Methods: Retrospective review of 750 consecutive MRI studies was performed with 55 imaging studies meeting inclusion criteria for patient positioning, image alignment, and quality. Five measurements were performed including the distance from mid-lateral acromion to lateral ANVB, mid-lateral acromion to medial ANVB, greater tuberosity to lateral ANVB, vertical distance between inferior anatomic neck and lateral ANVB, and angle the ANVB crosses the humerus. Height, gender, and age were recorded. Analysis was performed using ANOVA and Pearson correlation tests.

Results: The lateral ANVB was below the inferior articular margin of the humeral head by an average of 12.9 ± 3.9 mm and within a 22 mm window. It was an average of 57.4 ± 5.1 mm from the lateral mid-acromion, and 34.7 ± 4.3 mm below the greater tuberosity. The angle formed by the ANVB crossing the humerus averaged 19.5 ± 3.9 degrees upward from medial to lateral. Height and gender directly impacted measurements.

Conclusions: The use of the inferior humeral head articular margin provides a radiographic landmark to aid intraoperative lateral ANVB assessment which may be helpful during percutaneous fracture fixation.

The incidence and surgical treatment of proximal humerus fractures (PHFs) is increasing.[25] They account for about 5% of all fractures and 10% in the elderly.[12,13,34,35] Passaretti et al reported that a high-energy traumatic mechanism (sports trauma or vehicle collision) was found as the cause of injury in 30.1% of male patients between 18 and 60 years of age. Low-energy traumatic mechanisms (occurring on the street while running or walking, public transport, or at home) were observed in 39.7% of male patients older than 65 years.[36] Evolving surgical techniques and implant designs have directly led to the increase in surgical management of PHFs.[24,28] Use of a minimally invasive deltoid splitting technique for placing locking plates and intramedullary nails has shown advantages in some studies in decreased surgical time, shorter hospital stay, improved wound healing, and better early functional outcomes compared to the conventional deltopectoral approach.[19,30,31] The increased use of minimally invasive techniques and percutaneous placement of screws has drawn attention to risks including injuring the axillary neurovascular bundle (ANVB).[1,11,35,40,43]

The axillary nerve and posterior humeral circumflex artery provide the main source of innervation and blood supply to the lateral shoulder as they course together on the undersurface of the deltoid around the lateral humerus.[9,26,44] Axillary nerve injuries are the most common nerve injury with proximal humeral fractures and can range from lateral arm anesthesia to atrophy of the deltoid and subsequent decreased abduction strength.[38] The posterior humeral circumflex artery courses with the axillary nerve and inadvertent injury of this vessel can lead to avascular necrosis of the

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humeral head.[5,8,9] Injury to the NVB can have devastating effects on patients' functional status.[17] Despite concerns for injury to the ANVB, the frequency of injury either after initial injury or surgical intervention is difficult to quantify in the literature.[1,49,51]

Multiple authors have described relative safe operative zones for the axillary nerve based on external measurements from anatomic landmarks (Table I). Cadaveric studies attempting to delineate operative "safe zones" are limited due to small sample size, variations in selected osseous landmarks, and potential disruption of anatomy during dissection.[44,45] Measurements are influenced by changes in patient positioning and limb traction.[4,10] An additional limitation of earlier studies is the failure to assess the corresponding relevant vascular structures. External markings provide little guidance for laterally inserted screws when less invasive means of fixation are used.[2,6,16,39]

To date no study has incorporated imaging measurements to help guide surgical procedures in the region of the ANVB. The purpose of this study was to use MRI-based measurements to delineate the relationship between radiographic landmarks and the ANVB to provide more accurate intraoperative assessment of axillary nerve and posterior humeral circumflex artery location.

Materials and methods

After IRB approval, two separate radiologists fellowship-trained in musculoskeletal radiology retrospectively reviewed 750 shoulder MRI examinations at a single academic institution from January 1, 2015, to December 31, 2016. All patients less than 18 years old or with a history of prior shoulder surgery, complete rotator cuff tear, or anatomic abnormality, including tumor, arthritic changes, and aneurysm, exhibiting mass effects on surrounding tissues were excluded.

Examinations were performed using either Philips Achieva 1.5T device, Philips Achieva 3 T, Siemens Skyra 3T, Siemens 1.5T Sympony, Siemens 3T Prisma, Philips Ingenia 1.5T, or GE Twinspeed 1.5T. Proper patient positioning was critical to obtaining reproducible measurements. All shoulder examinations were performed with the patient in the supine position and shoulder in minimal abduction or adduction, flexion or extension, and internal or external rotation (Fig. 1). When ordered, abduction, and external rotation (ABER) sequence was performed with the shoulder in abduction and external rotation. Patient positioning and examination parameters were set to optimize spatial and contrast resolution, minimize artifact, and provide clear visualization of tissues

Table I
Historical axillary neurovascular bundle studies

Study[*]	Average distance (range)[†]	Measurement reference[‡]
Burkhead et al[6]	57 mm (41-71 mm)	Anterolateral corner of acromion
	58 mm (43-74 mm)	Midpoint acromion
	55 mm (31-73 mm)	1 cm medial to posterolateral corner of acromion
Duparc et al[14]	34 mm (30-48 mm)	Insertion of deltoid on acromion—posterolateral corner of acromion
Prince et al[40]	58.7 mm	Lateral undersurface of acromion
Hoppenfeld et al[21]	70 mm	Not documented
Cetik et al[7]	60.8 mm (52-69 mm)	Anterior edge of acromion
	48.7 mm (43-55 mm)	Posterior edge of acromion
Vathana et al[48]	67 mm (47-89 mm)	Anterior edge of acromion
	63 mm (43-82 mm)	Posterior edge of acromion
Maman et al[33]	48.5 mm (30-60mm)	Inferior anterolateral tip
	50.8 mm (35-68 mm)	Inferior edge of the mid-lateral acromion
	51.7 mm (35-70 mm)	Posterolateral corner of acromion
Sung et al[45]	65.1 mm (51-87 mm)	Upper margin of mid-portion of acromion
Gurushantappa and Kuppasad[18]	67.1 mm (58-74 mm)	Midpoint deltoid insertion
	35.6 mm (22-44 mm)	Anteromedial tip of coracoid process
	74.6 mm (36-88 mm)	Posterolateral aspect of acromion process
	2.45 mm (16-36 mm)	Midpoint of vertical distance of deltoid muscle
Chen et al[8]	35 mm (32-41 mm)	Prominence of greater tuberosity and superior border of axillary nerve
	63 mm (52-70 mm)	Anterior-inferior border of acromion
	22 ± 7 degrees (8-37 degrees)	Axillary nerve angle with respect to humeral long axis
Lin et al[29]	45.6 mm	Greater tuberosity
Spiegelberg et al[43]	62 mm (45-81 mm)	Anterolateral edge of acromion
	21/26 nerve "traversed perpendicular to humeral long axis"	Axillary nerve angle with respect to humeral shaft axis
Clavert et al[11]	65 mm (40.5-71.35 mm)	Lateral border of acromion
Smith et al[42]	72 mm (62-85 mm)	Lateral edge of acromion
Stecco et al[44]	56 mm (49-61 mm)	Apex of humeral head
	69 mm (64-75 mm)	Acromion
Kamineni et al[23]	51 mm (35-85 mm)	Tip of acromion anteriorly
	57 mm (35-70 mm)	Tip of acromion along lateral arm
	12 mm (7-15mm)	Anterior width of neurovascular bundle
	6 mm (4-13 mm)	Lateral width of neurovascular bundle
Nijs et al[35]	55.8 mm (43.4-63.9 mm)	Lateral edge acromion at mid-humerus
Cheung et al[10]	66.6 mm (58.4-72.4 mm)	Mid-acromion to axillary nerve superior border
Uz et al[47]	78 mm (64-88 mm)	Posterolateral acromial corner
Ikemoto et al[22]	53.2 mm (43-64 mm)	Anterior-lateral acromial edge
Bono et al[4]	60.9 mm (45-69 mm)	Proximal humeral head (apex)
	17.2 mm (7-40 mm)	"Surgical neck" (distance below inferior anatomic/superior surgical neck)
Gardner et al[16]	35.5 mm (32.1-42.5 mm)	Lateral prominence of greater tuberosity
	63.3 mm (53.2-70.4 mm)	Undersurface of acromion (anterior raphe line)
	22 degrees (4-36 degrees)	Superior obliquity under raphe (humeral axis)

[*] First author of study.
[†] Average distance from reference point to axillary neurovascular bundle.
[‡] Reference point for measurement to axillary neurovascular bundle.

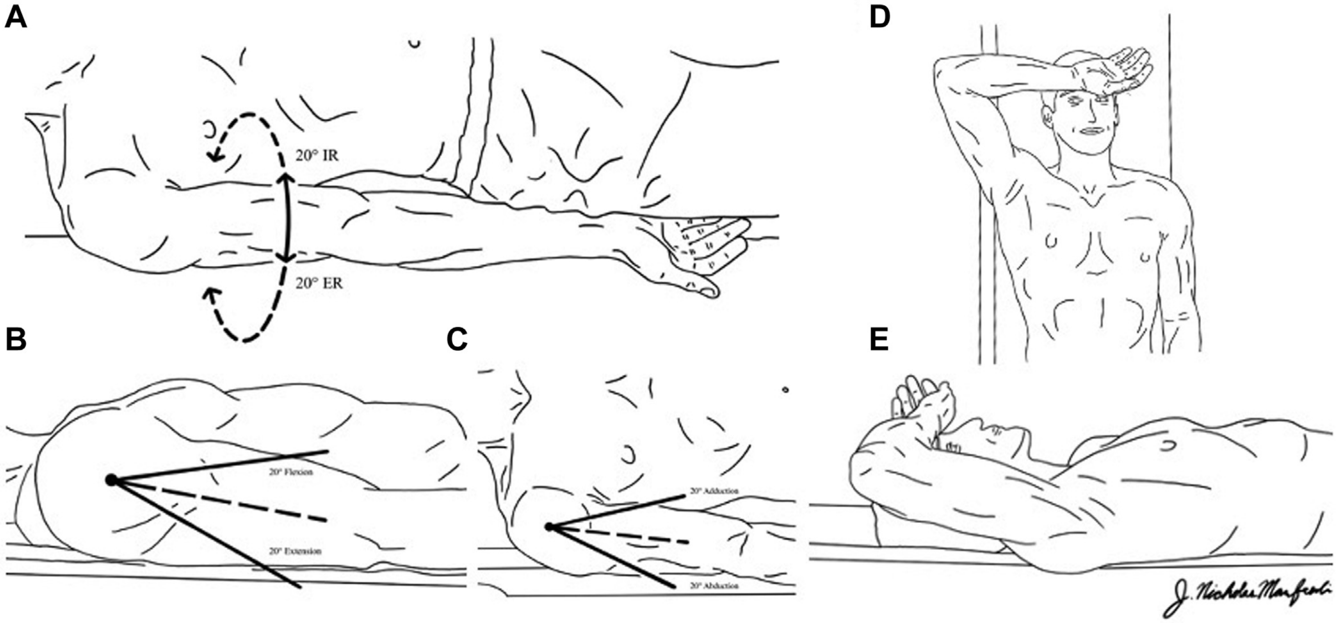

Figure 1 Patient positioning for MRI imaging. (**A**) Internal/external rotation parameters. (**B**) Flexion/extension parameters. (**C**) Abduction/adduction parameters. (**D**) ABER* view from front. (**E**) ABER* position view from side. *ABER-abduction and external rotation.

(cartilage, bone, rotator cuff tendons, capsule, and glenoid labrum). Multi-phased-array shoulder coil was used for all studies. In studies including ABER sequence, a flexible or ring coil was used for that sequence. Each study was performed utilizing AX T2 fat saturation (FS) (TR 3000, TE 60, Matrix 300 x 210, Gap 0, NSA 3, slice thickness 4 mm), coronal T2 FS (TR 3021, TE 60, Matrix 276 x 210, Gap 0, NSA 2, slice thickness 4 mm), sagittal T1 (TR 500, TE 10, Matrix 320 x 266, Gap 0, NSA 3, slice thickness 4 mm), coronal PD FS (TR 2322, TE 20, Matrix 332 x 224, Gap 0, NSA 4, slice thickness 4 mm), and sagittal T2 FS (TR 3296, TE 60, Matrix 296 x 230, Gap 0, NSA 3, slice thickness 4) sequences.

The axillary nerve was defined as the proximal circumflex humeral artery and surrounding interplanar tissues as the axillary nerve was not always able to be visualized as a unique structure. This is supported by an anatomic study by Stecco et al in which the PCHA was "interwoven" with the axillary nerve.[44]

Fifty-five imaging studies (7%) met optimal patient positioning criteria and were included for analysis. All measurements were conducted on a single selected optimal coronal slice (key image) (Fig. 2A). Determination of the key image was based on its location and image quality. The key image location displayed the center of the lateral humeral shaft on the sagittal view and had minimal motion artifact to allow precise identification of the ANVB. Patients with images not meeting these criteria were excluded. Patient age, gender, height, and imaging side were recorded for all patients.

Each key image had 5 measurements performed using osseous landmarks and the axillary neurovascular bundle (Fig. 2A). The measurements included 1. lateral most point of mid-acromion to lateral ANVB, 2. lateral most point of mid-acromion to medial ANVB, 3. superior-lateral most point of the greater tuberosity to the lateral ANVB, 4. vertical distance along the lateral cortex between the lateral ANVB and the transposed inferior humeral articular margin, 5. trans-humeral neurovascular bundle angle, which represents the angle a line connecting the medial and lateral axillary neurovascular bundles makes as it crosses the long axis of the proximal humeral shaft (Fig. 2A). The lateral ANVB on MRI was defined as the posterior humeral circumflex artery and surrounding intraplanar soft tissue elements. The medial ANVB was defined as the anterior humeral circumflex artery and surrounding intraplanar soft tissues. The bundle measurements were made to the vascular structures for reproducibility. All measurements were performed by the radiologist.

Statistical analysis

Analysis was performed on each group of measurements using Statistical Analysis System (SAS) version 9.4 (SAS Inc. Cary, NC). The data were analyzed using mean, standard deviation, and ANOVA to determine statistical significance of the measurements. The relationship between the landmark measurements and patient height and age were each individually examined using Pearson correlation. Statistical significance was defined as *P* value less than .05.

Results

Table II displays the demographic characteristics of the study population. In every case the lateral ANVB was inferior to the inferior articular margin of the humeral head and within a 22 mm window (Fig. 3). The lateral ANVB on average was 57.4 mm (46.5 − 67.2 mm) below the lateral mid-acromion (Fig. 2B, line 1). The lateral mid-acromion distance to the medial axillary neurovascular bundle was 70.9 mm (58 − 87.4 mm) (Fig. 2B, line 2). The mean distance from the greater tuberosity to the lateral ANVB was 34.7 mm (23.4 − 44 mm) (Fig. 2B, line 3). The distance distal to the lateral projection of the inferior articular margin of the humeral head averaged 12.9 mm (5.5 − 21.1 mm) (Fig. 2B, line 4). The trans-humeral ANVB angle formed as the nerve crossed the humeral axis in the coronal plane was 19.6 degrees (12 − 32 degrees) (Fig. 2B, angle α). Patient age did not influence measurements. The acromial and greater tuberosity distance measurements were associated with patient height (Table III). Extremity side, left or right, influenced the inferior articular margin measurement which was also the only measurement not different between men and women (Table III).

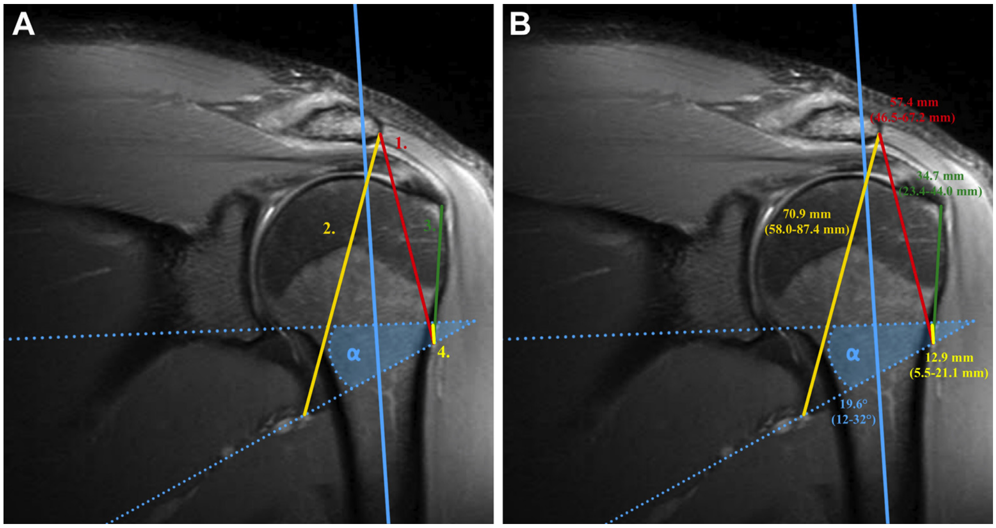

Figure 2 (**A**) Key image measurements overlaid on T2-weighted MRI. 1: Acromion to lateral ANVB. 2: Acromion to medial ANVB. 3: Greater tuberosity to lateral ANVB. 4: Vertical distance below inferior humeral articular margin. α: Trans-humeral angle (THA). (**B**) Results for each key image measurement overlaid on T2-weighted MRI.

Table II
Demographics

Demographic	N	Age (yr)[*]		Height (cm)[†]	
		Mean/Std Dev	Range	Mean/Std Dev	Range
Total	55	52/14.5	(22-81)	171/9.8	(152.4-191.77)
Male	28	50/16.7	(22-81)	176.4/7.6	(152.4-191.77)
Female	27	54/11.7	(34-78)	165.2/7.6	(152.4-180.34)
Left	29	52/15	(22-78)	172/9.8	(155-192)
Right	26	53/14.1	(25-81)	169/9.8	(152-185)

[*] Age at time of MRI.
[†] One patient height was not available (female, right).

Discussion

Concern for axillary neurovascular bundle injury during surgery warrants intraoperative attention. The path of this C4-C6 nerve derivation is known, originating from the posterior cord of the brachial plexus immediately posterior to the coracoid process, descending anterior to subscapularis until crossing the inferolateral border of subscapularis 3 – 5 mm medial to its musculotendinous junction, and dividing into anterior and posterior trunks between the anterior and posterior heads of triceps muscle in the quadrangular space after passing immediately adjacent to the shoulder capsule while accompanied by the posterior circumflex humeral artery.[3,6,46] A superolateral cutaneous branch also exits to supply sensation over deltoid, becoming subcutaneous at the posterolateral corner of the acromion.[3] The posterior trunk provides motor innervation to teres minor and posterior deltoid, whereas the anterior trunk supplies motor function the middle and anterior deltoid.[3] Structural variations of axillary nerve innervation of musculature have been described previously in literature, with the most common formations exhibiting decreased innervation in the anterosuperior deltoid, suggesting safer operative incisions in this region.[44] After innervation of musculature, the axillary nerve courses in the subdeltoid fascial plane to innervate the posteroinferior-lateral shoulder capsule. Thus, the nerve lies in an area that can be intersected by fixation screws.[32] While intraoperative imaging is routinely used in PHF fixation to assess reduction and implant placement, there are no described methods utilizing intraoperative imaging to help identify the lateral location of the ANVB. Using rigidly standardized MRI imaging to localize the ANVB, we noted that the lateral ANVB was consistently below the inferior articular margin of the humeral head. While no ideal safe

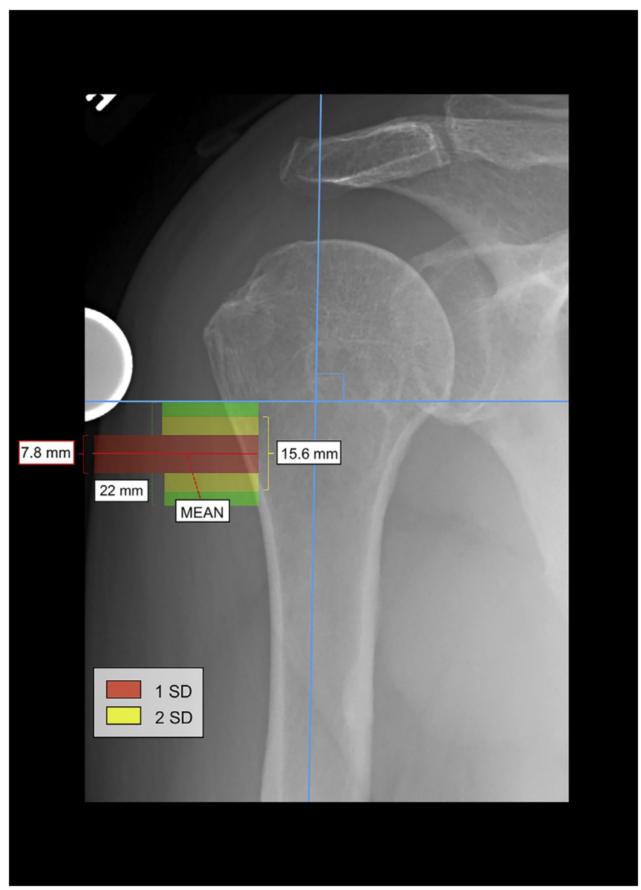

Figure 3 Danger zones based on inferior articular margin. *Red:* mean distance from inferior articular margin of humeral head to lateral ANVB ± 1 standard deviation. *Yellow:* mean distance from inferior articular margin of humeral head to lateral ANVB ± 1-2 standard deviations

Table III
MRI measurement results

Measurement	N	Mean/Std Dev (mm)	Range (mm)	Differences		Pearson correlation	
				Gender (female vs male)	Side of body (left vs right)	Age* (r/p)	Height‡ (r/p)
Lateral acromion to lateral NVB	55	57.39/5.09	46.5-67.2	$P < .0001$	$P = .7666$	−0.045 0.742	0.592 <0.0001
Lateral acromion to medial NVB	55	70.9/6.45	58-87.4	$P < .0001$	$P = .6962$	−0.097 0.483	0.61 <0.0001
Greater tuberosity to lateral NVB	55	34.68/4.28	23.4-44	$P < .0050$	$P = .3353$	−0.079 0.567	0.443 0.0008
Inferior articular margin of humeral head to lateral NVB (vertical distance)	55	12.93/3.89	5.5-21.1	$P = .6754$	$P = .0050$	−0.128 0.352	−0.123 0.377
Trans-humeral NVB angle†	55	19.55†/3.91†	12†-32†	$P = .0099$	$P = .914$	−0.014 0.919	0.24 0.081

NVB, neurovascular bundle; *r*, Pearson product-moment correlation coefficient; *P*, *P* value; *trans-humeral angle*, angle NVB crosses the humerus in reference to long axis of humeral shaft.
* Pearson age correlation performed on n = 55.
† Represented in degrees.
‡ Pearson height correlation n = 54 due to one missing height.

zone exists, the use of the inferior articular margin of the humerus as an intraoperative landmark may provide an effective, reproducible intraoperative guide to avoid lateral axillary neurovascular injuries.

The true incidence of traumatic injuries to the axillary nerve after shoulder trauma is unknown as many may be subclinical. The axillary nerve is the most commonly injured nerve after proximal humerus fractures and may be injured in around 50% of shoulder fractures and dislocations.[37,49,50] Similarly, theoretical concerns of iatrogenic injuries are prevalent in the literature but limited data exist describing their actual clinical incidence.[35,40] EMG identified axillary nerve injuries have been as high as 42% with the deltopectoral approach and 33% with the deltoid splitting approach.[8] A systematic review identified a 3% injury with a deltopectoral approach and a 7% injury the anterolateral deltoid splitting approach.[53] These studies are limited by low numbers and the need for electrophysiologic testing.

Our outcomes were consistent with prior anatomic studies in the literature. The average middle acromion to lateral ANVB measurement from all of the studies in Table I, irrespective of whether the superior, inferior, or lateral acromial border was used, was within 5 mm of our measurements. When assessed using only the most similar measurement method, there was a difference of less than 2 mm.[35] The average greater tuberosity and trans-humeral AVNB measurements were also very consistent. The average greater tuberosity distances reported by Chen et al and Gardner et al were within 1 mm of our findings along with their reported average trans-humeral ANVB angles which both within 2.5 degrees of our measurements.[8,15] Finally, comparing our inferior articular margin measurement to the only literature report by Bono et al, we reported the average distance being about 4 mm less with a much smaller range and standard deviation. These findings support the assessment of ANVB positioning using advanced imaging.[4]

Isolated injury to the axillary nerve can be difficult to diagnose after an injury or surgery without a high index of suspicion as patients can remain functional.[43,52] The inability to perform a functional examination of the deltoid due to pain along with intact axillary sensation can initially mask anterior axillary nerve injuries.[1,49,50] Postoperatively, non-specific weakness in forward flexion and abduction may be attributed to many other factors besides an anterior axillary nerve injury including implant positioning, adequacy of reduction, or postoperative pain and stiffness.[41] In addition, a patient's rotator cuff strength may initially compensate for decreased deltoid function on examination with early fatigue being the only clue of injury.[32,52] These nonspecific presentations of weakness coupled with the good recovery potential of neuropraxic injuries may conceal the true extent of this problem.[27,49] In addition, older patients, in whom most of these fractures occur, may not have the same nerve recovery potential or rotator cuff strength to attain the same functionally significant recovery as younger patients.[52] Furthermore, nerves impinged under a screw head or transected during screw insertion would not be expected to recover at the same rate as those with pure traction neuropraxia.

Both the anterior circumflex humeral artery and the PCHA supply blood to the humeral head with the anterior circumflex humeral artery reportedly being more critical in nonfracture cases and the PCHA more critical in fracture cases.[5,20] Injuries to the PCHA over the lateral shoulder are, to our knowledge, not described in the literature. The lack of reported lateral PCHA vessel injuries is likely multifactorial, but further disruption of vasculature in the setting of a displaced fracture is inadvisable as baseline perfusion is likely limited.

This study is not without limitations. The retrospective use of sequential MRI studies from one institution may not provide a true representative sample of the population. Despite strict imaging alignment and measurement protocols, it is not possible to mitigate the inherent observer bias associated with this type study. Owing to the small size of the axillary nerve and difficulty in discerning it at times, the posterior humeral circumflex artery and associated bundle structures were used as a surrogate for measurement purposes. It is not possible to determine if this technique accounted for all clinically significant branches of the axillary nerve. The study design does not account for morphological variations in the acromion or humerus. Likely an insignificant difference, MRI measurements were point to point on the cortex vs. traditional rigid caliper measurement techniques. Although different, these point-to-point measurements are clinically more reproducible than the "finger-to-finger" measurements performed intraoperatively by surgeons. Finally, while it would be ideal to carry out this study with the inclusion of inter- and intra-rater reliability, the amount of work required to rescreen 750 MRIs and then read 55 of those MRIs with five measurements per image made this an unrealistic goal for this study.

The key finding of this study is the relationship between the lateral axillary neurovascular bundle and the inferior articular margin. In every case, the lateral ANVB was inferior to the inferior articular margin of the humeral head and within a 22 mm window (Fig. 2). Identification of the inferior articular margin is easily reproducible and identifiable on intraoperative fluoroscopy as well as plain radiographs. This relationship dictates following as near anatomic reduction as possible that transverse screws placed above the inferior articular margin should be at decreased risk of injury to the ANVB. Conversely, calcar screws either originating in this region (as with a plate) or traversing this region (as with a nail) must be placed with added precaution.

Conclusion

Percutaneous screws placed at or above the level of the inferior articular margin of the humeral head are safe and will avoid the ANVB. Those placed within a 22 mm window below lateral projection of the inferior articular margin place the ANVB at risk for injury and extra caution should be used.

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