Safe Zone for Superolateral Entry Pin Into the Distal Humerus in Children: An MRI Analysis

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Abstract

Background The radial nerve is at risk for iatrogenic injury during placement of pins, screws, or wires around the distal humerus. Unlike adults, detailed anatomic information about the relationship of the nerve to the distal humerus is lacking in children.

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This work was performed at the Department of Orthopedics, Rutgers, New Jersey Medical School, Newark, NJ, USA.

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Question/purposes This study evaluates the relationship of the radial nerve to the distal humerus in a pediatric population on conventional MRI and proposes an anatomic safe zone using easily identifiable bony landmarks on an AP elbow radiograph.

Methods To determine the course of the radial nerve at the lateral distal humerus, we reviewed 23 elbow radiographs and MRIs of 22 children (mean age, 9 ± 4 years; range, 3–12 years) obtained as part of their workup for various elbow conditions. We described a technique using distance ratios calculated as a percentage of the patient's own transepicondylar distance, defined as the distance measured between the apices of the medial and lateral epicondyles, on the AP elbow radiograph and the midcoronal MR image. The cross-reference tool on a Picture Archiving and Communication System was then used to identify axial MR image at the level where the transepicondylar distance was measured. On this axial image, a line was drawn connecting the medial and lateral epicondyles (the transepicondylar axis) and its midpoint was determined. The radial nerve angle was measured by a line from the radial nerve to the midpoint of the transepicondylar axis and a line along the lateral half of the transepicondylar axis. On this axial slice, the closest distance from the nerve to the underlying cortex of the distal humerus was measured. To further localize the nerve along the distal humerus, predetermined percentages of the transepicondylar distance were projected proximally from the level of the transepicondylar axis along the longitudinal axis of the humerus on the midcoronal MR image. At these designated heights, the corresponding axial MR image was identified using the cross-reference tool and the nerve was mapped in a similar fashion. We then proposed a simpler method using a best-fit line drawn along the lateral supracondylar ridge on the AP radiograph to define the safe zone for lateral pin entry.

Results On axial MR images, the radial nerve was located in the anterolateral quadrant with a mean radial nerve angle of 54° (range, 35° – 87°) at 0% transepicondylar distance (23 MRIs), 41° (range, 24° – 63°) at 50% transepicondylar distance (23 MRIs), and $\geq 10^\circ$ at 75% transepicondylar distance (on the 13 MRIs that extended this far cephalad). The mean closest distance between the radial nerve and the underlying humeral cortex was 10 mm (range, 3–26 mm) at 0% transepicondylar distance and 7 mm (3–16 mm) at 50% transepicondylar distance. On the AP elbow radiograph, the height of the lateral supracondylar ridge, determined by a best-fit line drawn along the lateral cortex of the ridge, diverged from the most proximal extent of the ridge at a point located at 60% transepicondylar distance (range, 51%–76%). At the corresponding location on the axial MR image, the nerve was located anterolaterally with a mean radial nerve angle of 39° (range, 15° – 61°) and a mean distance of 6 mm (range, 2–10 mm) from the underlying humerus.

Conclusions Our data suggest that percutaneous direct lateral entry Kirschner wires and half-pins can be safely inserted in the distal humerus in children along the transepicondylar axis, either at or slightly posterior to the lateral supracondylar ridge, when placed caudal to the point located where the lateral supracondylar ridge line diverges from the proximal extent of the supracondylar ridge on AP elbow radiograph.

Introduction

The insertion of percutaneous pins and wires into the lateral distal humerus can cause injury to the radial nerve [12, 21, 23, 28, 30–32]. At this location, the variable course of the radial nerve leaves few absolute safe planes for placement of Kirschner wires, external fixator half-pins, transfixion wires (eg, Ilizarov), and retrograde flexible intramedullary nails. In adults, the reported frequencies of nerve injury with various methods of external fixation placed around the elbow range from 0% to 43% with the radial nerve being the most commonly affected [4, 9, 20–22, 25, 31, 32]. The true incidence of intraoperative radial nerve injury with these techniques when treating fractures and deformities of the upper extremity children is not well known [22].

In adults, the anticipated location of the radial nerve at the distal humerus is well described in the literature with strategies that reference anatomic landmarks and numerous absolute, proportionate, and percentage morphologic measurements [2, 3, 5, 8, 13–17, 27]. Difficulty in obtaining pediatric cadaveric specimens makes similar anatomic investigations in children unfeasible, leaving surgeons with only adult safe zone parameters and anecdotal strategies on how to minimize the risk of radial nerve injury during pin placement.

To our knowledge, an anatomic description of the radial nerve in children at the lateral distal humerus to help guide safe placement of pins has not been published. Because of varying limb size and proportion during growth, we developed a novel method to map the course of the radial nerve that uses a proportional measurement, independent of age and size, that is measurable on both an AP elbow radiograph and an elbow MRI. We then used this information to develop a straightforward parameter on the AP elbow radiograph that can be applied intraoperatively to describe a safe corridor with relation to the radial nerve for pin insertion around the distal humerus in children.

Patients and Methods

After institutional review board approval, MRIs and matched radiographs of the elbow were retrospectively collected in children between the ages of 3 and 17 years over an 11-year period (2000–2011) using a Picture Archiving and Communication System (PACS) web medical imaging archive retrieval database. MRIs were obtained during the routine workup for a skeletal or soft tissue lesion, trauma, or infection. We excluded patients with any tumors or pathology causing substantial alteration to the normal anatomy of the distal humerus and surrounding soft tissue (eg, fractures with > 4 mm of displacement). Thirty-two MRIs were identified, of which 23 scans in 22 patients met the inclusion criteria for the study. The mean age of the 22 patients included was 9 ± 4 years (range, 3–12 years), consisting of 15 males and seven females.

MRI diagnoses were lateral humeral condyle fracture (nine patients, all fractures with lateral gapping ≤ 4 mm), other elbow fractures (seven patients), other bony abnormalities (four patients), soft tissue trauma or elbow effusion (two patients), and normal (one patient) (Table 1). One patient (Patient Numbers 7 and 8) had two MRI studies that were both included: the initial MRI was obtained after successful closed reduction of an elbow dislocation and the second MRI was obtained 1 year later after the patient sustained repeated trauma to the same elbow. Nine patients were excluded: four with inadequate or incomplete MRI sequences, three too young, one without corresponding radiographs, and one with a cubitus varus deformity.

All MRIs were obtained with a 1.5-T magnet strength using a standard extremity coil and performed within 3 months of the elbow radiographs. Imaging studies were evaluated on a PACS workstation (Centricity RIS-I 4.2 Plus; GE Healthcare, Milwaukee, WI, USA). The readers could freely set display parameters such as zoom, brightness, contrast, and cross-reference of coronal and axial

Table 1. Summary of patient characteristics

Patient number	Age (years)	Sex	Laterality	Diagnosis on MRI	Elbow flexion	Height of most proximal axial MR image (percent of transepicondylar distance)
1	3	F	L	Lateral condyle fracture with < 2 mm of displacement	80°	103
2	3	M	L	Lateral condyle fracture with < 2 mm of displacement	35°	67
3	3	M	R	Lateral condyle fracture with 3 mm of displacement, healing	41°	97
4	4	F	R	Lateral condyle fracture with < 3 mm of displacement	18°	84
5	5	M	R	Normal	3°	46
6	5	M	L	Supracondylar fracture with intraarticular extension, nondisplaced, and a minimal extension deformity	22°	86
7	5	F	L	Heterotopic ossification at coronoid process	60°	109
8	6	F	L	Radial neck fracture, nondisplaced	4°	77
9	6	M	L	Lateral condyle fracture with < 2 mm of displacement	37°	78
10	7	M	R	Coronoid process bone bruise	23°	76
11	7	M	L	Radial head subluxation with nondisplaced radial head fracture	37°	58
12	7	F	R	Diffuse muscle edema	15°	143
13	8	M	L	Medial epicondyle fracture with < 4 mm of displacement	76°	91
14	8	M	R	Lateral condyle fracture, nondisplaced	79°	50
15	8	M	L	Lateral condyle fracture with < 3 mm of displacement	2°	73
16	9	M	L	Lateral condyle fracture, nondisplaced	79°	131
17	9	M	L	Radial neck fracture, nondisplaced	58°	68
18	10	M	R	Capitellar bone bruise	24°	65
19	10	F	L	Radial neck and proximal ulna fracture, nondisplaced	61°	80
20	10	M	R	Lateral condyle fracture with 4 mm of displacement, healing	40°	60
21	11	F	R	Trochlear osteochondral lesion, nondisplaced	63°	71
22	11	F	R	Posterior elbow soft tissue swelling, consistent with cellulitis	47°	95
23	12	M	L	Elbow effusion	23°	68

M = male; F = female; R = right; L = left.

images. Three investigators, including a fellowship-trained pediatric orthopaedic surgeon (TB) and two senior radiology residents (AM, UT), reviewed all MRI studies to select those that adequately visualized the radial nerve in consensus. Axial and coronal T1-weighted images were selected a priori, to minimize measurement variability, and used to measure morphometric parameters using the Line Measure Tool.

Evaluation of the Radial Nerve Using the Transepicondylar Distance

To determine the location of the radial nerve, the following steps were sequentially followed: (1) the transepicondylar distance [17], the distance in millimeters between the

apices of the medial and lateral epicondyles, was measured on the AP elbow radiograph (Fig. 1A); (2) the transepicondylar distance was measured on the midcoronal T1-weighted image of the same elbow (in millimeters) showing both the medial and lateral epicondyles in profile (Fig. 1B). For both the radiograph and MR images, if no epicondylar ossification center was present, the most medial and lateral bony points adjacent to the epicondyles were used; (3) on the midcoronal MR image, a line with the same length as the transepicondylar distance (measured in Step 2) was drawn proximally and vertically from the axis line of the transepicondylar distance along the longitudinal axis of the humerus (Fig. 2A). The axial MR image corresponding to the proximal extent of this line was assigned to represent the height of the nerve at 100% transepicondylar distance, half the distance of this line was assigned

Fig. 1A–B The transepicondylar distance (solid line) is shown on the (A) AP elbow radiograph and on the (B) midcoronal T1-weighted MR image (dashed line) of the same patient. The transepicondylar

distance was defined by the line measuring the largest distance between the medial and lateral epicondyles of the distal humerus.

to represent 50% transepicondylar distance, and the plane where this line bisected the transepicondylar distance was assigned to represent 0% transepicondylar distance (Fig. 2A–C); (4) the radial nerve was then located at the most proximal axial MR image obtained on the MRI. The distance from the most proximal axial image to the point representing 0% transepicondylar distance on the midcoronal image was measured by using the cross-reference tool. This distance was then converted to a percentage of the transepicondylar distance by dividing the height of the most proximal axial image by the transepicondylar distance (measured in Step 2) and multiplying it $\times 100$. Percentages were used because suggested absolute safe zone distances do not account for differences in size, thereby potentially limiting the amount of bony surface area available in the lateral distal humerus for fixation if applied to all children; (5) the radial nerve angle was measured on the axial plane, between the lateral half of the transepicondylar axis and a line drawn from the radial nerve to the midpoint of the transepicondylar axis (Fig. 2B–C). The transepicondylar axis defined a line drawn spanning the medial and lateral epicondyles on the axial T1-weighted image at the level of the transepicondylar distance. The radial nerve angle was measured at 0%, 50%, and 100% transepicondylar distance, and at the most proximal axial MR image (calculated as a percentage of transepicondylar distance) by scrolling to the designated axial image and superimposing the transepicondylar axis to maintain the reference line. Positive angles represented the location of the nerve anterior to the transepicondylar axis (ie, orientations toward the anterior aspect of the distal humerus) and negative angles

represented the location of the nerve posterior to the transepicondylar axis; and (6) the closest distance from the radial nerve to the humerus was measured on the axial plane. This distance was defined as the closest distance from the nerve to the underlying distal humerus cortex (in millimeters) measured on the axial MR image corresponding to 0%, 50%, and 100% transepicondylar distance as well as at the most proximal axial image (Fig. 2B–C).

Evaluation of the Radial Nerve Using the Lateral Supracondylar Ridge Line

Because the radial nerve was consistently anterolateral to the lateral supracondylar ridge on our initial MRI analysis and this bony landmark is easily visualized radiographically, we sought to develop a simple, less time-consuming approach of determining the height of the ridge from which to reference the location of the nerve. Our initial MRI analysis also determined that a safe zone for direct lateral distal humerus pin fixation included an area lying within the caudal 60% to 80% of a line equivalent in length to the patient's own transepicondylar distance projected proximally from the intersection of the transepicondylar distance and the longitudinal distal humerus axis. A preliminary pilot study revealed that the proximal point at which the ridge diverged from a line drawn along the lateral supracondylar ridge correlated to a region defined within the upper limits of this safe zone (Fig. 3). We therefore sought to develop a correlation among this point along the ridge, the transepicondylar distance, and the location of the radial

Fig. 2A–C To measure the radial nerve angle and the closest distance from the radial nerve to the humerus, lines are initially drawn representing 0% (solid line), 50% (dashed line), and 100% (dashed line) of the transepicondylar distance on the T1-weighted midcoronal MR image (A). The location of these lines is determined by projecting the specified percentage distances of the transepicondylar distance (measured on the midcoronal MR image) proximally along the midlongitudinal axis of the distal humerus. The double arrow solid line represents 100% transepicondylar distance projected along the longitudinal axis of the distal humerus. Next, the cross-reference tool is used to identify the T1-weighted axial MR image corresponding best to the level at 0% transepicondylar distance (B). On this image, the radial nerve angle (θ) is measured using a coordinate system that includes the transepicondylar axis (dashed line) and the axis

perpendicular to this line at the midpoint between the epicondyles (dotted line). h is designated a positive value if the radial nerve lies anterior to the lateral projection of the transepicondylar axis and negative value if it lies posterior to the lateral projection of the transepicondylar axis. On the same image, the closest distance from the radial nerve to the underlying humerus (D) is measured (solid double arrow). (C) The T1-weighted axial image corresponding best to the level at 50% transepicondylar distance is selected and h is measured using the same coordinate system that is superimposed at this image as is D . This technique is repeated at 100% transepicondylar distance and at the most proximal axial MRI image. TEA = transepicondylar axis; ME = medial epicondyle; LE = lateral epicondyle; TB = triceps brachii; RN = radial nerve.

nerve using the AP elbow radiograph and MRI of the same elbow of the same included patients.

On the AP elbow radiograph, the best-fit line along the lateral supracondylar ridge was drawn (Fig. 3) and a point was placed along the line where it began to deviate from the curvature of the proximal extent of the ridge. At the level of this point, a second line was drawn perpendicular to the longitudinal axis of the humerus. We then measured the distance from this line to the transepicondylar distance (in millimeters) along the longitudinal axis of the humerus. This measurement was converted to a percentage of transepicondylar distance by dividing it by the patient's transepicondylar distance (measured on the same radiograph). This ratio was then multiplied by the transepicondylar distance measured on the patient's midcoronal MR image and the resulting distance was projected proximally from the transepicondylar distance along the longitudinal humeral axis on the midcoronal MR image. The MR axial image most closely corresponding to this height was identified using the cross-reference tool. On this image, the radial nerve angle and closest distance

from the nerve to the underlying distal humerus cortex were measured in a similar fashion to our initial method.

All measurements (Table 2) were performed by three independent readers (TB, AM, UT). Two of the observers (TB, JK, a senior orthopaedic resident) assessed both MRI and radiographs in a subset of 12 patients twice at least 2 weeks apart to assess interobserver and intraobserver reliability of the measurement techniques. All measurements on radiographs were made blinded to measurements on MRI.

Statistical Analysis

Statistical analysis was performed with use of SAS software (Version 9.2 for Windows; SAS Institute, Cary, NC, USA). Intraobserver and interobserver reliability was estimated using intraclass correlation coefficient (ICC) as described by Winer [34]. The interobserver reliability, agreement among the three observers for each of the measurements, was estimated with a more general linear

Fig. 3 To locate the radial nerve at the most proximal extent of the lateral supracondylar ridge, a best-fit line is drawn along the ridge (dashed white line) on the AP elbow radiograph. A point is identified where the supracondylar ridge begins to divert proximally from this line (marked “x”). A line is drawn from this point perpendicular to the longitudinal axis of the humerus (solid black line). The distance from the black line to the transepicondylar distance (solid white line with dots) is measured along the longitudinal axis of the humerus (solid double arrow line). This measurement is then converted to a percentage by dividing it by the transepicondylar distance to determine the height. This percentage is then multiplied by the transepicondylar distance (measured on the midcoronal MRI of the same patient) to determine the ridge height on the MRI. The nearest axial T1-weighted MR image corresponding to this height is selected using the cross-reference tool and θ and D are measured.

model to account for the observer differences. The intra-observer reliability was determined for all analyzed parameters using 12 randomly selected cases. According to Kuklo et al. [18], intra- and interobserver correlation of 0 to 0.24 reflected absent to poor, 0.25 to 0.49 low, 0.50 to 0.69 fair/moderate, 0.7 to 0.89 good, and 0.90 to 1.0 excellent correlation. The transepicondylar distance was plotted against stratification by the patient’s age at MRI. Simple regression analysis was used to assess the relationship between various morphometric measurements of the location of the radial nerve and transepicondylar distance percentage. The unpaired t-test was used to assess differences in the radial nerve angle, closest distance from the radial nerve to the humerus, and degree of elbow flexion ($\leq 45^\circ$ versus $> 45^\circ$). A p value of < 0.05 was considered significant for all analyses.

Results

Evaluation of the Radial Nerve Using Transepicondylar Distance

All 23 MRI studies imaged the radial nerve at 0% transepicondylar distance and at 50% transepicondylar distance, where the nerve was consistently located at least $> 20^\circ$ anterolaterally to the transepicondylar axis in the axial plane: mean radial nerve angle at 0% transepicondylar distance was 54° (range, 35° – 87°), which decreased to 41° (range, 24° – 63°) at 50% transepicondylar distance (Fig. 4). For the 13 MRI studies with axial slices that extended to 75% transepicondylar distance, the radial nerve was beyond a 10° arc anterior to the transepicondylar axis in the axial plane. Four MRIs extended to 100% transepicondylar distance, where the radial nerve angle ranged from 0° to 50° . The closest distance between the radial nerve and the underlying humeral cortex was a mean of 9.5 mm (3–26 mm) at 0% transepicondylar distance and 7 mm (3–16 mm) at 50% transepicondylar distance (Fig. 5).

The mean transepicondylar distance was 44.4 mm (range, 31–63 mm) on AP elbow radiographs and 45.9 mm (range, 33–56 mm) on midcoronal MR images. There was a mean difference between the transepicondylar distance on radiographs and MRI of 1.5 mm ($p < 0.02$); both measurements tended to increase with age ($p < 0.05$). There was no statistically different association found between side or sex and radial nerve angle and closest distance from the nerve to the humerus (all p values > 0.25).

The interobserver ICC ranged from 0.65 to 0.99 for the distance and angle measurements on radiographs and MR images ($p < 0.001$ for all measurements). Intraobserver reliability was moderate for the closest distance from the radial nerve to humerus at 0% transepicondylar distance (0.67), good for the closest distance from the radial nerve to humerus at the most proximal axial MR image (0.84), and excellent for all other radiographs and MRI measurements (0.93–0.99).

Evaluation of the Radial Nerve Using the Lateral Supracondylar Ridge Line

On the AP elbow radiograph, the point at which the lateral supracondylar ridge diverges from the lateral supracondylar ridge line corresponds to a mean of 60% transepicondylar distance (range, 51%–76%). Nineteen MRIs imaged the nerve to 60% transepicondylar distance; the mean radial nerve angle was 39° (range, 15° – 61°), and the mean closest distance from the radial nerve to the humerus was 6 mm (range, 2–10 mm).

The radial nerve angle was larger in greater degrees of elbow flexion ($> 45^\circ$ compared with $\leq 45^\circ$) at 0%

Table 2. Thirteen anatomic radiographic and MRI measurements

Radial nerve evaluation method	Measurement	Description
Transepicondylar distance method	AP transepicondylar distance	Distance between the medial and lateral epicondyles on AP elbow radiograph (mm)
	MRI transepicondylar distance	Distance between the medial and lateral epicondyles on midcoronal T1-weighted MR image (mm)
	Elbow flexion angle on MRI	Amount of elbow flexion on midsagittal MRI (degrees)
	Radial nerve angle at 0% transepicondylar distance	Angle θ on Fig. 2; determined from the axial MR image at the level where the MRI transepicondylar distance is measured (degrees)
	Closest distance from radial nerve to humerus at 0% transepicondylar distance	Measurement D on Fig. 2; determined from the axial MR image at the level where the MRI transepicondylar distance is measured (mm)
	Radial nerve angle at 50% transepicondylar distance	Angle θ on Fig. 2; determined from the axial MR image at the level corresponding to 50% transepicondylar distance proximal to where the MRI transepicondylar distance is measured (degrees)
	Closest distance from radial nerve to humerus at 50% transepicondylar distance	Measurement D on Fig. 2; determined from the axial MR image at the level corresponding to 50% transepicondylar distance proximal to where the MRI transepicondylar distance is measured (mm)
	Height of most proximal axial MR image	Distance from 0% transepicondylar distance to the point along the distal humerus at which the most proximal axial MR image is obtained; measured on midcoronal image (mm)
	Radial angle at most proximal axial MR image	Angle θ on Fig. 2; determined from the most proximal axial MR image (degrees)
	Closest distance from radial nerve to humerus at most proximal axial MR image	Measurement D on Fig. 2; determined from the most proximal axial MR image (mm)
Lateral supracondylar ridge line method	Percent transepicondylar distance on AP-lateral supracondylar ridge line	Technique described in Fig. 3; determined on AP elbow radiograph using lateral supracondylar ridge line method
	Radial nerve angle at lateral supracondylar ridge line	Angle θ on Fig. 2; determined from the axial MR image at the level corresponding to percent transepicondylar distance on AP-lateral supracondylar ridge line (degrees)
	Shortest distance from radial nerve to humerus at lateral supracondylar ridge line	Measurement D on Fig. 2; determined from the axial MR image at the level corresponding to percent transepicondylar distance on AP-lateral supracondylar ridge line (mm)

transepicondylar distance, 50% transepicondylar distance, and at the lateral supracondylar ridge line point ($p < 0.05$ for all measurements). However, in all of these locations, the closest distance between the nerve and the underlying humeral cortex was not statistically altered by elbow flexion.

The interobserver reproducibility for the two readers was found to be good for calculation of the percent transepicondylar distance on AP-lateral supracondylar ridge line (ICC, 0.81) and excellent for all MRI measurements (ICC, 0.90–0.94). The intraobserver reliability for the calculation of the percent transepicondylar distance on the AP-lateral supracondylar ridge line was found to be good (ICC, 0.725) and excellent for all MRI measurements (ICC, 0.97).

Discussion

The radial nerve is at inherent risk for injury from percutaneous pinning and with various external fixation methods around the distal humerus. This anatomic study of the

radial nerve in children set out to describe the variation of the nerve at the distal humerus and determine a safe working zone for the nerve at the distal humerus using MRI and radiographic analysis.

Our study had several limitations. First, radiographic distances may not correspond exactly to MRI distances because of soft tissue or magnification variations. However, the magnitude of such alterations was small (eg, the mean difference between the transepicondylar distance measured on radiographs and MRI was 1.5 mm). Second, although the best slice was chosen for anatomic analysis, the position of the elbow during imaging could have resulted in off-axis measurements to the anatomic orthogonal axes of the distal humerus (ie, we assumed the axial MR images were on a plane perpendicular to the longitudinal humeral shaft axis). We did not assess this in this study.

Third, nearly all the studies demonstrated pathology around the elbow. This may account for some variability in the data, but this variation cannot be quantified in this study

Fig. 4 Percent transepicondylar distance and radial nerve angle for the 23 MRIs reviewed. Percent transepicondylar distance represents the longitudinal height at which the nerve was assessed as a percentage of transepicondylar distance and then projected proximally from the transepicondylar distance along the longitudinal axis of the humerus. Zero percent transepicondylar distance corresponds to the level of the transepicondylar distance. Fifty percent transepicondylar distance corresponds to the height of half the transepicondylar distance. All other percent transepicondylar distance measurements represent the location of the nerve at the most proximally obtained axial MR image. The greater the percent transepicondylar distance, the more proximal along the arm is the point at which the radial nerve was assessed.

Fig. 5 Percent transepicondylar distance and the closest distance to the radial nerve from the humeral cortex for the 23 MRIs reviewed. The greater the percent transepicondylar distance, the more proximal along the arm is the point at which the nerve was assessed.

without including a control group or obtaining comparison imaging of the contralateral elbow to determine reference values of the normal radial nerve anatomy. MRIs in children usually necessitate conscious sedation or anesthesia and are difficult to obtain in asymptomatic children for many practical reasons. Likewise, validation of our results either in cadavers or surgical patients is problematic in the pediatric population. Although in practice we operate

primarily when pathology is present, making the findings clinically applicable, other pathological states (eg, bleeding and swelling after fracture or deformity) may alter nerve location and bony landmarks. Displaced fractures in this region may disrupt the normal position of the radial nerve and make it difficult to draw the lateral supracondylar ridge line. However, most pediatric fractures around the distal humerus (eg, supracondylar fractures) are successfully anatomically aligned with closed reduction, after which the lateral supracondylar line can be drawn on the AP fluoroscopy image, before pinning.

Fourth, the total number of limbs with adequate MRIs was modest. Increasing the sample size to include patients uniformly distributed throughout a wide age range of pediatric patients may decrease the confidence intervals of our data and further define the largest potential absolute safe zone for avoiding the nerve. Fifth, the lack of MRI scanning of the more proximal aspect of the humerus resulted in few data points at this location and an inability to map the nerve where it laid directly lateral to the humerus. More elbow MRIs, that include more proximal MRI slices, could be evaluated in a future study. Finally, we did not assess the effect of forearm rotation on the position of the nerve. Because of these limitations, our recommended safe zone for the radial nerve was restricted to describing a strict lateral entry point that was well away from the nerve at its dorsal to ventral crossing point on the lateral aspect of the distal humerus (ie, within the caudal 60% of the transepicondylar distance projected proximally from the transepicondylar axis along the longitudinal humeral axis is safer than more cephalad placement). Although the nerve may be located anterior to the lateral supracondylar ridge for at least 100% transepicondylar distance, we hesitate to draw any conclusions regarding the location of the nerve at this region because only four MRIs contained axial images extending > 100% transepicondylar distance.

Nerve injury can occur during insertion of transfixion wires and half-pins as well as during dissection, drilling, and corticotomy [7]. To avoid intraoperative radial nerve injury, Tetsworth et al. recommend that transfixion Kirschner wires in the coronal plane should be inserted at the proximal margin of the epicondyles [32]. For half-pins, several authors advocate modifying the standard lateral introduction point to one just posterior to the lateral supracondylar ridge, exiting the anteromedial humeral cortex [15, 17, 26]. Some authors recommend a miniopen approach and pin insertion under direct visualization as a result of the anatomic variability of the radial nerve in this region [6, 7]. Regardless of the methods used to protect the nerve, strict adherence to the standard surgical technique when inserting lateral half-pins includes: blunt dissection to the bone, the use of a soft tissue protective sleeve placed

directly on the bone, and minimizing motion between the sleeve and the bone during pin insertion.

Radial nerve injury can occur when inserting a proximal lateral entry descending pin during percutaneous cross-pinning (“Dorgan’s” technique) of pediatric supracondylar humerus fractures [29, 30]. This technique achieves bicolumnar fixation by inserting a second superolateral pin through the lateral cortex, proximal to the fracture, and driving it across the fracture into but not through the medial condyle. To avoid injuring the nerve using the “Dorgan’s” pin, several authors recommend that the proximal Kirschner wire pierce the skin posterior to the lateral midline just above the level of the fracture and using a starting point just posterior to the ridge [1, 11, 29, 30]. Eberhardt et al. anecdotally maintained that this technique is safe because the proximal antegrade pin is “at least 2 cm distal” to the radial nerve [10]. To avoid endangering the nerve during retrograde flexible nailing of pediatric humerus fractures, Lascombes et al. recommended that entry holes in the distal humerus be made 20 mm above the lateral epicondyle [19].

Although sound surgical technique can minimize the risk of nerve injury, to our knowledge, we are unaware of anatomical morphometric studies of the radial nerve or published safe working zones in the lateral distal humerus in children. Previously reported safe zones in adults [2, 3, 5, 13–15, 24, 33] do not account for varying humeral dimensions in children and studies that rely on measurement of the total length of the humerus to calculate a ratio for the location of the nerve may be difficult to practically apply. Usually, when performing surgery around the distal humerus, the proximal end and shoulder are draped and out of the surgical field complicating the use of such measurements intraoperatively either with palpation or with fluoroscopy.

Kamineni et al. measured the distance from the lateral epicondyle to the radial nerve in 70 adult cadaveric specimens expressing this height as a percentage of the transepicondylar distance [17]. They observed the nerve to be no closer than 1.4 times the transepicondylar distance when projected proximally from the lateral epicondyle and concluded that direct lateral placement of half-pins can be placed safely, if within the caudal 70% of the patient’s own transepicondylar distance projected from the lateral epicondyle. Although we chose to reference the location of the nerve with respect to the longitudinal humeral axis (to allow us to measure the lateral angle of the radial nerve), our results were compatible with their data. We found that within the caudal 60% of the transepicondylar distance, the nerve was anterior to the lateral supracondylar ridge in all subjects, crossing the intramuscular septum more cephalad, thereby confirming this safe lateral corridor in children.

On the axial plane, we found wide variability in the closest distance from the radial nerve to the humeral

cortex, mean 9.5 ± 5 mm at 0% transepicondylar distance, 7 ± 3 mm at 50% transepicondylar distance, and 6 ± 2 mm at the point identified by the lateral supracondylar ridge line. The close proximity of the nerve to the humerus in this region may explain the inherent risk of direct or indirect nerve injury. Indirect injury may occur by inadvertent skating of the half-pin from the sharp lateral supracondylar ridge onto the anterior humerus or by wrapping up soft tissues or “tenting” the nerve around the screw threads. Although increasing elbow flexion greater than 45° did not alter the distance of the nerve from the underlying cortex, it did increase the radial nerve angle. It seems reasonable to conclude that flexing the elbow during lateral pinning may move the nerve further anterior and reduce the risk of injury.

We developed the lateral supracondylar ridge line method to define a safe and straightforward parameter that can be transferred to all pediatric patients and be applied intraoperatively. We believe this method is reproducible with the radial nerve consistently located anterior to the transepicondylar axis at the point where the lateral supracondylar ridge line diverges from the ridge. Further studies using MRI or ultrasound [1, 14] may be able to assess the position of the elbow where the radial nerve is at its most anterior position and improve our ability to define the absolute proximal safe zone in children. In conclusion, we recommend percutaneous lateral-entry Kirschner wires and half-pins placed in the distal humerus should be placed caudal to a point where the lateral supracondylar ridge diverges from the lateral supracondylar ridge line, either at or slightly posterior to the lateral supracondylar ridge, and aiming slightly anteromedial (Fig. 3).

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