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Original Research

# Utility of Ultrasound for Identifying Median Nerve Changes Indicative of Acute Carpal Tunnel Syndrome After Distal Radius Fracture

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A R T I C L E I N F O

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*Purpose:* Ultrasound offers a fast and inexpensive way to evaluate the median nerve. However, there is a paucity of data assessing ultrasound in acute trauma. Our study aimed to characterize median nerve changes indicative of acute carpal tunnel syndrome (ACTS) in a cadaveric distal radius fracture (DRF) model.

*Methods:* We used 10 upper-extremity specimens. We induced ACTS (carpal tunnel pressure >40 mm Hg) in a distraction-only model and then used a DRF model as a neutral position, under traction, or wrist extension. We measured the median nerve cross-sectional area (CSA), height, and width with ultrasound in each model. We used a novel calculation, height-width ratio (HWR), to describe nerve shape. A low HWR indicates an elliptical shape; as the HWR increases toward one, the shape becomes more circular. The CSA measurements and HWR at pressures >40 mm Hg were used to calculate a 95% confidence interval, which defined the threshold for ACTS.

*Results:* Wrist distraction created carpal tunnel pressures >40 mm Hg in all specimens. Distraction increased CSA compared with baseline (9.1 ± 0.9 $mm^2$ vs 6.3 ± 1.2 $mm^2$, $P < .001$). Under ACTS-level pressures, the thresholds for CSA and HWR were 8.5 $mm^2$ and 0.41, respectively. HWR significantly increased with distraction compared with baseline (0.47 ± 0.10 vs 0.28 ± 0.09, $P = .006$). Most neutral DRF models ($n = 8$, 80%) met the CSA threshold for ACTS, whereas all specimens with a DRF extended or under traction had CSAs above the ACTS threshold. Compared to the baseline, the shape of the median nerve was more circular in all DRFs, including neutral (0.28 ± 0.09 vs 0.39 ± 0.13), under traction (0.43 ± 0.09), and extended (0.45 ± 0.09).

*Conclusions:* ACTS should be suspected in patients with median nerves demonstrating increased CSA and adopting a more circular shape. Fracture positioning impacts median nerve CSA with wrist extension, causing the greatest change. Median nerve HWR may offer an easier ultrasonographic alternative to CSA.

*Type of study/level of evidence:* Diagnostic III.

Carpal tunnel syndrome (CTS) is the most prevalent peripheral neuropathy[1] and is typically diagnosed by history, physical examination, and electrodiagnostic studies. However, electrodiagnostic studies have limitations; they are invasive, not readily available, and expensive. Ultrasound offers a noninvasive, fast, and inexpensive way to evaluate the median nerve and is emerging as a new accurate diagnostic test for CTS[2,3] with a sensitivity and specificity of up to 91% and 94%, respectively.[4–6] CTS presents with focal enlargement of the median nerve at the wrist,[7,8] which can be measured via ultrasonography as an increased nerve cross-sectional area (CSA). Morphological changes in the cross-sectional nerve shape have also been reported.[9]

Although studies have demonstrated the utility of ultrasound in the diagnosis of CTS,[3,7,8,10,11] there is a paucity of data assessing ultrasound in acute trauma. Acute CTS (ACTS) is a recognized complication after hand trauma, such as distal radius fracture (DRF),[12] with an incidence of 4% to 31%.[13–15] Moreover, wrist traction and fracture displacement are associated with an increased likelihood of complications after DRFs[13,16,17] and may increase the

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risk of developing ACTS.[13,18,19] ACTS is progressive, develops rapidly, and presents as painful paresthesia in the median nerve distribution. Failure to recognize ACTS and perform nerve decompression can lead to permanent median nerve dysfunction or complex regional pain syndrome (CRPS).[12,20–22]

ACTS is challenging to diagnose. Currently, physical examination is one of the few ways to diagnose ACTS, but it can be difficult after acute injury. DRFs are the most common fractures seen in the emergency department.[23] Therefore, we selected an intraarticular DRF model for this study. The purpose of our study was to characterize median nerve changes and assess the utility of ultrasound for the diagnosis of ACTS in various DRF settings. We hypothesized that the median nerve CSA would increase in ACTS, similar to that observed in nonacute CTS.

## Materials and Methods

We decided to model three different intraarticular DRF scenarios: in a neutral position (to represent nondisplaced fracture), with traction (eg, over-distracted external fixation), and in extension (to mimic fracture displacement). This was a cadaveric study using 10 upper extremities amputated at the mid-humerus. We were unable to directly measure carpal tunnel pressure in the distal radius model because the DRF violated the volar cortex and reduced the accuracy of carpal tunnel pressure measurements. However, distraction alone has been shown to increase carpal tunnel pressure in a predictable manner in a cadaver model.[24] Hence, we used the wrist distraction model with a 2.7 kg weight to create carpal tunnel pressures corresponding to ACTS (equal to or greater than 40 mm Hg[25]) and measured median nerve CSA and height-width ratio (HWR) for each specimen. Thus, the median nerve CSA from the wrist distraction model was used as a proxy indicator for ACTS for each specimen. After creating the DRF model, median nerve ultrasound measurements were recorded with the wrist in a neutral position (nondisplaced fracture) during the suspension of a 2.7 kg weight (fracture under traction) and at 30° wrist extension (displaced fracture). Therefore, the distraction model and measurements were completed first, followed by the DRF models and measurements.

### *Carpal tunnel pressure measurement*

To measure the carpal tunnel pressure, the transverse carpal ligament was punctured at a point halfway between the hook of the hamate and scaphoid tubercle using a hollow metal tube with a sharp beveled tip. This was accomplished using a Centurion Compass compartment pressure monitoring kit (Grayline Medical, Inc). Carpal tunnel pressures greater than 40 mm Hg have been reported to indicate ACTS.[25]

### *Median nerve ultrasonography*

The median nerve was evaluated with high-resolution ultrasonography using a Sonimage HS2 Ultrasound Machine (Konica Minolta, Inc) by a hand fellow with training in musculoskeletal ultrasonography. After training, the fellow performed median nerve measurements that were then checked by a second trained ultrasound operator to confirm adequate training and performance. All median nerve measurements were completed by a single operator. We employed a direct tracing method to identify the site of maximal enlargement of the median nerve at the wrist, up to 3 cm proximal to the distal wrist crease. At the point of maximal enlargement, we recorded the median nerve CSA ($mm^2$), height (mm), and width (mm) as measured by ultrasonography. This method has been used in several studies.[10,11,26–29] After outlining the circumference of the median nerve, the Sonimage HS2 Ultrasound Machine calculated nerve CSA (Fig. 1). The median nerve HWR was calculated to characterize the cross-sectional shape of the nerve. A low HWR indicates an ellipsoid shape; as the HWR increases toward 1, the nerve shape becomes more circular.

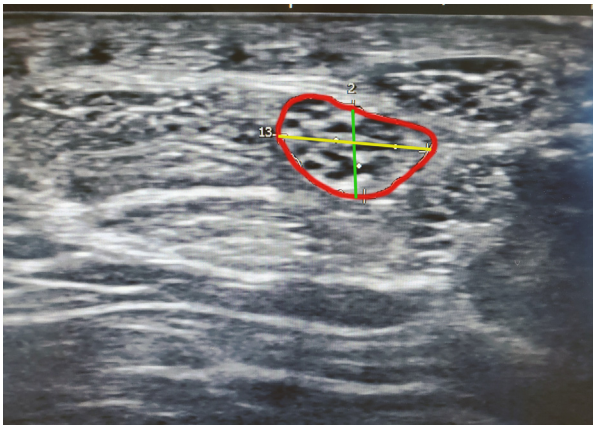

**Figure 1.** Image of median nerve and ultrasonography measurements. The red line represents the outline of the nerve used to calculate the CSA. The green line denotes nerve height. The yellow line indicates nerve width.

### *Specimen suspension*

The experimental design was based on a previously published work.[24] For each specimen, the forearm was held in neutral rotation, and two half-pins were drilled through the radius and into the ulna at the mid-forearm level. Next, the specimen was suspended vertically in a vice with the hand positioned downward. A finger trap was placed on the middle finger and sutured in position to prevent slippage. The sequence of events was as follows: distraction model (baseline measurements then distraction with 2.7 kg), DRF in the neutral position, DRF with traction, and DRF in wrist extension.

### *Wrist distraction model*

The distraction force selected was a 2.7 kg weight. Previous studies have validated the use of 2.7 kg weight suspension on cadaveric upper extremities with the wrist in a neutral position to create carpal tunnel pressures equal to or greater than 40 mm Hg.[24,25] The weight was suspended from the middle finger by a string with the wrist in the neutral position (Fig. 2). The weight was suspended for a maximum of 5 minutes. Carpal tunnel pressure and median nerve ultrasound measurements were recorded at baseline and during the suspension of the weight. This same technique was used in the DRF traction model (see below).

### *Distal radius fracture model*

A dorsal incision was made on each specimen, and an intraarticular AO type C1 DRF was produced using a previously described technique.[30] First, we excised a 1 cm dorsally-based wedge 2.5 cm proximal to the radiocarpal joint using an oscillating saw. This simulated the dorsal comminution. Then, we created a sagittal split in the plane between the scaphoid and lunate fossa (Fig. 3). Each specimen was resuspended, and median nerve CSA, height, and width were recorded. The maximal point of nerve enlargement was identified each time before measurements were taken. The measurements were taken in three different DRF

**Figure 2.** Photograph of the experimental design for weight suspension. The cadaveric specimen is mounted on a vice with the hand pointed downwards. The weight was suspended from the middle finger by a string with the wrist in a neutral position.

**Figure 3.** Photograph of a specimen following the creation of DRF. There is a sagittal split between the scaphoid and lunate fossa and a transverse split 2.5 cm proximal to the radiocarpal joint.

models: (1) in a neutral position (to represent nondisplaced fracture), (2) with 2.7 kg traction (eg, over-distracted external fixation), and (3) in wrist extension (to mimic fracture displacement). Displacement was created by positioning the specimen at 30° of wrist extension. The vice was rotated so the coronal plane of the forearm placed the wrist in a 30° extension with the horizontal plane and kept the sagittal plane of the forearm perpendicular to the horizontal plane. The DRF models were performed sequentially on specimens, and the median nerve was allowed to return to its original morphology before the next model was placed.

**Table 1**
Carpal Tunnel Pressure in the Wrist Distraction Model

| Cadaveric Specimen | Carpal Tunnel Pressure (mm Hg) | |
|---|---|---|
| | At Baseline | With a 2.7 kg Weight |
| 1 | 10 | 63 |
| 2 | 13 | 56 |
| 3 | 7 | 52 |
| 4 | 29 | 59 |
| 5 | 17 | 47 |
| 6 | 8 | 42 |
| 7 | 10 | 47 |
| 8 | 9 | 49 |
| 9 | 13 | 61 |
| 10 | 10 | 62 |

### *Data analysis*

Composite data were stored in a preformatted spreadsheet in Microsoft Excel (Microsoft 2016). The median nerve CSA measurements and HWR from the wrist distraction model at carpal tunnel pressures >40 mm Hg (indicative of ACTS) were used to calculate a 95% confidence interval. CSA and HWR values below the lower bound of the 95% confidence interval did not meet the threshold for ACTS.

We performed statistical analysis using IBM SPSS software version 28.0 (IBM Corporation). Shapiro-Wilk testing demonstrated that carpal tunnel pressure did not follow a normal distribution; therefore, median values were reported for this continuous variable. Median nerve CSA, height, width, and HWR followed a normal distribution; therefore, mean values and standard deviations were reported for these continuous variables. We used the paired *t* test to evaluate differences in median nerve CSA, height, width, and HWRs between the groups. The statistical significance was set as a two-tailed value of $P \leq .05$.

## Results

At baseline, the median carpal tunnel pressure was 10 mm Hg. In the wrist distraction model, the 2.7 kg weight produced carpal tunnel pressures greater than 40 mm Hg in all specimens (Table 1). The highest carpal tunnel pressure was observed in specimen 1 (63 mm Hg), which also experienced the greatest change in pressure (+53 mm Hg). The suspension of the 2.7 kg weight (distraction) significantly increased median nerve CSA (9.1 ± 0.9 mm$^2$ vs 6.3 ± 1.2 mm$^2$, $P < .001$) and height (2.1 ± 0.5 mm vs 1.4 ± 0.3, $P = .003$) compared with baseline. However, median nerve width significantly decreased with the suspension of the weight than without the weight (4.5 ± 0.6 mm vs 5.1 ± 1.0 mm, $P = .031$). Therefore, the HWR significantly increased with distraction compared with baseline (0.47 ± 0.10 vs 0.28 ± 0.09, $P = .006$). This indicates that the median nerve, in its region of the largest size, became less elliptical and more circular with increased carpal tunnel pressure. The 95% confidence interval for CSA and HWR during distraction when carpal tunnel pressures were >40 mm Hg were 8.5–9.6 mm$^2$ and 0.41–0.53, respectively.

After DRF, the median nerve CSA for each specimen was compared with the 95% confidence interval from the wrist distraction model. Most specimens with nondisplaced DRFs were above the CSA threshold for ACTS (n = 8, 80%). However, only three specimens in the neutral position (30%) were above the HWR threshold for ACTS. When the DRF models were placed under traction, all specimens demonstrated median nerve CSAs above the ACTS threshold, and 60% (n = 6) of specimens demonstrated HWRs above the ACTS threshold. Similarly, all DRFs in wrist extension

**Table 2**
Ultrasonography Measurements of the Median Nerve in the Three DRF Models

| Ultrasonographic Measurements | Fracture in Neutral Position | Fracture With Traction | Fracture in Wrist Extension | *P* value (Neutral Position vs With Traction) | *P* value (Neutral Position vs Wrist Extension) | *P* value (With Traction vs Wrist Extension) |
|---|---|---|---|---|---|---|
| Mean CSA (mm$^2$) | 9.75 ± 1.37 | 11.60 ± 1.81 | 13.73 ± 2.21 | .003* | <.001* | .004* |
| Mean nerve height (mm) | 2.16 ± 0.47 | 2.21 ± 0.32 | 2.82 ± 0.35 | .790 | .012* | <.001* |
| Mean nerve width (mm) | 5.75 ± 1.13 | 5.30 ± 0.99 | 6.40 ± 0.88 | .169 | .116 | .015* |
| Mean HWR | 0.39 ± 0.13 | 0.43 ± 0.09 | 0.45 ± 0.09 | .227 | .155 | .760 |

* Statistical significance

demonstrated median nerve CSAs above the ACTS threshold, and 80% demonstrated HWRs above the ACTS threshold.

The ultrasound characteristics of the median nerve changed with fracture fragment positioning (Table 2). DRF under traction or wrist extension (displaced fracture) had a greater median nerve CSA compared with neutral position (nondisplaced) (11.6 ± 1.81 mm$^2$ vs 9.75 ± 1.37 mm$^2$; 13.73 ± 2.21 mm$^2$ vs. 9.75 ± 1.37 mm$^2$, respectively). Additionally, DRF models in wrist extension (displaced) had a greater CSA than those with traction (13.73 ± 2.21 mm$^2$ vs 11.6 ± 1.81 mm$^2$, $P = .004$). The HWR also changed with the fracture fragment position (Fig. 4). Compared with the baseline, the shape of the median nerve was more circular in the neutral position DRF (0.28 ± 0.09 vs 0.39 ± 0.13), with traction (0.28 ± 0.09 vs 0.43 ± 0.09), and in wrist extension (0.28 ± 0.09 vs 0.45 ± 0.09). There was no statistically significant difference in the HWR between the DRF models ($P > .05$).

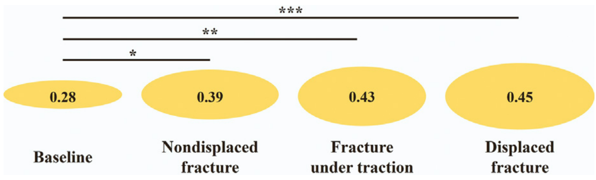

**Figure 4.** Diagram of the HWR of the median nerve for baseline and DRF models: neutral position (nondisplaced), under traction, and in wrist extension (displaced). A low HWR indicates an ellipsoid shape; as the HWR increases toward 1, the nerve shape becomes more circular. *$P = .036$, **$P = .009$, and ***$P = .013$.

## Discussion

This study assessed the utility of ultrasound for evaluating potential ACTS in a DRF cadaver model and characterized ultrasound changes in the median nerve during increased carpal tunnel pressure. Furthermore, we report on the morphological changes in nerve shape associated with increased carpal tunnel pressures. We demonstrated that changes in carpal tunnel pressure could be detected as increased median nerve CSA by ultrasound. We report three key findings: (1) a median nerve CSA threshold of 8.5 mm$^2$ and HWR threshold of 0.41 could identify the clinical risk of ACTS; (2) fracture fragments with traction or wrist extension had a larger CSA than nondisplaced fractures; and (3) increased carpal tunnel pressure is associated with a change in nerve shape, resulting in a more circular appearance at higher pressures that are represented by a nerve HWR. Therefore, the median nerve HWR may offer an ultrasonographic alternative that is easier to measure than CSA to evaluate potential ACTS.

Our median nerve CSA threshold value of 8.5 mm$^2$ at the wrist is consistent with prior studies that report cut-off CSA values of 8.5–10 mm$^2$.[3,10,11,26,27,31] However, these studies assessed patients with nonacute CTS. Our results offer a reference range for ACTS that warrants clinical validation. Physical examination with repeated longitudinal assessments remains the best avenue for diagnosing ACTS.[22] Nonetheless, our data suggest that neuromuscular ultrasound may be an accurate diagnostic test for ACTS,[2] especially in situations when an examination is difficult to perform. CSA can be easily visualized, and ultrasound offers a readily available and fast evaluation. This may have increased utility in patients unable to articulate symptoms (eg, incapacitated, intensive care unit patients or evaluating the nerve after an anesthetic block is given to facilitate a reduction). The adjunct use of neuromuscular ultrasound may be part of physical examination in upper-extremity trauma when there is a concern for ACTS.

This study evaluated the changes in the median nerve CSA in intraarticular DRF with three different fragment positions: neutral wrist position, with traction, and wrist extension. Almost all neutral position fractures in our cadaveric models reached the CSA threshold for ACTS. This is a higher incidence than broadly reported in the literature (4%-31%)[13–15] but may be secondary to our fracture pattern. AO type C fractures are a risk factor for ACTS, and patients presenting with AO type C fractures have triple the odds of developing ACTS.[32,33] Fracture fragments under traction or wrist extension induced a greater increase in median nerve CSA than when in the neutral position, suggesting that the median nerve experiences increased carpal tunnel pressure when DRFs are displaced (during wrist extension) or under traction. Fractures were placed under traction during external fixation. External fixation has been theorized to cause median neuritis and possible CRPS.[18,19] These complications may be a consequence of increased carpal tunnel pressure. Evidence demonstrates a linear relationship between distraction force and carpal tunnel pressure,[24] and carpal tunnel pressure has been demonstrated to increase to over 40 mm Hg during fracture manipulation.[34] Similarly, fracture displacement is a risk factor for ACTS,[13] and wrist extension can induce intraneural vascular changes associated with CTS[35] and increase carpal tunnel pressures compared with the neutral position.[24] All of this aligns with our findings. Alternatively, the increased incidence of ACTS (as indicated by CSA measurements) may be related to the cadaveric nature of our study. There may be in vivo processes that counteract carpal tunnel pressure or increases in median nerve CSA that cannot be replicated in cadaveric specimens. Therefore, future investigations are warranted to corroborate our findings.

We used a novel calculation, HWR, to describe the cross-sectional shape of the median nerve. Strikingly, the HWR increased with wrist distraction and DRF, indicating that the median nerve became more circular with higher carpal tunnel pressures. We believe there are likely multiple mechanisms for the altered nerve dimensions, one of which is due to a thickened nerve and increased pressure inside the carpal tunnel. The median nerve undergoes morphological changes secondary to compression: the nerve narrows at the site of compression and increases in size proximal (and distal) to the compression. The circumference (outer lining) of the nerve is unchanged, causing the nerve to adopt a new shape. The nerve's elliptical shape becomes more circular to permit a greater area while maintaining the same circumference. This geometric change can be characterized by the nerve HWR, which offers an alternative metric for using an absolute threshold value for CTS diagnosis, as with CSA thresholds. The present use of an absolute threshold value is limited by population variability. The median nerve CSA is known to vary along its length, with patient age, sex, and ethnicity.[28] The use of a ratio minimizes these influences and may offer a more specific measurement tool for ACTS. Fewer specimens met the HWR threshold for ACTS than the CSA threshold: 80% of nondisplaced DRF specimens, 100% of DRF models under traction, and 100% of displaced DRF specimens were above the CSA threshold for ACTS, compared to 30%, 60%, and 80%, respectively, which met the HWR threshold. Therefore, the HWR may hold greater specificity for detecting ACTS. However, this speculation is beyond the data in our study. As with any cadaver study, these findings regarding the nerve HWR warrant clinical exploration, investigation, and validation.

This study has limitations. First, this is a cadaveric study and does not reflect all clinical conditions for the in vivo fractured wrist. Therefore, caution should be taken when drawing conclusions from these data. Second, ultrasonography is operator-dependent, particularly when defining the boundary of the median nerve to measure CSA. However, our threshold value was similar to the values in the literature. Following a traumatic or distracting force, the surrounding tissues stretch and relax over time, which may cause the forces, and thus the carpal tunnel pressure, to decrease. In this study, the measurements were taken at a single time point in the immediate posttraumatic period, so it is possible that our results overestimated the incidence of ACTS. Finally, there is no standardized protocol for measuring median nerve CSA. However, direct tracing is the most commonly used method.[10,11,26,27,29] Furthermore, calculating CSA by direct measurement or ellipsoid formula yields similar results.[29] As with all cadaveric studies, these findings warrant clinical validation in future work. Further studies evaluating the changes in median nerve morphology following DRF in vivo compared to the nonfractured wrist are warranted.

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