Original Article

Ultrasonographic Assessment of Median Nerve in Carpal Tunnel Syndrome in Comparison with Nerve Conduction Studies

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Abstract

Background: Carpal Tunnel Syndrome (CTS) is a common peripheral neuropathy often affecting the dominant hand and interfering with daily activities. While nerve conduction studies (NCS) remain the diagnostic standard, high-frequency ultrasound (USG) and color Doppler are increasingly used for detecting early structural changes. This study evaluated the diagnostic utility of these sonographic methods in comparison to NCS. **Material and Methods:** This cross-sectional study was conducted at a tertiary care hospital in central India over one year. A total of 110 clinically suspected CTS patients were included after screening for eligibility. Median nerve assessment was performed using a high-frequency linear probe (7–13 MHz). Sonographic parameters including cross-sectional area (CSA), flattening ratio, palmar bowing of flexor retinaculum, and intraneural vascularity were measured and correlated with NCS grading. **Results:** Of 110 patients, 92 demonstrated intraneural vascularity. CSA was significantly higher in vascularity-positive patients. ROC analysis identified CSA as the most accurate parameter (AUC 0.80), followed by flattening ratio and palmar bowing. CSA values progressively increased with advancing NCS grades. Doppler vascularity showed 85% sensitivity and an overall diagnostic accuracy of 84.5%. **Conclusion:** High-frequency ultrasound, particularly CSA measurement, correlates well with NCS severity and serves as a reliable, non-invasive diagnostic tool. Doppler vascularity adds supplementary diagnostic value when combined with structural parameters.

Keywords: Carpal Tunnel Syndrome, Median Nerve, High-Frequency Ultrasound, Color Doppler, Nerve Conduction Studies, Cross-Sectional Area.

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Introduction

CTS first described by Paget in 1854 is the most common entrapment neuropathy characterized by compression of the median nerve at the wrist level.[1] The condition affects 2.7–5.8% of the adult population with a lifetime incidence of 10–15% and shows a female preponderance with a female-to-male ratio between 2–5:1.[2] CTS contributes significantly to work-related disability and often requires surgical management when conservative therapy fails.[3]

Pathophysiologically CTS involves compression-induced venous obstruction, nerve edema, ischemia and eventual axonal injury.[4] These lead to characteristic sonographic findings including proximal nerve swelling, flattening at the compression site and increased vascularity forming the basis for ultrasound evaluation.[3,5]

Current diagnosis primarily relies on clinical signs and nerve conduction studies (NCS) the latter being considered the gold standard despite limitations.[6] NCS may yield false-negative results in 10–25% of clinically suspected cases and involves cost, time and patient discomfort.[6] Clinical tests such as Phalen's & Tinel's have variable diagnostic performance, with Tinel's sensitivity ranging from 25–75% and specificity from 70–90%.[7,8]

High-frequency ultrasonography offers a non-invasive, real-time evaluation of the median nerve.[9,10] Cross-sectional area (CSA) measurement at the wrist has Level A evidence for CTS diagnosis.[9] However, reported CSA cutoffs vary widely (9–14 mm²), with sensitivity and specificity ranging from 57–94% and 57–98% respectively.[9,10]

Color Doppler assessment of nerve vascularity has also shown promise. Mallouhi reported 95% sensitivity and 71% specificity for vascularity in CTS diagnosis.[3] Other studies support these findings, but no consensus exists on integrating grayscale and Doppler parameters.[11]

Despite existing research, comprehensive evaluation of multiple ultrasonographic parameters across CTS severity grades remains limited. The comparative diagnostic accuracy of these parameters and their complementary role to NCS require further investigation.

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This study aims to assess the diagnostic accuracy of high-frequency ultrasound and color Doppler in CTS and correlate these findings with NCS. The primary objectives include evaluating the diagnostic validity of CSA, flattening ratio, palmar bowing and nerve vascularity and identifying the most reliable ultrasonographic criteria. The study further explores the correlation between ultrasound and electrodiagnostic grades to assess whether ultrasound may serve as a reliable alternative or adjunct to NCS in CTS diagnosis and severity grading.

Materials and Methods

This cross-sectional, time-bound study was conducted in the Department of Radio-diagnosis at a Medical College Hospital after obtaining clearance from the Institutional Scientific Review Board and Ethics Committee. The study spanned one year. A total of 110 patients, clinically suspected of CTS and referred for wrist ultrasound, were enrolled. Inclusion criteria were age above 18 years and written informed consent. Patients with wrist trauma, prior wrist surgery or wrist tumors were excluded. Detailed clinical history was obtained, including symptoms of tingling, numbness, wrist pain, hand weakness and nocturnal symptom aggravation. Clinical tests such as Phalen's and Tinel's were documented.

Ultrasound was performed using a high-frequency linear transducer (7–13 MHz) with patients in supine position. The median nerve was examined in both transverse and longitudinal planes from the proximal segment to the tunnel inlet. Cross-sectional area (CSA) was measured nerve swelling was defined as CSA >9 mm² or a >2 mm² difference compared to proximal level. Nerve flattening was assessed using a flattening ratio (major to minor axis ≥3). Palmar bowing was measured by displacement of the flexor retinaculum apex ≥2 mm from the line joining the trapezium tubercle to the hook of hamate. Color Doppler was adjusted to detect low-flow vascular signals, using a pulse repetition frequency of 800–900 Hz. Intraneural vascularity was recorded as present or absent based on visualization of flow signals. Ultrasound findings were compared with nerve conduction studies (NCS). NCS was considered abnormal if median nerve sensory conduction latency exceeded 49 ms and/or distal motor latency exceeded 4.4 ms, with normal ulnar conduction. Data were recorded in Microsoft Excel and analyzed using SPSS software. Quantitative variables were expressed as mean and standard deviation. ROC analysis assessed diagnostic performance. A p-value <0.05 was considered statistically significant.

Results

A total of 110 patients were evaluated. Based on ultrasonographic grading, the majority were classified as moderate CTS with CSA between 13–14.9 mm² (43.64%). Mild cases (9–12.9 mm²) comprised 31.82%, while severe cases (>15 mm²) accounted for 24.55% [Table 1].

Table 1: Distribution of Patients According to USG Grading

USG Grade (CSA in mm²)	No. of Patients	Percentage (%)
Mild (9–12.9)	35	31.82
Moderate (13–14.9)	48	43.64
Severe (>15)	27	24.55

Table 2: Comparison of USG Parameters with Nerve Vascularity

USG Parameter	Vascularity Present (Mean ± SD)	Vascularity Absent (Mean ± SD)	p-value
Nerve Swelling (CSA)	16.26 ± 5.43	11.54 ± 3.37	0.0005
Nerve Flattening Ratio	3.36 ± 0.51	3.07 ± 0.53	0.02
Palmar Bowing of FR	2.58 ± 0.56	2.71 ± 0.67	0.06

Intraneural vascularity was present in 83.6% of patients. CSA and flattening ratio were significantly higher in patients with vascularity. Median nerve CSA was greater in vascularity-positive cases compared to those without vascularity. Flattening ratio also showed a significant difference. However, palmar bowing did not differ significantly between the groups [Table 2].

Table 3: Diagnostic Validity of Nerve Vascularity Compared to NCS

Parameter	Value (%)
Sensitivity	85.19
Specificity	50.00
PPV	99.00
NPV	5.88
Accuracy	84.50

Diagnostic validity analysis of vascularity showed high sensitivity (85.19%) and excellent positive predictive value (99%). Specificity was moderate (50%) and negative predictive value was low (5.88%). Overall diagnostic accuracy was 84.5%, indicating vascularity as a useful adjunct parameter [Table 3].

Table 4: ROC Analysis of Individual USG Parameters

USG Parameter	AUC	p-value	95% CI	Cutoff	Sensitivity (%)	Specificity (%)
Nerve Swelling (CSA)	0.800	0.02	0.631 – 0.845	10.5	71.0	70.6
Nerve Flattening Ratio	0.738	0.01	0.503 – 0.765	3.5	76.3	75.1
Palmar Bowing of FR	0.736	0.045	0.505 – 0.768	2.2	76.3	75.2

Receiver operating characteristic (ROC) analysis demonstrated that CSA had the highest diagnostic performance (AUC 0.80), followed by flattening ratio (AUC 0.738) and palmar bowing (AUC 0.736). All parameters were statistically significant. Optimal cutoff values were 10.5 mm² for CSA, 3.5 for flattening ratio and 2.2 mm for palmar bowing [Table 4].

Table 5: Comparison of Nerve Swelling Across NCS Grades

NCS Grade	Mean CSA (mm²) ± SD
CTS	8.42 ± 0.79
Grade II	11.63 ± 2.51
Grade III	15.96 ± 2.52
Grade IV	21.00 ± 1.31
Grade V	25.00 ± 0.00
Normal	10.50 ± 0.70
p-value	< 0.0001

Comparison of CSA across NCS severity grades revealed a progressive increase in CSA with advancing severity. Mean CSA ranged from 8.42 mm² in early CTS to 25 mm² in Grade V. The correlation between CSA and NCS grades was statistically significant ($p < 0.0001$), supporting the role of ultrasound in severity assessment [Table 5].

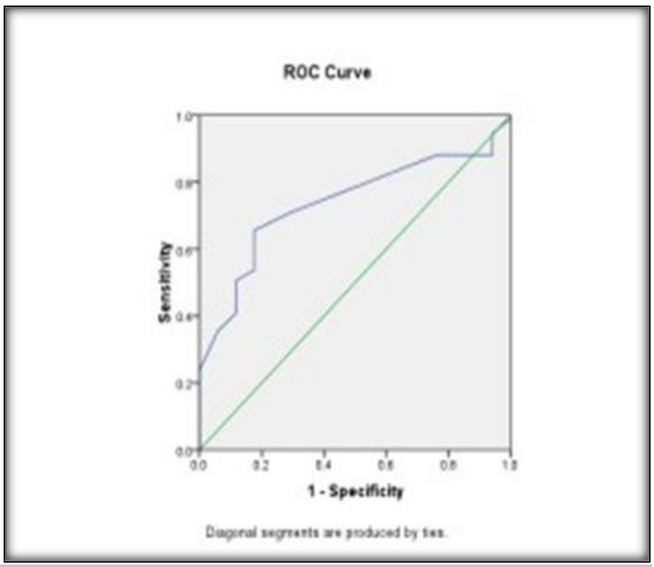

Figure 1a: ROC Curve for CSA of Median Nerve

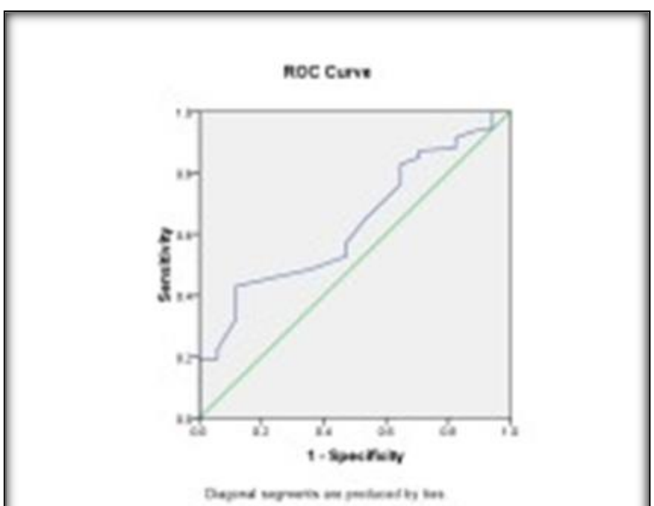

Figure 1b: ROC for the Flattening Ratio

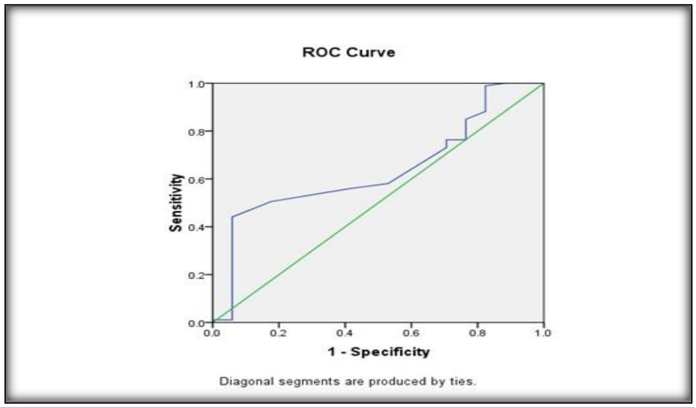

Figure 1c: ROC Curve for Palmar Bowing of Flexor Retinaculum

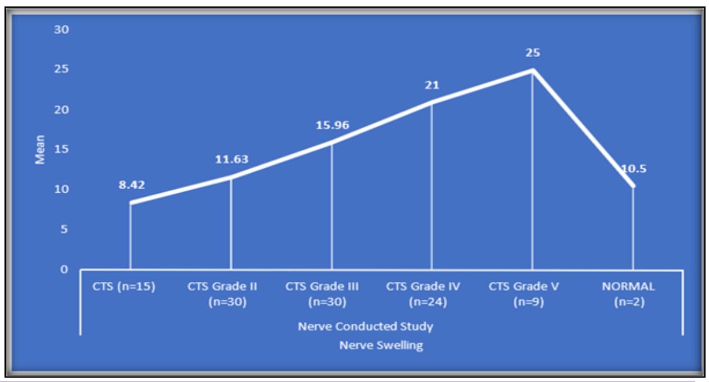

Figure 2: Comparison of Median Nerve Swelling (CSA) Across Nerve Conduction Study Grades

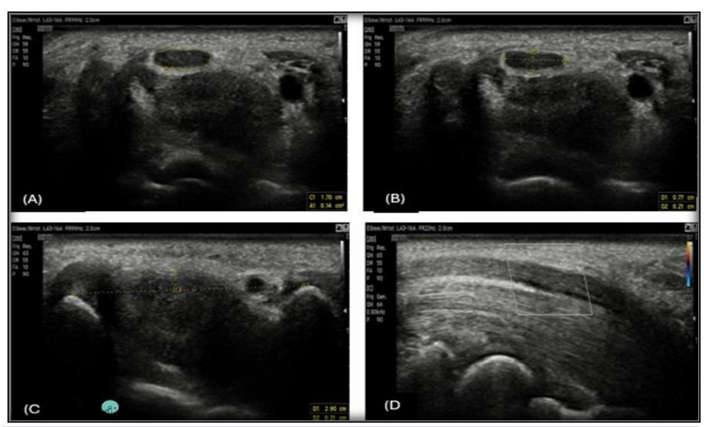

Figure 3: Ultrasound and Doppler findings in Grade III CTS patient

On USG B-mode – 43 yr old female came with complain of right hand numbness and is proven case of NCS grade III CTS.
[Figure 3A]. shows swelling of right median nerve with cross sectional area of 0.14 cm2 at flexor retinaculum.
[Figure 3B]. shows flattening of median nerve
[Figure 3C]. shows palmar bowing of flexor retinaculum.
On Color doppler -
[Figure 3D]. shows no intraneural vascularity s/o Moderate CTS, hence correlating with nerve conduction studies

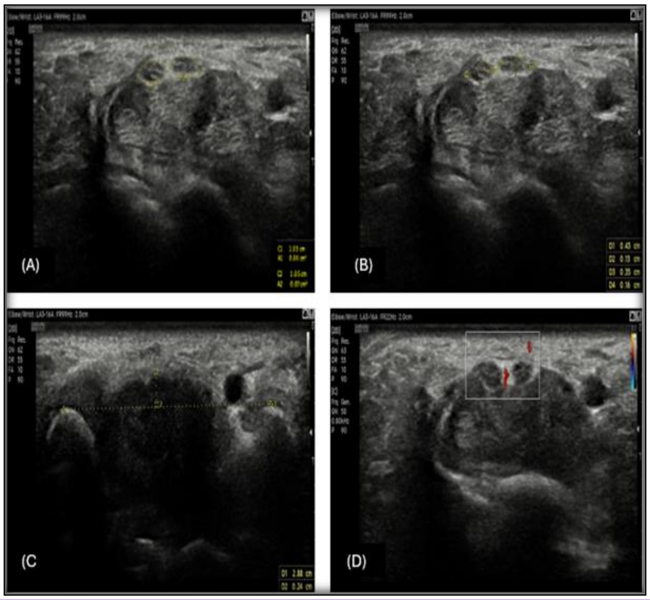

Figure 4: Ultrasound and Doppler findings in Grade III CTS with bifid median nerve and persistent median artery

On USG B- mode - 32 yr old female came with complain of right hand tingling sensations and is proven case of NCS grade III CTS.
[Figure 4A]. shows Bifid right median nerve with cross sectional area of 0.13 cm2 at flexor retinaculum.
[Figure 4B]. shows flattening of both the trunks of median nerve
[Figure 4C]. shows palmar bowing of flexor retinaculum.
On Color doppler -
[Figure 4D]. shows presence of persistent median artery of forearm. s/o Moderate CTS, hence correlating with nerve conduction studies.

Discussion

This study critically evaluated the role of high-frequency ultrasound and color Doppler in diagnosing CTS using NCS as reference. Ultrasonographic grading based on CSA classified most patients into the moderate category [Table 1]. Significant associations were observed between vascularity and ultrasonographic parameters, particularly CSA and flattening ratio [Table 2]. Diagnostic validity analysis demonstrated high sensitivity but limited specificity for Doppler vascularity [Table 3]. ROC analysis confirmed CSA as the most accurate ultrasonographic parameter, followed by flattening ratio and palmar bowing [Table 4; Figure 1a,1b,1c]. CSA strongly correlated with NCS severity, progressively increasing with disease stage [Table 5; Figure 2]. These findings confirm that ultrasound, particularly CSA measurement, closely reflects electrophysiological severity and detects early structural changes before functional impairment.

CSA remains the most robust ultrasonographic marker for CTS, consistent with meta-analyses reporting pooled sensitivities of 77.6–82% and specificities of 78.7–86.8%.[12,13]

In this study CSA showed strong diagnostic power, with a cutoff of 10.5 mm² yielding 71% sensitivity and 70.6% specificity (AUC: 0.800) [Table 4]. These values align with previously reported thresholds (9–14 mm²).[9,13] While flattening ratio (AUC: 0.738) and palmar bowing (AUC: 0.736) provided additional information, their standalone diagnostic utility remains limited due to measurement variability and anatomical overlaps [Table 4; Figure 1].[14,15]

The study's stratification using CSA mild (9–12.9 mm²), moderate (13–14.9 mm²) and severe (>15 mm²) categories provided a practical clinical framework [Table 1] consistent with Kang et al.'s observations correlating CSA with NCS grades.[16] However the overlapping CSA ranges between moderate and severe groups highlight the need for integrating clinical findings and additional dynamic parameters such as wrist-to-forearm CSA ratios to enhance specificity.[6]

Color Doppler demonstrated high sensitivity (85.19%) in detecting vascularity in severe CTS [Table 3], consistent with prior reports linking hypervascularity to nerve edema and ischemia.[15] Chronic compression likely induces neoangiogenesis via hypoxia-inducible factor-1α and vascular endothelial growth factor pathways.[15,17] Despite high sensitivity, vascularity showed limited specificity (50%) and low negative predictive value (5.88%) restricting its use as a sole diagnostic marker [Table 3].[15]

A strong association was noted between vascularity and nerve swelling, with higher CSA values in vascularity-positive cases [Table 2] suggesting vascular proliferation reflects advanced microvascular remodeling and axonal loss.[15,18] Doppler vascularity correlated particularly with higher NCS grades (III–V). Quantitative Doppler metrics may offer further objectivity and warrant future investigation.[17,19]

CSA correlated strongly with NCS severity ($p < 0.0001$), progressively rising from early CTS to Grade V [Table 5; Figure 2] reflecting progressive demyelination and axonal degeneration.[16,18] However, ultrasound also detected early changes missed by NCS, 31.82% of mild CSA cases had normal NCS [Table 1].[6,20] Also some severe CSA cases demonstrated only moderate NCS abnormalities likely due to anatomical variations or subclinical nerve hypertrophy.[13]

Ultrasound and NCS serve complementary roles. While NCS assesses functional impairment, ultrasound visualizes structural alterations, proving particularly useful in NCS-negative but clinically symptomatic patients.[6,20] This is especially relevant in resource-limited settings where ultrasound offers cost-effective and rapid evaluation.[6,20,21]

Operator dependency remains a limitation for ultrasound with measurement variability affected by transducer pressure, angulation and tracing technique. CSA can be overestimated by 10 to15% if the hyperechoic epineurium is included.[9,14]

Anatomical variants such as bifid median nerves or persistent median arteries may also confound assessment without meticulous scanning.[9,14]

Dynamic ultrasonographic assessments may overcome some static limitations. Techniques such as nerve mobility studies, speckle-tracking elastography and 3D volumetric analysis offer quantitative data on nerve deformation and stiffness.[9,13] Kwon et al. demonstrated stronger correlation of 3D CSA measurements with NCS compared to 2D (r = 0.81 vs. 0.57) though widespread use remains limited by availability.[16]

In clinical practice CSA >9 mm² combined with supportive symptoms may suffice for CTS diagnosis in primary care, reserving NCS for atypical or surgical cases.[13,21] Serial CSA and vascularity measurements can also monitor treatment response following interventions such as corticosteroid injection or hydrodissection.[17,20]

Further multicenter research is necessary to establish population-specific CSA thresholds and composite scoring models incorporating multiple ultrasonographic parameters. Artificial intelligence-driven automated analysis may help reduce interobserver variability, particularly in high-volume centers.[9,20]

Conclusion

High-frequency ultrasound and color Doppler serve as valuable adjuncts to NCS in CTS diagnosis, providing complementary structural and hemodynamic information. CSA remains the most reliable ultrasonographic marker, though its interpretation should consider vascularity, technical variables and clinical context. With advancing technology, ultrasound may assume an expanded role in early diagnosis, severity grading and treatment monitoring in CTS.

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Conflicts of interest

There are no conflicts of interest.

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