ABENHA MEDICAL JOURNAL bmj

Print ISSN 1110-208X.

Online ISSN 2357-0016

Role of High-Resolution Ultrasound Compared to Magnetic Resonance Imaging in Assessment of Abnormalities of the Median Nerve in Carpal Tunnel Syndrome

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Received:
Accepted:

Abstract:

Background: Carpal Tunnel Syndrome (CTS) is the most common entrapment neuropathy, predominantly impacting the median nerve at the wrist. Accurate diagnosis is crucial to avoid permanent nerve damage and optimize patient outcomes. Aim: To compare the diagnostic utility of high-resolution ultrasound (HRUS) and magnetic resonance imaging (MRI) in assessing structural abnormalities of the median nerve in patients with CTS. **Methods:** This prospective comparative study was performed at Benha University Hospitals over six months (July–December 2024), involving 50 adult patients diagnosed with CTS. All patients underwent nerve conduction studies, HRUS, and MRI. Key imaging parameters—including cross-sectional area (CSA), flattening ratio (FR), and palmar bowing (PB)—were measured and analyzed. **Results:** A total of 50 patients with clinically and electrophysiologically confirmed CTS were evaluated using HRUS and MRI. The mean age was 47.9 ± 11.6 years, with a female predominance (66%) and a mean BMI of 26.04 ± 3.61 kg/m². Diabetes mellitus was the most common comorbidity (42%). Ultrasound revealed elevated median nerve CSA in 94% of patients, altered echogenicity in 90%, and elevated bowing and flattening indices in 60% of cases each. Muscle atrophic changes were detected in 6%, and structural abnormalities were noted in 32%—most commonly tenosynovitis (62.5%). **Conclusion:** Both HRUS and MRI provide reliable, non-invasive assessment of median nerve abnormalities in CTS. HRUS, due to its accessibility, cost-effectiveness, and dynamic capabilities, may serve as a first-line imaging tool in CTS diagnosis.

Key words: Carpal Tunnel Syndrome; High-Resolution Ultrasound; MRI, Median Nerve; Cross-sectional Area.

Introduction

Carpal tunnel syndrome (CTS) is the most common peripheral entrapment neuropathy, accounting for over 60% of work-related upper limb musculoskeletal disorders in Europe and affecting a substantial number of working-age adults globally [(1).] In Egypt, the estimated prevalence ranges from 1.7% to 3.1%, with higher incidence among women and individuals engaged in repetitive manual labor [(2).] CTS results from compression of the median nerve within the carpal tunnel at the wrist, leading to symptoms such as numbness, tingling, and pain in the hand, with potential impairment of motor function and grip strength in advanced stages [(3).]

Diagnosis of CTS is primarily clinical, supported by electrodiagnostic studies like nerve conduction studies (NCS). However, these tests can be uncomfortable for patients and carry a false-negative rate of 10–20%, underscoring the need for alternative imaging-based diagnostic tools [(4).]

High-resolution ultrasound (HRUS) has emerged as a valuable diagnostic modality for CTS, offering advantages such as non-invasiveness, cost-effectiveness, and real-time dynamic imaging. HRUS allows for precise measurement of the cross-sectional area (CSA) of the median nerve and detection of structural changes including nerve swelling, flattening, and palmar bowing of the flexor retinaculum [(5,6).]

Magnetic resonance imaging (MRI), on the other hand, provides superior soft tissue contrast and multiplanar anatomical detail, enabling visualization of the nerve, surrounding tendons, and bony structures. MRI findings characteristic of CTS include median nerve swelling, flattening within the tunnel, and elevated signal intensity [(7).]

This study aims to compare HRUS and MRI in the evaluation of median nerve abnormalities in patients with clinically diagnosed CTS, with the goal of identifying the more practical and accurate modality for routine clinical use.

Patients and Methods

This was a prospective comparative study conducted at Benha University Hospitals over a 6-month period, from July 2024 to December 2024. It involved a total of 50 patients clinically diagnosed with CTS were recruited from the outpatient neurology and radiology departments. All patients provided informed written consent before participation. The primary aim of the study was to compare the diagnostic utility of HRUS and MRI in assessing structural abnormalities of the median nerve in patients with CTS. ultimately determining the most accurate and effective imaging modality for these conditions.

Before enrolling any examination, informed consent was obtained from the participating patient. Furthermore, all necessary official approvals were secured, including permission from the Dean of the Faculty of Medicine and the administration of Benha University Hospitals. This part of the work was approved by the Benha Faculty of Medicine Research Ethics Committee (Approval No. MS-16-6-2024) in accordance with institutional and national research ethics guidelines.

Inclusion criteria Patients were eligible for inclusion if they were over 18 years of age and had a confirmed diagnosis of CTS. Exclusion criteria included a history of wrist trauma, fractures, or previous wrist surgery, as well as any known motor neuron disease or proximal neurologic disorder that could mimic CTS symptoms. Patients with anatomical variations of the median nerve, such as a bifid median nerve or a persistent median artery, were also excluded. Additionally, those who declined to participate were not included in the study.

The exclusion criteria for the study were as follows: if they had any history of trauma, fracture, or prior surgical intervention involving the wrist, as these factors could alter the anatomical structure of the carpal tunnel and potentially confound imaging findings. Additionally, individuals with proximal neurologic disorders such as cervical radiculopathy or brachial plexopathy, which may cause symptoms similar to CTS, were excluded to avoid diagnostic overlap. Patients with motor neuron diseases were also not eligible, as these systemic conditions can affect nerve function independently of median nerve compression. Anatomical variants of the median nerve, including bifid median nerve and persistent median artery, were excluded due to their potential to interfere with consistent measurement and interpretation on both ultrasound and MRI. Lastly, any patient who declined to provide informed consent or expressed unwillingness to participate was excluded from the study.

Each participant underwent a **detailed clinical assessment**, including full history taking (personal, occupational, medical, and family history), and a general physical examination focusing on vital signs and body mass index (BMI). NCS were performed using a Caldwell Sierra Wave system to measure median nerve latency, amplitude, and conduction velocity. This electrophysiological assessment was used to confirm CTS diagnosis and determine its severity. Although electrodiagnostic studies remain a reference standard for CTS diagnosis, they can be associated with discomfort and have been reported to yield false-negative results in up to 20% of cases.

Radio diagnostic imaging commenced with **HRUS** employing a linear array transducer operating between 10 and 12 MHz. Patients were positioned comfortably, seated with the forearm supported on a table, palm facing upward, and fingers semi-extended. The median nerve was scanned along its course within the carpal tunnel, utilizing both longitudinal and transverse planes. CSA measurements were obtained at the distal wrist crease employing a continuous boundary tracing method. Additional metrics included the flattening ratio (FR)—calculated as the ratio of transverse to anteroposterior diameters—and palmar bowing (PB) of the flexor retinaculum. PB was quantified by measuring the vertical distance from a line drawn between the trapezium and hamate bones to the most anterior aspect of the retinaculum. Following ultrasound, all patients underwent **MRI** on a 3-Tesla system. Transverse T1-weighted turbo spin echo sequences were acquired with slice thickness of 3.0 mm, repetition time (TR) of 893 ms, and echo time (TE) of 13 ms. Image analysis focused on median nerve CSA at the hook of the hamate level, along with assessment of flattening and PB. Due to its superior soft tissue contrast and multiplanar capability, MRI facilitates detailed visualization of nerve morphology and surrounding structures, proving valuable in CTS diagnosis, particularly in complex or equivocal cases.

The HRUS protocol adhered to **established imaging signs and diagnostic criteria** for median nerve evaluation within the carpal tunnel. The nerve was identified by its characteristic honeycomb echotexture situated between the flexor tendons and the retinaculum. Assessments included nerve morphology, continuity, and echogenicity in both imaging planes. Key features analyzed comprised CSA at the distal wrist crease, nerve swelling, and shape alterations such as flattening. FR was calculated to quantify anteroposterior compression. PB of the retinaculum was evaluated as an anterior protrusion overlying the nerve. Dynamic scanning was also performed to assess nerve mobility and detect any structural anomalies or anatomical variants. These sonographic findings were compared to MRI results to determine HRUS accuracy and diagnostic utility in identifying median nerve abnormalities in CTS.

Statistical analysis

Data processing utilized IBM SPSS (version 22). Qualitative variables were summarized as counts and percentages, while quantitative data were expressed as medians for non-normally distributed variables and means ± standard deviations for normally distributed data, as verified by the Kolmogorov-Smirnov test. Group comparisons employed Chi-Square tests, with Monte Carlo correction applied when expected cell counts fell below five in over 25% of cases. Diagnostic validity indices—sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV)—were computed. A p-value ≤ 0.05 was considered statistically significant.

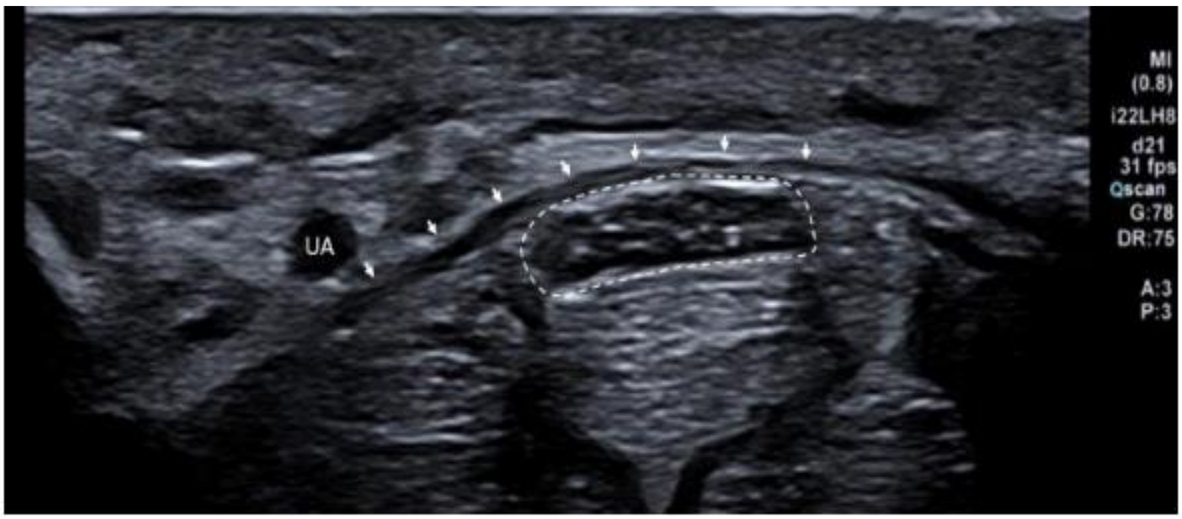

Figure 1: Normal Median Nerve (dotted line) at the level of the FLR (arrows) [28]

Results

The study included a total of 50 patients clinically diagnosed with CTS. The mean age of the study population was 47.9 ± 11.6 years, indicating a predominance of middle-aged individuals, which aligns with the typical age group affected by CTS. The mean BMI was 26.04 ± 3.61 kg/m², suggesting that most patients were in the overweight range, a known risk factor for the development of CTS. In terms of gender distribution, females represented the majority, accounting for 66% (n=33) of the patients, while males comprised 34% (n=17). This female predominance is consistent with previous epidemiological data indicating a higher prevalence of CTS in women, particularly those in the perimenopausal and postmenopausal age groups. Regarding occupational status, 29 patients (58%) were employed, while 21 (42%) were non-employed. The relatively high proportion of employed individuals may reflect the association between CTS and repetitive hand or wrist movements typically encountered in workplace settings. Comorbid medical conditions were also documented, with diabetes mellitus (DM) being the most prevalent, affecting 21 patients (42%). Hypertension (HTN) was reported in 9 patients (18%), and ischemic heart disease (IHD) in 4 patients (8%). The high frequency of diabetes among patients highlights its role as a significant risk factor for peripheral nerve entrapment. Laterality of symptoms showed a marked right-sided predominance, with 82% (n=41) of patients affected on the right side and only 18% (n=9) on the left. This may be attributed to dominant hand use in daily activities, which can exacerbate median nerve compression over time. **(Table 1)**

HRUS revealed a variety of diagnostic features in the assessment of median nerve abnormalities among the 50 studied patients with CTS. One of the most prominent findings was altered nerve echogenicity, observed in 45 patients (90%). This change typically reflects nerve edema or disruption of the normal fascicular pattern and is a consistent indicator of nerve compression. Only 5 patients (10%) retained normal echogenicity. The CSA of the median nerve, a key sonographic parameter, was elevated in 47 patients (94%), which strongly supports its diagnostic utility in CTS. Enlargement of the CSA at the level of the distal wrist crease is one of the most reliable ultrasound features of the syndrome. Only 3 patients (6%) showed a normal CSA, possibly indicating early or mild disease or a false-negative result. The bowing of the flexor retinaculum, quantified as the bowing index, was found to be elevated in 30 patients (60%). This anterior bulging of the retinaculum is a classic sign of elevated pressure within the carpal tunnel and further supports the diagnosis of CTS in the majority of cases. Similarly, the flattening index, which measures the ratio of the nerve’s transverse to anteroposterior diameter, was also elevated in 60% of patients, reflecting deformation of the median nerve due to chronic compression. Signs of thenar muscle atrophy, an indicator of long-standing or severe disease, were relatively rare, identified in only 3 patients (6%), while the remaining 94% showed no atrophic changes. This suggests that most of the patients were likely in the earlier stages of CTS or had not yet developed significant motor involvement. Despite the high prevalence of individual sonographic abnormalities such as elevated CSA and altered echogenicity, only 16 patients (32%) were classified as having distinct structural abnormalities based on the overall ultrasound assessment. This discrepancy may reflect the reliance on combined imaging criteria or the need for correlation with clinical and electrophysiological findings before confirming sonographic diagnosis. Among the patients with identifiable abnormalities (n=16), the most common finding was tenosynovitis, observed in 10 cases (62.5%). This was followed by neuroma-in-continuity (NIC) in 3 patients (18.8%) and synovial hypertrophy in another 3 patients (18.8%). These associated pathologies emphasize the value of ultrasound not only in assessing the median nerve but also in detecting surrounding soft tissue abnormalities that may contribute to or mimic CTS. **(Table 2)**

MRI findings revealed several characteristic features associated with CTS in the studied population. An elevated T2 signal intensity of the median nerve, indicating edema or inflammation, was observed in 45 patients (90%), making it one of the most prevalent MRI findings. This hyperintense signal on T2-weighted images is commonly associated with nerve compression and correlates well with clinical severity. Additionally, an elevated CSA at the proximal tunnel was detected in 40 patients (80%), consistent with proximal nerve swelling due to entrapment. Distal flattening of the median nerve, another hallmark of CTS on MRI, was present in 28 patients (56%), while palmar bowing of the flexor retinaculum was noted in 29 patients (58%). Both findings reflect elevated intracarpal pressure and structural distortion of the nerve and surrounding tissues. The fascicular pattern of the nerve, normally seen as a well-defined structure, was preserved in only 3 patients (6%), while 47 patients (94%) exhibited disruption or loss of this pattern, indicating structural nerve injury in advanced cases. Signal alteration within the median nerve was present in 17 patients (34%), which may suggest chronic compression or axonal injury. Overall, MRI identified structural or pathological abnormalities in 27 patients (54%), indicating a higher sensitivity of MRI in detecting a broader range of conditions contributing to CTS beyond the nerve itself. Among the MRI-detected abnormalities, tenosynovitis was the most common, seen in 14 patients (51.9%). Other associated findings included ganglion cysts in 5 patients (18.5%), minimal edema of the carpal tunnel in 4 patients (14.8%), and traumatic neuroma in another 4 patients (14.8%). These findings highlight the added diagnostic value of MRI in identifying secondary or contributing lesions that may influence treatment decisions and surgical planning. (**Table 3).**

Table 1: Distribution of patient characteristics in the studied patients (n = 50)

	Studied patients (N=50)	
	Mean	**±SD**
Age	47.9	11.6
BMI	26.04	3.61
Gender	**N**	**%**
Male	17	34%
Female	33	66%
Working status		
employed	29	58%
Non-employed	21	42%
Comorbidities		
DM	21	42%
HTN	9	18%
IHD	4	8%
Side		
RT	41	82%
LT	9	18%

Table 2: Distribution of U/S findings in the studied patients (N=50)

	Studied patients (N=50)	
	N	**%**
U/S echogenicity		
Yes	45	90%
No	5	10%
U/SCSA		
Normal	3	6%
Elevated	47	94%
U/S bowing index		
Normal	20	40%
Elevated	30	60%
U/S flattening index		
Normal	20	40%
Elevated	30	60%
U/S muscle atrophic changes		
Yes	3	6%
No	47	94%
Abnormality by U/S		
Abnormality	16	32%
Noabnormality	34	68%
Type of abnormality		
Tenosynovitis	10	62.5%
Neuroma-in-continuity(NIC)	3	18.8%
Synovial hypertrophy	3	18.8%

A comparative analysis of CSA measurements obtained by HRUS and MRI revealed a statistically significant agreement between the two imaging modalities. Among the 47 patients identified by ultrasound as having an elevated CSA, 40 (85.1%) were also confirmed to have elevated proximal CSA on MRI, indicating a strong concordance. In contrast, all three patients identified with normal CSA by ultrasound also had normal MRI findings, resulting in 100% agreement in this subgroup. The strength of agreement between the two methods was measured using Cohen’s Kappa coefficient, which was calculated at 0.447, suggesting a moderate agreement between HRUS and MRI in assessing CSA. The result was statistically significant with a p-value of 0.003, indicating that the observed concordance is unlikely to be due to chance. It is also notable that while MRI detected proximal CSA increase in 80% of the total sample (40/50), ultrasound identified elevated CSA in a slightly higher proportion (94%, or 47/50). This suggests that while both modalities are generally consistent in detecting CSA enlargement, ultrasound may demonstrate slightly higher sensitivity or may be more operator-dependent, potentially identifying subtler variations in nerve size. Overall, these findings reinforce the diagnostic value of both HRUS and MRI in evaluating CSA of the median nerve, with ultrasound offering a reliable and less expensive alternative to MRI, particularly in initial screening and follow-up of CTS cases. **(Table ٤).**

Table 3. Distribution of MRI findings in the studied patients.

	Studied patients (N=50)	
	N	**%**
MRIelevatedT2signal		
Yes	45	90%
No	5	10%
MRI proximal CSA		
Yes	40	80%
No	10	20%
MRI distal flattening		
Yes	28	56%
No	22	44%
MRI bowing		
Yes	29	58%
No	21	42%
MRI fascicular pattern		
Yes	3	6%
No	47	94%
MRI signal alteration		
Yes	17	34%
No	33	66%
Abnormality by MRI		
Abnormality	27	54%
No abnormality	23	46%
Type of abnormality		
Tenosynovitis	14	51.9%
Ganglion cyst	5	18.5%
Minimal edema of the tunnel	4	14.8%
Traumatic neuroma	4	14.8%

Table ٤. Comparison between MRI and Ultrasound (U/S) regarding Cross-Sectional Area (CSA) (N = 50)

			MRI Proximal CSA		**Total**	**Kappa**	***P*-VALUE**
			NO	**YES**			
US CSA	**Normal**	**No.**	**3**	**0**	**3**	0.447	**0.003**
		% within US CSA	100%	0.00 %	100 %		
		%Within MRI Proximal CSA	30%	0.00 %	6%		
	Elevated	No.	7	**40**	**47**		
		% within US CSA	14.9%	85.1 %	100 %		
		%Within MRI Proximal CSA	70%	100%	94%		
Total		No.	10	**40**	**50**		
		% within US CSA	20%	80%	100 %		
		%Within MRI Proximal CSA	100%	100%	100 %		

Discussion

Peripheral neuropathy refers to sensory and motor deficits resulting from various metabolic or structural disorders. CTS is the most common entrapment neuropathy in the upper limbs, affecting 2–3% of the general population [8]. Multiple risk factors contribute to CTS, with diabetes being the most common systemic association, alongside pregnancy, rheumatoid arthritis, obesity, hypothyroidism, and specific metabolic or depositional disorders like gout and amyloidosis [9,10].

CTS may also result from localized compression due to anatomical variants or mass lesions such as ganglion cysts or tenosynovitis. Compression triggers pathophysiological changes starting with impaired axonal transport and progressing to epineural and endoneural edema, demyelination, and ultimately axonal degeneration if untreated [11,12]. Chronic compression may lead to fibrosis and can predispose to double crush syndrome [13].

Clinical diagnosis of CTS is supported by NCS, which evaluate motor latency and sensory conduction velocity [14,15]. However, imaging modalities like HRUS and MRI have gained prominence. HRUS offers a non-invasive, dynamic, and real-time assessment of nerve morphology, although it is operator dependent [16], while MRI provides excellent soft tissue contrast and is particularly useful in atypical presentations and detecting secondary causes [17].

This prospective study involved 50 patients with CTS at Benha University Hospitals from July to December 2024. The mean age was 47.9 ± 11.6 years, with a female predominance (66%) and a high prevalence of diabetes (42%). The right side was affected in 82% of patients, which is consistent with findings from previous literature [18,19].

Ultrasound revealed altered echogenicity in 90% of cases, elevated CSA in 94%, and elevated bowing and flattening indices in 60% of cases each. Muscle atrophic changes were present in only 6%, while 32% showed ultrasound-detected structural abnormalities, predominantly tenosynovitis (62.5%) [18]. These results are in line with previous studies that demonstrated the diagnostic value of HRUS in detecting median nerve enlargement and compressive changes [8,19].

CSA has been a key diagnostic parameter. Prior studies have suggested threshold values between 6.1 mm² and 13 mm² depending on the population studied [20–22]. In our study, there was significant agreement between HRUS and MRI in detecting elevated CSA, with a Kappa value of 0.447 ($p = 0.003$), supporting the utility of both methods. MRI detected elevated T2 signal in 90%, elevated proximal CSA in 80%, distal flattening in 56%, and flexor retinaculum bowing in 58%. Fascicular disruption was noted in only 6%, and 34% showed signal alteration suggestive of denervation. Overall, MRI identified structural abnormalities in 54% of patients, including tenosynovitis (51.9%), ganglion cysts (18.5%), and traumatic neuroma (14.8%).

These findings are consistent with Alkaphoury & Dola [18], who reported similar detection rates for both CSA and secondary abnormalities across modalities. MRI demonstrated superior sensitivity in identifying signal changes and muscle denervation, which may not be visible on ultrasound [23]. Kim et al. [24] emphasized the higher diagnostic performance of MRI in chronic CTS, especially in evaluating the extent of nerve damage and surrounding structures. Moreover, MR neurography offers detailed visualization of the intraneural fascicular pattern and adjacent tissue pathology, complementing ultrasound findings [25].

While both US and MRI provided comparable information regarding CSA, bowing, and flattening indices, MRI showed a higher detection rate of secondary causes such as ganglia and deep edema. This supports a tiered diagnostic approach where ultrasound serves as a first-line tool, followed by MRI in cases requiring further evaluation.

Conclusion

This study compared HRUS and MRI in assessing median nerve abnormalities in patients with CTS. HRUS proved to be an effective first-line imaging modality due to its accessibility, real-time assessment, and high diagnostic accuracy, particularly for CSA and morphological changes. MRI served as a valuable complementary tool, especially in identifying secondary causes and muscle denervation changes that may not be recognized by US. Based on our findings, HRUS should be utilized as the initial imaging method following clinical assessment, while MRI is recommended in cases of equivocal findings, suspected atypical pathology, or when evaluating chronic or recurrent CTS.

Conflict of Interest and Funding Statement

The authors declare that there is no conflict of interest. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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To cite this article: Hazim M. Omar, Hamada M. Khater, Mohamed A. Tawfik. Role of High-Resolution Ultrasound Compared to Magnetic Resonance Imaging in Assessment of Abnormalities of the Median Nerve in Carpal Tunnel Syndrome. BMFJ XXX, DOI: 10.21608/bmfj.2025.396105.2483.