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Diagnostic Value of Magnetic Resonance Imaging in the Diagnosis of Carpal Tunnel Syndrome

Abstract

Introduction: Carpal tunnel syndrome (CTS) is a common compressive neuropathy of the upper limb. Given the variable performance of conventional diagnostic approaches, quantitative magnetic resonance imaging may assist clinical decision-making. This study evaluated the diagnostic value of quantitative magnetic resonance imaging metrics.

Materials & Methods: In a cross-sectional diagnostic study of 30 patients at a university center, clinical severity of CTS was assessed using the validated Persian Boston Carpal Tunnel Questionnaire, and electrodiagnostic testing and classified-involvement as mild, moderate, or severe. Wrist magnetic resonance imaging with routine sequences was performed with observer blinding to clinical and electrodiagnostic data. The median nerve cross-sectional area at the distal tunnel outlet, intraneural signal intensity, and the signal intensity ratio of nerve to hypothenar muscle were measured and compared with normal subjects. Analyses used appropriate tests with a significance threshold of $p<0.05$.

Results & Discussion: The median nerve cross-sectional area was larger in patients than in normal (11.36±1.89 vs 9.70±1.63 mm^2; $p<0.05$). Intraneural signal intensity was higher in patients (597.13±52.95 vs 501.67±40.50; $p<0.05$). The nerve-to-hypothenar signal intensity ratio was also increased (1.31±0.26 vs 0.80±0.13; $p<0.01$).

Conclusion: Quantitative magnetic resonance imaging metrics demonstrate significant discriminatory power between patients and normal and may serve as adjuncts in the diagnostic pathway. This pattern accords with the pathobiology of compression (edema and structural change) and supports the utility of quantitative magnetic resonance imaging as a complement to clinical examination and electrodiagnostic testing. Standardization of measurement sites and thresholds, and multicenter prospective studies, are required to translate these findings reliably to practice.

Keywords: Carpal Tunnel Syndrome, Magnetic Resonance Imaging, Median Nerve, Electrodiagnosis

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Introduction

Carpal Tunnel Syndrome (CTS) is a common compressive neuropathy of the upper limb that occurs as a result of entrapment of the median nerve within the carpal canal and classically presents with nocturnal paresthesia, pain, and decreased sensation in the median nerve distribution, and in advanced cases with weakness and atrophy of the thenar muscles. The prevalence of CTS in the general population is estimated to be approximately 1%, and its incidence has been reported to be three times higher in women than in men.(1) Numerous risk factors have been proposed for this disorder, including obesity, repetitive movements and forceful use of the hand and wrist, pregnancy, genetic predisposition, and rheumatoid arthritis; an association with hypothyroidism has also been observed in some studies.(2-5) Occupational exposures such as working with vibrating tools, prolonged computer use, or activities involving sustained and unfavorable wrist positions may increase the risk of CTS, although the strength of evidence in this area is heterogeneous.(6) Clinically, patients typically report numbness, tingling, and a burning sensation in the thumb, index, middle, and radial half of the ring finger; pain may radiate to the forearm and even the arm. More nonspecific symptoms such as wrist pain and reduced grip strength are also common.(7)

Although other hypotheses regarding possible sites of nerve compression, such as the thoracic outlet region or between the heads of the pronator teres muscle, have been proposed, these perspectives have largely remained at the level of experimental evidence.[8] If left untreated, thenar weakness and atrophy may develop due to inadequate denervation.[9] The causes of CTS are often multifactorial, and in many patients the exact etiology cannot be clearly identified. In addition to individual and occupational factors, trauma may also be considered a predisposing factor.[3, 10, 11] In some cases, increased pressure within the tunnel may result from an increase in intracanal contents, for example masses such as lipomas and ganglion cysts or vascular anomalies, or from a reduction in the capacity of the tunnel space.[12] From a pathophysiological perspective, the carpal tunnel is an osteofibrous canal with a floor formed by the carpal bones and a roof constituted by the flexor retinaculum, and it contains nine flexor tendons and the median nerve.[1] Any factor that increases intracanal pressure, such as sustained wrist flexion, may lead to ischemia, edema, and impaired nerve conduction in the median nerve.[13]

The diagnosis of CTS relies on a combination of history taking, physical examination, and electrodiagnostic tests; however, there is no clear consensus on a definitive gold standard.[6] Provocative maneuvers such as the Phalen, Tinel, Durkan, and hand elevation tests are commonly used in clinical practice, but they demonstrate variable sensitivity and specificity and are not sufficient for diagnosis when used alone.[3] Electromyography and nerve conduction velocity studies can demonstrate median nerve conduction abnormalities, but false-negative rates of approximately 10% and false-positive rates of approximately 15% have been reported, and these tests do not fully guarantee differentiation between primary and secondary CTS.[14, 15] Therefore, in borderline or clinically electrodiagnostically discordant scenarios, the need for complementary evidence is felt.[16, 17]

Imaging can serve as a useful diagnostic adjunct. In recent years, MRI and ultrasonography have been employed to assess quantitative indices of the median nerve.[18, 19] In MRI, parameters such as the cross-sectional area (CSA) of the median nerve, the signal intensity ratio of the nerve to the hypothenar muscle (SIR), the anteroposterior width to flattening ratio of the nerve, and bowing of the flexor retinaculum have been proposed.[20-23] Some evidence suggests that increased CSA and SIR correlate with the presence and even the severity of disease; however, heterogeneity of protocols, differences in measurement location, inlet versus outlet of the tunnel, and the lack of agreed-upon thresholds make clinical application challenging.[14] A systematic review reported that a CSA greater than approximately 9 mm² yields a sensitivity of 87.3% and a specificity of 83.3% for diagnosis; nevertheless, methodological variability and population heterogeneity limit the generalizability of this threshold.[24] In particular, data related to quantitative assessment at the distal outlet of the tunnel, where localized nerve swelling may predominate, have been less studied and warrant further investigation.[25]

Given the considerable socioeconomic burden of CTS, which accounts for a substantial proportion of the costs associated with work-related musculoskeletal disorders, and the limitations of conventional diagnostic tools, a systematic evaluation of the diagnostic value of MRI appears necessary.[7, 26] The aim of the present study was to determine the diagnostic performance of quantitative MRI parameters, particularly CSA and SIR, in CTS, with a focus on measurements at the carpal tunnel outlet, and to compare these parameters with clinical and electrodiagnostic findings.

Materials & Methods

Study design and setting

This research was a cross-sectional diagnostic study conducted over an 18-month period in the orthopedic outpatient clinic and the affiliated clinic of Shahid Sadoughi Hospital, Yazd. The objective was to assess the diagnostic value of quantitative MRI indices in carpal tunnel syndrome and to compare them with clinical and electrodiagnostic evaluations.

Study population and sampling method

The study population consisted of patients presenting to the orthopedic clinic and hospital clinic with classic symptoms of CTS. Sampling was performed consecutively among eligible patients during the study period. A healthy control group, when available, was selected from volunteers without CTS symptoms and with a normal physical examination, and was considered for approximate age and sex matching.

Inclusion and exclusion criteria and sample size

Inclusion criteria included all patients with a history of wrist or hand pain and symptoms consistent with median nerve involvement within its innervation territory, such as nocturnal paresthesia, numbness, and radiating pain to the forearm or arm, along with supportive clinical findings.

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Exclusion criteria included diabetes mellitus, acromegaly, previous wrist fracture, prior wrist surgery, pregnancy, and any other condition that could affect nerve diameter or signal characteristics or the tunnel space, based on the judgment of the orthopedic surgeon or radiologist.

Table 1: Characteristics of the Study Sample

Indicator	Value
Age (years), mean ± SD	44.25 ± 9.22
Body mass index (BMI; kg/m²), mean ± SD	28.68 ± 3.71
Sex: female, n (%)	23(76.6%)
Sex: male, n (%)	7(23.3%)
Affected hand: right, n (%)	22(73.3%)
Affected hand: left, n (%)	7(23.3%)

A minimum of 30 patients was considered for inclusion. Given the exploratory nature of the study and practical limitations, this sample size was deemed sufficient for an initial estimation of the diagnostic performance of imaging indices and for conducting group comparisons.

Study procedures

Demographic information including age, sex, body mass index, and dominant hand, as well as relevant medical history, was recorded. Clinical severity of CTS was assessed using the validated Persian version of the Boston Carpal Tunnel Questionnaire (BCTQ),[27] which consists of two subscales, Symptom Severity with 11 items and Functional Status with 8 items. The translation, cultural adaptation, and psychometric properties of this version have been confirmed in the Iranian population; for example, Cronbach's alpha values for the subscales were approximately 0.85 to 0.90, and intraclass correlation coefficients for test-retest reliability ranged from approximately 0.83 to 0.91.[28] In another study, a Cronbach's alpha of 0.859 and convergent validity with the QuickDASH were reported.[29] Electrodiagnostic evaluation using EMG and nerve conduction velocity studies was performed according to the recommended AANEM protocols[30] and independently of the imaging team. Eligible patients were enrolled after clinical screening. Severity of involvement was classified into mild, moderate, and severe groups based on AANEM guidelines. Subsequently, all eligible participants were referred for MRI. To prevent any form of bias, the imaging team and MRI evaluators were blinded to the EMG and nerve conduction results as well as the Boston questionnaire scores.

Wrist imaging of the involved hand or hands and, when necessary, the contralateral side was performed using an MRI system in accordance with the institutional protocol and with an appropriate wrist coil. Routine sequences included T1-weighted, T2-weighted, and STIR images in axial and coronal planes. Imaging parameters were set based on institutional standards to ensure reproducibility and adequate signal quality. Prior to imaging, the presence of any metallic objects or MRI contraindications was assessed, and informed consent was obtained.

Definitions and measurement methods for indices:[20]

• Median nerve CSA: measured at the carpal tunnel outlet at the level of the hook of the hamate by precise tracing of the nerve boundary on axial images. When necessary, measurements at the tunnel inlet at the level of the pisiform were also recorded for comparison.

• Signal intensity ratio: defined as the ratio of the signal intensity of the median nerve to that of the hypothenar muscle on the same slice and sequence.

• Carpal tunnel cross-sectional area: determined by delineating the tunnel boundaries based on osseous landmarks and the flexor retinaculum on a standardized axial slice.

Each index was measured twice by an experienced radiology evaluator and, when possible, independently by a second evaluator. In cases of significant discrepancy, a consensus decision was reached.

Primary outcomes and ethical considerations

Primary outcomes included median nerve CSA, signal intensity ratio, and carpal tunnel cross-sectional area. Patients were categorized into mild, moderate, and severe groups based on electrodiagnostic severity to allow comparison of MRI indices across severity levels. When control subjects were available, comparisons between patients and healthy controls were also performed. The study was conducted in accordance with the principles of the Declaration of Helsinki.[31] Written informed consent was obtained from all participants. Identifying information was considered confidential and was analyzed only in coded form.

Data analysis and description

Data were entered into and analyzed using SPSS software version 22. Continuous variables were reported as mean ± standard deviation or median with interquartile range, after assessment of distribution normality as appropriate, and categorical variables were described as frequency and percentage.

• Independent t tests, or their nonparametric equivalents in cases of non-normality, were used to compare patients and controls.

• One-way analysis of variance, or the Kruskal–Wallis test, was used to compare the three electrodiagnostic severity groups, and appropriate post hoc tests were applied when significant differences were observed.

• Associations between MRI indices and Boston questionnaire scores as well as electrodiagnostic severity were assessed using correlation coefficients, Pearson or Spearman as appropriate.

• A statistical significance level of p<0.05 was considered.

Results

A total of 30 participants were evaluated. The sex distribution showed that 23 individuals (76.6%) were women and 7 individuals (23.3%) were men. The affected hand was reported to be the right hand in 22 cases (73.3%) and the left hand in 7 cases (23.3%). The mean age of patients was 44.25±9.22 years, and the mean body mass index was 28.68±3.71 kg/m². These baseline characteristics were used to describe the study population and to contextualize subsequent imaging comparisons. Full details are presented in Table 1.

Summary

Overall, the three predefined quantitative MRI indices, including median nerve signal intensity, signal intensity ratio (SIR), and cross-sectional area (CSA), were significantly higher in patients with CTS compared to healthy individuals. This pattern aligns with the pathophysiological hypothesis of increased intracanal pressure in the carpal tunnel, leading to nerve edema/swelling and subsequent signal and volumetric changes, thereby reinforcing the role of quantitative MRI as a complementary tool to clinical and electrodiagnostic assessment.

Discussion

The findings of this study demonstrated that in patients with CTS, all three quantitative MRI indices, median nerve signal intensity, median nerve-to-hypothenar muscle signal intensity ratio (SIR), and median nerve cross-sectional area (CSA), were significantly higher than those of normal individuals. This concordant pattern is expected from the pathophysiology of nerve compression, namely increased tunnel pressure, nerve edema/swelling, and tissue changes, and supports the utility of quantitative MRI indices as a complement to clinical examination and electrodiagnostic evaluation in ambiguous scenarios.

The alignment of these results with existing literature, which reports correlations between MRI indices and both presence and severity of CTS, is notable. As demonstrated in the classic study by Ochiai et al.,[23] CSA, SIR, and flattening ratio of the median nerve, along with palmar bowing of the flexor retinaculum, correlate with electrodiagnostic severity and provide a relatively comprehensive picture of the mechanical load on the nerve. In that study of 105 affected wrists, precise MRI quantification and correlation with EMG/NCV clearly paved the way for leveraging quantitative markers. Our findings regarding the significant differences in CSA and SIR between CTS patients and healthy individuals parallel these observations.

Table 2. Comparison of Patients with Carpal Tunnel Syndrome and Normal Individuals According to MRI Indices

MRI Indices	Group	Mean	SD	P-value
Signal intensity of the median nerve	Normal	501.67	40.50	<0.05
	CTS	597.13	52.95	
Signal intensity ratio of the median nerve to the hypothenar muscle (SIR)	Normal	0.80	0.13	<0.01
	CTS	1.31	0.26	
Cross-sectional area of the median nerve (CSA; mm²)	Normal	9.70	1.63	<0.05
	CTS	11.36	1.89	

Another study that evaluated CSA, SIR, flattening ratio, and retinaculum bowing in parallel demonstrated that the combination of these indices not only aids diagnosis but also predicts disease severity via ROC analysis. This is consistent with our findings of systematic increases in all three indices in CTS patients, supporting a multi-parameter approach to MRI interpretation. Furthermore, these studies highlight the impact of measurement location (tunnel inlet versus outlet), which contributes to heterogeneity in threshold values, sensitivity, and specificity across the literature.[20]

A prospective study comparing MRI and ultrasonography in 26 CTS patients and 19 healthy controls emphasized the role of CSA in both modalities. The practical implication is that MRI, beyond its discriminative capacity, provides complementary structural information (e.g., crowding, tendons, and retinaculum) relevant for pre- and post-surgical decision-making.[32] Comparison of MRI indices in our study with these findings demonstrates significant convergence.

The value of SIR, defined as the standardized ratio of nerve signal to a muscular reference, is also confirmed in the literature. Allam et al.,[33] using a 1.5 T field and water-sensitive sequences such as T2-SPAIR, showed that nerve/hypothenar SIR and diffusion parameters (ADC) significantly differ between patients and controls across multiple tunnel levels. A critical methodological point is the dependency of results on the measurement level (pisiform at the inlet versus hook of hamate at the outlet), which must be explicitly reported. This sensitivity to measurement location partly explains heterogeneity in thresholds across studies.[33]

For other structural markers, flexor retinaculum bowing is notable, as it has been reported to correlate with symptom severity and may inform preoperative decision-making. One study demonstrated the association of retinaculum bowing with clinical signs and suggested it should be assessed alongside volumetric and signal indices.[22] Our observation of parallel increases in volumetric and signal indices in the CTS group reinforces this combined approach.

Regarding the optimal CSA measurement site, MRI data suggest that CSA at the tunnel inlet (pisiform level) often provides higher discriminatory value than at the outlet, although localized swelling at the outlet (hook of hamate) may predominate in some patients. One study explicitly reported differences between the pisiform and hook of hamate, emphasizing the diagnostic value of inlet CSA.[34] Nonetheless, population and protocol differences may shift this pattern, so measurement site should be clearly reported, and both levels assessed when feasible.

The role of MRI relative to other modalities must be considered in the clinical context. Although electrodiagnostic studies remain the first-line method for quantifying conduction deficits, MRI has specific utility for atypical cases, secondary causes (masses, variants), and evaluation of patients resistant after decompression. Recent studies have introduced MR neurography and even DTI as advanced tissue-mapping tools providing additional information in selected cases; however, protocol standardization and threshold determination in this domain remain under development.[35-37]

In comparative summary, our results regarding increased CSA and SIR align with the majority of existing literature. Yet, as others have emphasized, heterogeneity in protocols, ROI definitions, measurement site, and population characteristics (age, sex, BMI) complicates meta-analysis and establishment of unified thresholds. Therefore, the clinical utility of MRI indices is maximized when used within a decision-making algorithm alongside EDX/US[1], and each center should establish internal cut-offs based on ROC/AUC[2] analysis relative to its referral population.

Limitations

This study has several limitations. First, the small sample size (n = 30) reduces the precision of estimates and affects generalizability. Second, the cross-sectional design does not allow evaluation of longitudinal changes in MRI indices with treatment (e.g., post-decompression). Third, it is single-center, introducing potential selection bias. Fourth, inter-rater reliability of MRI measurements was not reported. Fifth, ROC/AUC, effect sizes, and 95% confidence intervals for practical thresholds were not provided. Sixth, no stratified analysis was conducted for potential confounders (age, sex, BMI), nor was a systematic comparison of tunnel inlet versus outlet performed in all participants. These issues could be addressed in future multicenter prospective studies with standardized measurement protocols.

Conclusion

This study demonstrated that three MRI-based quantitative indices, including median nerve signal intensity, median nerve-to-hypothenar muscle signal intensity ratio (SIR), and median nerve cross-sectional area (CSA), are significantly higher in patients with carpal tunnel syndrome compared to healthy individuals. This pattern is consistent with the pathophysiology of nerve compression and its effects on nerve structure and signal, supporting the use of quantitative MRI as a complement to clinical examination and electrodiagnostic testing.

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Conflicts of Interest

The authors declare no conflicts of interest related to this study.

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