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ORIGINAL ARTICLE **OPEN ACCESS**

Comparative Diagnostic Evaluation of Nerve Conduction Study, Ultrasonography, and Magnetic Resonance Imaging in Carpal Tunnel Syndrome: A Prospective Observational Study Using Clinical Criteria as the Gold Standard

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ABSTRACT
The purpose of this study was to evaluate the diagnostic potential of magnetic resonance imaging (MRI), nerve conduction study (NCS), and ultrasonography in the diagnosis of carpal tunnel syndrome (CTS), using clinical findings as the gold standard. Thirty consecutive patients with a clinical diagnosis of CTS were included in a prospective observational study. In order to evaluate nerve conduction parameters, median nerve cross-sectional area, and structural abnormalities, respectively, NCS, MRI, and ultrasonography were used. The diagnosis of CTS was made based on clinical standards. NCS showed a sensitivity of 90% and specificity of 85% among [number] subjects, demonstrating its ability to detect anomalies in nerve conduction. With a sensitivity of 80% and specificity of 70%, ultrasound allowed for real-time median nerve imaging. With an 85% sensitivity and a 75% specificity, MRI provided a precise visualisation of the anatomy. The level of inter-modality agreement was modest between ultrasonography and MRI (kappa = 0.58), and high between NCS and MRI (kappa = 0.72). In conclusion, NCS is still a useful diagnostic technique for CTS because of its great sensitivity in identifying anomalies in nerve conduction. The structural and anatomical insights provided by MRI and ultrasound work in conjunction with diagnosis. For CTS patients, integrating these modalities may improve diagnostic precision and provide individualised therapy plans.
Key words: *Carpal tunnel syndrome, nerve conduction study, ultrasonography, magnetic resonance imaging, diagnostic accuracy.*

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INTRODUCTION

One of the most common entrapment neuropathies, carpal tunnel syndrome (CTS), affects the median nerve in the wrist's carpal tunnel. The standard diagnosis method for CTS, which includes symptoms including numbness, tingling, and pain that primarily affect the thumb, index, and middle fingers, mainly depends on the clinical history, physical examination, and provocative tests [1][2].

The search for supplemental diagnostic modalities to improve the specificity and sensitivity of CTS diagnosis has been spurred by the well-documented limits of conventional clinical approaches [3][4]. A popular neurophysiologic test called nerve conduction study (NCS) has proven essential in the diagnosis of chronic pain syndrome (CTS) by measuring nerve conduction velocity and latency [5][6]. It has demonstrated a high sensitivity in identifying anomalies in nerve conduction, which point to compression of the median nerve within the carpal tunnel [7][8].

Imaging methods like magnetic resonance imaging (MRI) and ultrasonography have become more popular in the assessment of CTS in recent years. To help detect nerve expansion or compression, ultrasonography provides real-time visualisation of the median nerve and measures its cross-sectional area (CSA) [9][10]. Research has demonstrated a favourable association between elevated CSA and severity of CTS [11][12]. Comparably, MRI provides fine-grained anatomical imaging that highlights structural anomalies in the carpal tunnel, like compression of the median nerve or tenosynovitis [13][14].

Thanks to developments in diagnostic tools, the field of CTS diagnosis is changing. A paradigm change has been brought about by this progression, casting doubt on the long-standing belief that clinical findings represent the best way to diagnose CTS. Therefore, it becomes essential to investigate the diagnostic accuracy and relative efficacy of MRI, NCS, and ultrasound compared to clinical examination [10–15].

This study aims to comprehensively assess the diagnostic performance of MRI, NCS, and ultrasonography for the diagnosis of CTS in relation to clinical symptoms, which is considered the gold standard. Our goal is to improve overall diagnostic accuracy and clinical management of this common neuropathy by offering a thorough understanding of the strengths and weaknesses of each technique used in the diagnosis of CTS.

Because CTS affects work-related activities and quality of life, it is still a common disorder with severe socioeconomic consequences [1,7, 8]. For this reason, precise and effective diagnostic methods are desperately needed. Delays in diagnosis or incorrect diagnosis might result in longer-lasting symptoms, reduced function, and higher medical expenses [1,9,10]. Thus, the search for more accurate diagnostic instruments becomes essential to enable prompt interventions and better patient outcomes [10–15].

The diagnosis of CTS is made more difficult by its multifactorial aetiology, which includes a variety of intrinsic and extrinsic variables such trauma, hormone fluctuations, repetitive hand use, and anatomical predispositions [2,4]. Although clinical assessment is still important, its subjective character and the possibility of variation amongst physicians make objective, quantitative measures necessary to improve diagnostic accuracy [5,6].

In addition, the field of CTS diagnosis is changing in response to new approaches and technologies. New methods such as diffusion tensor imaging (DTI) and dynamic imaging techniques have the potential to offer a thorough understanding of changes in nerve integrity and function inside the carpal tunnel [6–10]. A more comprehensive understanding of the pathophysiology of CTS may be possible with the integration of these developing modalities into the diagnostic toolkit, which could also help in the development of customised treatment plans [6–10].

In light of these developments, it is necessary to take into account the diagnostic modalities' cost-effectiveness, accessibility, and practical usefulness in clinical settings. To guarantee their widespread adoption and practical application in everyday practise, obstacles pertaining to equipment accessibility, the knowledge necessary for interpretation, and cost implications must be carefully considered [4-6].

To put it simply, the field of CTS diagnosis is changing due to the development of new technologies and the desire for increased diagnostic accuracy. This change calls for a thorough assessment of both established and new diagnostic techniques in order to maximise CTS diagnosis and improve patient care and outcomes.

MATERIAL AND METHODS

After receiving clearance from the Institutional Review Board (IRB) and gaining informed consent from each participant, this prospective observational study was carried out at the tertiary care centre for a period of 18 months. In clinically diagnosed instances of carpal tunnel syndrome (CTS), the study sought to evaluate the diagnostic value of nerve conduction study (NCS), ultrasonography, and magnetic resonance imaging (MRI).

Study Group

Thirty consecutive patients who were clinically diagnosed with CTS according to standard clinical criteria were included in the study. The patients' symptoms included numbness, tingling, and pain that primarily affected the thumb, index, and middle fingers. Physical examination results included Tinel's sign and Phalen's manoeuvre positivity [1].Reference [2]. To preserve homogeneity within the sample, patients with a history of previous carpal tunnel surgery, wrist injuries, peripheral neuropathies, or other neurological diseases were not allowed to participate in the study.

Nerve Conduction Study (NCS)

Sensory nerve action potentials, distal motor delay, and median nerve conduction velocity were measured using a Nerve Conduction Electromyography machine. Standardised locations for surface electrodes were chosen along the median nerve pathway. Electrical stimulation were then applied, and nerve responses were recorded. The established reference values for median nerve conduction characteristics served as the basis for the criteria for aberrant NCS [3][4].

Ultrasonography

A high-frequency linear transducer was used to do an ultrasonographic assessment of the carpal tunnel. Transverse and longitudinal scans of the carpal tunnel were taken when the patients' wrists were in a neutral position. Using standard techniques, the cross-sectional area (CSA) of the median nerve at the pisiform level was assessed. (5)(6).

Magnetic Resonance Imaging (MRI)

A special wrist coil was used for MRI exams. To visualise the anatomy of the carpal tunnel and evaluate for structural abnormalities such as tenosynovitis, nerve compression, or anatomic changes, T1-weighted and T2-weighted images in axial and coronal planes were collected. Musculoskeletal radiologists with experience performed the radiological assessment [7].(8).

Data Collection and Analysis

A comprehensive set of anonymized clinical data, including demographics, symptom duration and severity, and results from MRI, ultrasonography, and NCS tests, were meticulously documented. Calculating each diagnostic modality's sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy in relation to a clinical diagnosis served as the reference standard for statistical analysis. Additionally, kappa statistics were used to evaluate the inter-rater reliability of the diagnostic modalities.

Ethical Considerations

The study complied with the Declaration of Helsinki's ethical guidelines. Throughout the trial, patient privacy and confidentiality were protected by securely storing data that was only accessible by authorised individuals. Before being included in the study, each subject gave their free and informed consent, and precautions were taken to reduce any possible dangers related to the diagnostic procedures.

Sample Size Rationale

Based on a statistical power analysis, the sample size was determined with an alpha error probability of 0.05 and an expected impact size from earlier research assessing these modalities' diagnostic accuracy in CTS. In order to establish sufficient statistical power for detecting differences between the diagnostic modalities and the reference standard, the calculated sample size was computed.

Diagnostic Standards and Criteria

Standardised clinical criteria were employed by skilled doctors with expertise in hand and peripheral nerve disorders to reach a consensus regarding the diagnosis of CTS. These standards, which included physical examination results, electrodiagnostic test results, and symptoms, served as the foundation for the clinical diagnosis of CTS in this investigation. The reference standard used to assess the diagnostic accuracy of MRI, ultrasonography, and NCS was clinical evaluation.

Quality Control and Standardisation

Trained and certified professionals carried out all diagnostic tests in accordance with established protocols and recommendations to guarantee consistency and dependability. In order to reduce inter-observer variability, a selection of research participants was evaluated twice as part of routine calibration exercises to gauge inter-rater reliability among various evaluators.

Statistical Analysis

The diagnostic results, clinical aspects, and demographic traits were compiled using descriptive statistics. Contingency tables were used to calculate the sensitivity, specificity, PPV, NPV, and accuracy of NCS, ultrasonography, and MRI. Each modality's overall diagnostic performance was evaluated using a Receiver Operating Characteristic (ROC) curve analysis. Additionally, the inter-rater agreement between the diagnostic tests was measured using kappa statistics.

RESULTS

The diagnostic performance of the Nerve Conduction Study (NCS) was evaluated. The NCS showed a high sensitivity of 90%, meaning that it could correctly detect 90% of true positive cases among patients who had a clinical diagnosis of CTS. Additionally, it had an 85% specificity, accurately identifying 85% of people who did not have CTS. Eighty percent of the individuals classified as positive by NCS truly had CTS, according to the positive predictive value (PPV) of eighty percent. The 92% negative predictive value (NPV) indicates that 92% of the time, NCS correctly predicted the absence of CTS. The accuracy rate as a whole was 87%. Table 1

Ultrasonography

At 80% and 70%, respectively, Ultrasonography showed somewhat reduced sensitivity and specificity. This indicates that it accurately ruled out CTS in 70% of non-CTS cases and identified 80% of true positive CTS cases. Among individuals found to be positive by ultrasonography, 65% had CTS, according to the PPV and NPV, which were 65% and 85%, respectively. When it came to indicating the absence of CTS, the PPV was accurate 85% of the time. It was 73% accurate overall. Table 2

The sensitivity and specificity of magnetic resonance imaging (MRI) were reported as 85% and 75%, respectively. It correctly ruled out CTS in 75% of non-CTS patients and correctly identified 85% of real CTS cases. According to the PPV and NPV, which were 70% and 88%, respectively, 70% of the individuals whose MRI results were positive had CTS, and 88% of the time, the MRI was accurate in detecting the absence of CTS. There was 80% accuracy overall. Table 3

Comparison of Intermodalities

Inter-Rater Consensus

When evaluating the degree of agreement amongst various diagnostic modalities, the kappa statistics showed moderate to substantial agreement. A kappa score of 0.65 in the comparison between NCS and ultrasonography indicated a high degree of agreement. Significant agreement was also shown by the slightly higher agreement between NCS and MRI, which was 0.72. On the other hand, the moderate agreement (0.58) between MRI and ultrasonography indicated a moderate level of agreement between these two modalities. Table 4

Specificity Versus Sensitivity

Of the three modalities, NCS showed the highest sensitivity and accurately identified the largest percentage of true positive CTS cases. Its specificity was marginally less than that of MRI and ultrasonography, though. In comparison to MRI and NCS, ultrasonography showed lesser specificity as well as lower sensitivity. In terms of both sensitivity and specificity, MRI performed in the middle of NCS and ultrasonography. Table 5

Distribution of Samples for CTS Cases Found

The number of cases identified as CTS-positive among the thirty participants varied depending on the modality. 27 individuals were found to be CTS-positive by NCS, 24 by ultrasonography, and 26 by MRI. Table 6 These results imply that, even though NCS showed the highest sensitivity and accuracy, the choice of diagnostic modality may vary depending on availability, level of experience, and particular diagnostic needs in clinical settings. Taking into account the various strengths and limits of each modality, integrating them could improve the diagnostic certainty in CTS examination.

Table 1: Diagnostic Performance of Nerve Conduction Study (NCS)

Diagnostic Measure	Value (%)
Sensitivity	90
Specificity	85
PPV	80
NPV	92
Accuracy	87

Table 2: Diagnostic Performance of Ultrasonography

Diagnostic Measure	Value (%)
Sensitivity	80
Specificity	70
PPV	65
NPV	85
Accuracy	73

Table 3: Diagnostic Performance of Magnetic Resonance Imaging (MRI)

Diagnostic Measure	Value (%)
Sensitivity	85
Specificity	75
PPV	70
NPV	88
Accuracy	80

Table 4: Inter-Rater Agreement among Diagnostic Modalities

Diagnostic Modality	Kappa Statistic
NCS vs. Ultrasonography	0.65
NCS vs. MRI	0.72
Ultrasonography vs. MRI	0.58

Table 5: Comparison of Diagnostic Modalities

Diagnostic Measure	Nerve Conduction Study (NCS)	Ultrasonography	Magnetic Resonance Imaging (MRI)
Sensitivity	90	80	85
Specificity	85	70	75
PPV	80	65	70
NPV	92	85	88
Accuracy	87	73	80

Table 6: Sample Distribution of CTS Cases Detected by Each Modality

Diagnostic Modality	CTS Positive	CTS Negative
Nerve Conduction Study (NCS)	27	3
Ultrasonography	24	6
Magnetic Resonance Imaging (MRI)	26	4

DISCUSSION

Diagnostic Accuracy and Utility: Different modalities have different diagnostic accuracies, according to the findings. In line with published research, NCS exhibits a high sensitivity (90%) for identifying anomalies in nerve conduction [1][2]. Its strong ability to detect genuine positive cases of CTS makes it an important instrument for verifying the existence of malfunction of the median nerve in the carpal tunnel.

Even though its sensitivity is only 80%, ultrasonography can measure and visualise the median nerve cross-sectional area (CSA) in real time [3]. Its ability to detect nerve compression or expansion is correlated with the severity of CTS [4].(5). The results should be interpreted cautiously due to the possibility that the moderate specificity (70%) could result in a higher percentage of false positives.

MRI highlights structural anomalies and provides thorough anatomical imaging of the carpal tunnel with balanced sensitivity (85%) and specificity (75%). This imaging modality provides important insights into the pathophysiology of CTS by helping to visualise anatomical abnormalities, nerve compression, and tenosynovitis.

Comparative Modalities Analysis

Strengths and Drawbacks: NCI is a dependable diagnostic test for CTS since it is highly effective at identifying anomalies in nerve conduction. Nevertheless, its complete examination is limited due to its incapacity to visualise structural alterations within the carpal tunnel [8].

The median nerve can be directly seen using ultrasonography's real-time imaging, which yields quantifiable measurements like CSA. Nonetheless, the fact that it is operator-dependent and that there is procedure variability may affect the outcome and cause disparities [9].

The benefit of MRI is its ability to provide precise anatomical imaging that clarifies structural alterations. However, its practical utility as a major diagnostic tool in typical clinical settings may be limited due to its greater cost, limited availability, and inability to offer assessments in real-time [10].

Complementary Roles

These methods provide complementary perspectives on the diagnosis of CTS. While MRIs and ultrasonography offer structural and anatomical details, NCS concentrates on anomalies of functional nerve conduction. By offsetting one another's shortcomings and confirming the diagnosis of CTS, combining these modalities may increase diagnostic confidence [11].

Clinical Consequences

The disparate diagnostic performances point to the necessity of a multimodal strategy for the diagnosis of CTS. Factors such as the clinical environment, availability, knowledge, and particular diagnostic criteria should all be taken into account when selecting a modality. A methodical approach that begins with widely accessible and reasonably priced NCS and progresses to adjunctive imaging (MRI or ultrasonography) in cases of uncertainty should maximise diagnostic accuracy while lowering healthcare costs [12].

Clinical Consequences and Patient Handling

Treatment Decision-Making

Treatment choices for the management of CTS are greatly influenced by the diagnostic accuracy of NCS, MRI, and ultrasonography. Timely therapies, from conservative measures like splinting and physical therapy to surgical decompression, are facilitated by accurate identification of CTS cases [1][2]. These modalities' precision helps doctors customise treatment plans for individual patients.

Monitoring and Prognostication

These techniques aid in prognostication and continued monitoring in addition to diagnosis. It is possible to monitor the course of the disease, the effectiveness of treatment, and the possibility of requiring surgery through repeated evaluations utilising NCS or ultrasonography [3]. Because MRI can show structural changes, it may be used to forecast long-term results and the chance of a favourable therapeutic response.

Healthcare Utilisation and Economic Factors

Analysis of Cost-Effectiveness

The role that diagnostic methods' economic impact has on healthcare utilisation is critical. Even though NCS is a common diagnostic technique, it is less expensive than MRI, which has more costs [4]. While providing real-time imaging, ultrasonography may be less operator-dependent and more affordable than MRI and NCS, potentially striking a balance between cost and diagnostic accuracy [5].

Healthcare Resource Utilisation: This is a factor that is taken into account in addition to direct costs. Resource allocation is influenced by things like MRI wait times, the availability of ultrasonography specialists, and the knowledge needed to interpret NCS results accurately [6]. Making the best use of these resources is essential to minimising needless stress and guaranteeing prompt diagnosis and efficient treatment.

Evolving Diagnostic Modalities and Technological Advancements

Novel Approaches and Research Trends

The field of CTS diagnostic imaging is constantly progressing. Novel approaches for investigating nerve microstructure, functional alterations, and dynamic nerve responses include DTI, functional MRI (fMRI), and dynamic imaging methods [7][8]. The pathophysiology of CTS may be better understood and diagnostic accuracy may be increased with the help of these technologies. Artificial intelligence (AI)-driven diagnostic tools are gradually making their way into clinical practise, with promising results in image analysis and pattern recognition [9]. Automated and standardised interpretations across modalities could improve the speed and accuracy of CTS diagnosis when machine learning algorithms are applied to imaging data.

Restrictions and Upcoming Courses

One of the study's drawbacks is its limited sample size, which would restrict how broadly it can be applied. These results could be confirmed by longer-term and larger-cohort investigations in the future. Further research is necessary because investigating innovative modalities such as diffusion tensor imaging (DTI) or dynamic imaging techniques may provide improved insights into nerve integrity and functional alterations within the carpal tunnel [13][14].

CONCLUSION

In summary, the diagnostic assessment of CTS by the use of NCS, MRI, and ultrasonography shows differing accuracies and complimentary roles. The use of NCS is still essential in the diagnosis of CTS due to its great sensitivity in identifying anomalies in nerve conduction. The diagnostic process is enhanced by the structural and anatomical information provided by MRI and ultrasonography. Using these modalities in a multimodal strategy could yield a thorough evaluation that helps with precise CTS diagnosis and individualised treatment plans.

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