

Ultrasonography versus electrodiagnosis of median nerve before and after open carpal tunnel release surgery: which can better diagnose, predict and assess postoperative improvement?

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Abstract

Diagnosis of Carpal Tunnel Syndrome (CTS) relies on a structured clinical approach with Electrodiagnostic Studies (EDX) accepted as the gold standard in the diagnosis. Yet, Ultrasound (US) has emerged as a non-invasive alternative especially in assessing morphological changes. And so, to accurately diagnose CTS by a valid non-painful simple tool, objectively assess postoperative improvement and finally to predict postoperative clinical outcome from preoperative data; clinical, EDX, and US data were collected, compared and correlated pre- and 1 month postoperative. While US achieved diagnostic accuracy of 80% in CTS diagnosis, particularly Wrist Cross-Sectional Area (wCSA) and Wrist-Forearm Ratio (WFR), it remains less sensitive than EDX. The diagnosis of CTS using wCSA/WFR achieved a sensitivity of 80.0%/80.0% and a specificity of 100%/85.7%, at a cutoff score of 12.5mm²/2.1 or above. In addition, linear regression analysis showed that only compound motor action potential (CMAP) amplitude could predict postoperative clinical improvement. Sensitivity of EDX (93.33%) overcome that of the US in detection of postoperative improvement. US is less sensitive than EDX in diagnosing CTS, assessment and prediction of postoperative clinical outcome.

Key Words: carpal tunnel syndrome, electrodiagnostic tests, median nerve, surgical outcomes, ultrasound.

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Carpal Tunnel Syndrome (CTS) is one of the most common entrapment neuropathies affecting the upper limb and impacts work and daily activities. Diagnosis relies on a structured clinical approach, provocative maneuvers (e.g., Phalen test, Tinel sign), sensory testing and validated patient-reported outcome scales, primarily the Boston Carpal Tunnel Questionnaire (BCTQ) and its derivative, the CTS-6 scale. Electrodiagnostic studies (EDX) are accepted as the gold standard in the diagnosis of CTS as they can provide objective parameters that can better aid in grading severity by prognostication, as well as evaluate other possible causes of nerve dysfunction. In addition, EDX are important for determining the appropriate course of treatment. Yet EDX is often uncomfortable and lacks the visual utility of Ultrasound (US). However, US has emerged as a non-invasive alternative to assess morphological changes, such as increased wrist cross-sectional area (wCSA) to identify edema and compression, particularly for cases with normal EDX findings. While US is cost-effective and painless, its observer-dependency and

physiological severity makes it complementary rather than replacement to EDX in surgical planning.¹

Conservative treatment of CTS (splinting, corticosteroids) are preferred for mild-to-moderate cases, showing peak benefit at 3 months. Surgical interventions, primarily Open Carpal Tunnel Release (OCTR) or Endoscopic Carpal Tunnel Release (ECTR), is indicated for progressive deficits or persistent symptoms (>6 months). While ECTR offers faster recovery and smaller scars, OCTR remains the preferred approach in many guidelines due to superior visualization.²

Although it is a frequently asked question from patient suffering from CTS about necessity of surgery and magnitude of expected improvement postoperatively, yet there was no parameter whether EDX or US is a validated tool to address this inquiry.

Existing gaps include limited data on US-EDX-clinical correlations post-OCTR and predictive factors for outcomes; this study aims to compare the diagnostic accuracy of these modalities in CTS patients versus control subjects and as-

sess their role in predicting recovery after OCTR and assessing improvement.

Materials and Methods

Study design and participants

This was a prospective cross-sectional analytic study recruiting 30 symptomatic CTS patients (mean age 45.5 years) and 35 healthy controls from August 2023 to January 2025 at clinical neurophysiology unit, Kasr Alainy Medical school hospital, Cairo University. A total of 110 patients (173 wrists) were evaluated, with only 30 patients underwent OCTR surgery and came for follow up, thus they were included in the study. The protocol of our study was reviewed and approved by the Ethics Committee for research of our institution, approval on March 2024 and given code: MD-297-2023. Informed consent was taken for each subject.

Clinical criteria

Our diagnostic criteria for CTS were based on a score of ≥ 12 in CTS-6 scale as defined as a lower threshold in the previous literature. We excluded cases with prior wrist fracture, polyneuropathy, bifid median nerve, or space-occupying lesions and previous ipsilateral carpal tunnel release surgery. Participants were classified via Bland's severity scale to moderate (80%) and severe (20%) cases. BCTQ was used for CTS assessment pre and postoperative. This is a patient oriented and self-administered questionnaire with strong internal consistency, reproducibility and validity.³

Ultrasound

Machine and protocol

The studies were performed with a high frequency 5-17 MHz linear probe of a Esaote Diagnostic Ultrasound System (model MyLabX5) and done according to the recommendations of American Association of Neuromuscular and Electrodiagnostic Medicine (AANEM).⁴

Technique and parameters

The median nerve was viewed in short and long axis views. In short axis view, we assessed cross-sectional area (CSA) at 2 levels; forearm and wrist. At the level of the forearm, the median nerve was scanned 12 cm proximal to the distal wrist and measured by direct tracing excluding the hypoechoic epineurial rim. At the level of the Carpal Tunnel Inlet (CTI) or pisiform bone, CSA of the median nerve was measured with 12 mm² or more considered abnormal. Wrist-Forearm ratio (WFR) was calculated also at CTI. The wCSA was compared to the CSA of the median nerve in the forearm with a ratio above 2 considered abnormal. Flattening Ratio (FR) was calculated by dividing the length of its major axis by that of its minor axis at the level of the pisiform with a ratio above 3:1 considered abnormal. Tenting of the flexor retinaculum was measured through a line drawn between the apexes of the scaphoid and pisiform bones, then drawing and measuring a perpendicular line to

the flexor retinaculum. It was considered as a positive sign for CTS if the measured distance exceeded 3 mm. Hypervascularity of the median nerve was assessed by power Doppler imaging at the CTI (pisiform bone) and carpal tunnel outlet (hamate bone). The intraneural power Doppler signal was scored as present/absent, in which present represented one or more single vessel within median nerve, absent represented no power Doppler signal. Mobility was assessed by asking the patient to repetitively flex and extend fingers without moving the wrist. This sign considered positive if the median nerve could not slide easily over the flexor tendons. Echogenicity was labeled subjectively either normal preserved fascicular pattern or hypoechoic (lost fascicular pattern). In long axis view, the median nerve was explored for the notch sign which is defined as enlarged and hypoechoic median nerve then tapered down to a much thinner inside the tunnel and then expanded after the constriction point.⁵

Electrodiagnosis

Machine and protocol

EDX were done using Nihon Kohden Neuropak M1 MEB-9200 EMG machine Japan. They were done according to the recommendations of AANEM.⁶

Technique and parameters

We performed median/ulnar motor/sensory Nerve Conduction Studies (NCS) (Median nerve cutoffs: Distal Motor Latency (DML) ≤ 4.4 ms, Peak Sensory Latency (PSL) ≤ 3.5 ms, Sensory Conduction Velocity (SCV) ≥ 49 m/s) and needle electromyography for the muscles supplied by median nerve as Abductor Pollicis Brevis (APB) and flexor digitorum superficialis and to exclude cervical radiculopathy.⁶

All EDX measurements were performed in the sitting position using 25 kHz sampling frequency and supramaximal stimulation. For motor nerve studies, filter settings were 5-10000 Hz with screen sensitivities of 5 msec/div for latency and 5 mV/div for amplitude. Median nerve Compound Muscle Action Potential (CMAP) were recorded from the APB muscle via surface electrodes, with stimulation at the wrist and antecubital fossa. Sensory nerve studies utilized 5-2,000 Hz filters, with screen sensitivities of 2 ms/div for latency and 10 μ V/div for amplitude. Median Sensory Nerve Action Potential (SNAP) were recorded antidromically from the index finger following wrist stimulation to determine amplitude, latency, and conduction velocity.⁶

Surgery

Patients underwent standard OCTR via a 3-4 cm curvilinear incision 2 mm ulnar to the thenar crease under local or regional anesthesia.

Follow up

It was done one month after surgery, the time when most patients return to normal work and daily living activities so that the patient is able to use his hand more freely and had enough rest after surgery.

All EDX and US evaluations were performed by an experi-

enced clinical neurophysiologist and the OCTR surgery was done by an experienced orthopedic surgeon.

Statistical methods

Sample size was calculated using SAS 9.2 statistical analysis software. Data were coded and entered using the statistical package for the Social Sciences (SPSS) version 28 (IBM Corp., Armonk, NY, USA). Data was summarized using mean, standard deviation, median, minimum and maximum for quantitative variables and frequencies (number of cases) and relative frequencies (percentages) for categorical variables. Comparisons between groups were done using unpaired t test in normally distributed quantitative variables while non-parametric Mann-Whitney test was used for non-normally distributed quantitative variables. For comparison of pre and postoperative measurements within each patient, paired t test was used in normally distributed quantitative variables while non-parametric Wilcoxon signed rank test was used for non-normally distributed quantitative variables. For comparing categorical data, Chi square (χ^2) test was performed. Exact test was used instead when the expected frequency is less than 5. For comparison of serial measurements within each patient the non-parametric McNemar test was used. Correlations between quantitative variables were done using Spearman correlation coefficient. Linear regression analysis was done to predict significant items. Standard diagnostic indices including sensitivity and specificity were calculated as described by Galen. Receiver Operating Characteristic (ROC) curve was constructed with Area Under Curve (AUC) analysis performed to detect best cutoff value of significant parameters for detection of cases. P-values less than 0.05 were considered as statistically significant.

Results

Patient demographic and baseline information can be seen in Table 1.

Ultrasound results

Table 2 shows percentages of abnormalities in US data in the pre- and postoperative settings. Comparison of pre and postoperative data showed a high statistically significant difference ($p>0.001$) in wCSA and a statistically significant difference in WFR, FR, notch and echogenicity ($p=0.003$, 0.046, 0.011 and 0.013), while bowing, vascularity and mo-

Table 1. Baseline patient demographic, clinical and ultrasound data.

Variable	Median (SD)
Age, year	45.50±8.39
Male:Female	6:24
Hand R:L	16:14
CTS-6	18.72±3.61
Pre BCTQ	63.90±12.20
Moderate:Severe cases	24:6
wCSA, mm ²	19±8

wCSA, wrist cross-sectional area; BCTQ, Boston Carpal Tunnel Questionnaire; L, left; R, right.

Table 2. Distribution of ultrasound data in the pre- and postoperative settings.

		Preoperative		Postoperative	
		Count	%	Count	%
wCSA	Abnormal (Above 12 mm ²)	24	80.0	21	70.0
	Borderline (11 and 12 mm ²)	3	10.0	2	6.7
	Normal (up to 10 mm ²)	3	10.0	7	23.3
WFR	Abnormal (Above 2.0)	24	80.0	24	80.0
	Borderline (between 1.4 and 2)	5	16.7	5	16.7
	Normal (1.4)	1	3.3	1	3.3
FR	Abnormal (Above 3:1)	18	60.0	13	43.3
	Normal (up to 3:1)	12	40.0	17	56.7
Notch	Present	29	96.7	21	70.0
	Absent	1	3.3	9	30.0
Vascularity	Present	20	66.7	13	43.3
	Absent	10	33.3	17	56.7
Mobility	Restricted	27	90.0	23	76.7
	Free	3	10.0	7	23.3
Echogenicity	Lost fascicular pattern	28	93.3	19	63.3
	Preserved fascicular pattern	2	6.7	11	36.7

bility showed no statistically significant difference as shown in Table 3.

When compared pre and postoperative data to controls, all US parameters showed a high statistically significant value ($p>0.001$) with the exception of FR as shown in Table 4. Preoperatively, wCSA correlated significantly with DML (positive) but not with clinical scores; postoperatively, it correlated negatively with SNAP. Yet, no statistically significant correlation was found between wCSA and clinical scores. WFR showed significant preoperative correlation with Symptom Severity Scale (SSS), DML and CMAP with p value=0.045, 0.016 and 0.034; respectively. Postoperatively, WFR correlated significantly with DML and CMAP and PSL and SNAP showing positive correlations with latencies and negative correlations with amplitudes. FR and bowing signs showed no significant correlations with clinical or EDX data at either stage.

Linear regression analysis revealed that preoperative wCSA can significantly predict preoperative DML (Beta coefficient=12.247, $p=0.017$) and preoperative WRF can significantly predict preoperative CMAP (Beta coefficient=

-0.932, $p=0.023$). However, clinical and US findings did not correlate; increased CTS severity did not correspond with increases in wCSA, WFR, or FR, eliminating further linear regression analysis for these variables.

Specificity and sensitivity were done for accuracy of US and EDX in detection of improvement (taking the clinical improvement as the gold standard). Hence all patients had clinical improvement after surgery, the specificity of either US or EDX could not be performed as it necessitates the presence of unimproved cases. Sensitivity of EDX (93.33%) overcome that of the US (80%) as shown in Table 5.

We conducted ROC curve analysis to determine the optimal cutoff point to discriminate CTS patients from healthy controls. The wCSA had the highest sensitivity 80% and specificity 100% at 12.5 mm² with an AUC of 93.3%. The WFR followed with an AUC 90.4% and a cutoff of 2.1 (80% sensitivity and 85.7% specificity). The bowing sign showed less diagnostic accuracy, yielding sensitivity, specificity and AUC 80, 74.3 and 80.4% at a cutoff value of 3.75mm.

Table 3. Comparison of US and EDX data in the pre- and postoperative settings.

Cases	Preoperative					Postoperative					<i>p</i> value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
wCSA (mm ²)	19.00	8.00	17.00	5.00	39.00	16.00	7.00	14.00	7.00	33.00	<0.001
WFR	3.59	1.54	3.40	1.25	7.75	3.07	1.23	2.59	1.33	5.50	0.003
FR	3.25	0.66	3.15	2.12	4.75	2.99	0.65	2.91	1.87	4.91	0.046
Bowing	4.29	0.70	4.20	2.90	6.30	4.51	0.83	4.35	3.30	6.60	0.165
Cases	Preoperative					Postoperative					<i>p</i> value
	Count				%	Count				%	
Notch	Present			29	96.7				21	70.0	0.011
	Absent			1	3.3				9	30.0	
Vascularity	Present			20	66.7				13	43.3	0.090
	Absent			10	33.3				17	56.7	
Mobility	Restricted			27	90.0				23	76.7	0.102
	Free			3	10.0				7	23.3	
Echogenicity	Lost fascicular pattern			28	93.3				19	63.3	0.013
	Preserved fascicular pattern			2	6.7				11	36.7	
Cases	Preoperative					Postoperative					<i>p</i> value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
DML (ms)	6.68	2.29	6.05	4.75	16.40	5.37	1.54	4.90	3.75	10.50	<0.001
CMAP (mV)	5.60	2.99	6.11	0.18	12.26	5.06	2.41	5.21	0.17	8.96	0.352
PSL (ms)	5.44	0.90	5.40	4.08	7.86	4.49	0.68	4.47	3.50	6.40	<0.001
SNAP (μV)	14.35	7.24	13.00	4.30	34.00	20.81	13.15	17.50	4.30	47.20	<0.001
SCV (m/s)	33.11	5.33	33.00	20.20	43.60	38.87	5.81	38.15	27.80	49.20	<0.001

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Table 4. Comparison between cases and controls in the pre- and postoperative settings.

		Cases		Control		<i>p</i> value					
		Count	%	Count	%						
Pre Notch	Present	29	96.7	1	2.9	<0.001					
	Absent	1	3.3	34	97.1						
Pre Vascularity	Present	20	66.7	1	2.9	<0.001					
	Absent	10	33.3	34	97.1						
Pre Mobility	Restricted	27	90.0	1	2.9	<0.001					
	Free	3	10.0	34	97.1						
Pre Echogenicity	Lost fascicular pattern	28	93.3	2	5.7	<0.001					
	Preserved fascicular pattern	2	6.7	33	94.3						
Post Notch	Present	21	70.0	1	2.9	<0.001					
	Absent	9	30.0	34	97.1						
Post Vascularity	Present	13	43.3	1	2.9	<0.001					
	Absent	17	56.7	34	97.1						
Post Mobility	Restricted	23	76.7	1	2.9	<0.001					
	Free	7	23.3	34	97.1						
Post Echogenicity	Lost fascicular pattern	19	63.3	2	5.7	<0.001					
	Preserved fascicular pattern	11	36.7	33	94.3						
Cases						Control					<i>p</i> value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
Pre wCSA (mm ²)	19.00	8.00	17.00	5.00	39.00	9.00	2.00	8.00	6.00	12.00	<0.001
Pre WFR	3.59	1.54	3.40	1.25	7.75	1.83	0.37	1.80	1.29	2.75	<0.001
Pre FR	3.25	0.66	3.15	2.12	4.75	3.04	0.77	3.17	1.29	4.63	0.237
Pre Bowing	4.29	0.70	4.20	2.90	6.30	3.61	0.50	3.50	2.90	4.90	<0.001
Post wCSA (mm ²)	16.00	7.00	14.00	7.00	33.00	9.00	2.00	8.00	6.00	12.00	<0.001
Post WFR	3.07	1.23	2.59	1.33	5.50	1.83	0.37	1.80	1.29	2.75	<0.001
Post FR	2.99	0.65	2.91	1.87	4.91	3.04	0.77	3.17	1.29	4.63	0.776
Post Bowing	4.51	0.83	4.35	3.30	6.60	3.61	0.50	3.50	2.90	4.90	<0.001

Table 5. Sensitivity of ultrasound and electrodiagnostic studies in detection of postoperative improvement.

		Clinical improvement			
		Yes		No	
		Count	%	Count	%
US improvement	Yes	24	80.0	0	0.0
	No	6	20.0	0	0.0
EDX improvement	Yes	28	93.3	0	0.0
	No	2	6.7	0	0.0

EDX results

Median DML and PSL and SCV were abnormal preoperatively in all patients diagnosed with CTS. SNAP and CMAP were abnormal in 25 and 10 patients, respectively. Comparison of pre- and postoperative data showed a high statistically significant value ($p > 0.001$) in all parameters except CMAP as shown in Table 3.

When compared pre and postoperative data to controls, all EDX parameters showed a high statistically significant value ($p > 0.001$). The net result shows that comparing pre- and postoperative status was more effective at detecting improvement of the patient after surgery than comparing data to standardized cutoffs or control groups. Consequently, longitudinal comparison of a patient's own data is the most accurate method for assessing post-surgical improvement.

Linear regression analysis showed that CTS-6 scale and preoperative CMAP are mutually predictive (Beta coefficient = -0.496 and -0.639; respectively, $p = 0.001$), preoperative DML significantly predicts preoperative wCSA (Beta coefficient = 0.016, $p = 0.017$) and preoperative CMAP significantly predicts preoperative WFR (Beta coefficient = -0.191, $p = 0.023$).

Regression analysis showed also that preoperative CMAP significantly predicts postoperative difference in both SSS and total BCTQ scores (Beta coefficient = 1.176 and 1.789, $p = 0.012$ and 0.041). Although there was a statistically significant correlation between preoperative DML and postoperative difference in SSS score, yet preoperative DML could not predict it.

Discussion

CTS is the most common entrapment neuropathy affecting the upper limb with prevalence up to 8% in the general Egyptian population. Surgical release is one of the treatment options. Concerns have been raised regarding postoperative surgical outcome.

We enrolled subjects who decided to undergo OCTR as a treatment option provided by their surgeons, excluding early cases as they refused the surgery. Our diagnostic criteria for CTS were based on a score of ≥ 12 in CTS-6 scale and our EDX and US protocols followed AANEM guidelines.^{4,6} Our mean score was of 18.72 ± 3.61 , nearly similar to that of Kimura *et al.* (17.9 ± 5.2).⁷

The study reinforces the diagnostic superiority of EDX over US in a clinical setting. While US demonstrated an impressive AUC of 93.3% for a 12.5 mm^2 wCSA, EDX—specifically DML and PSL—achieved a perfect 100% sensitivity and specificity at thresholds of 4.45ms and 3.88ms, respectively.

wCSA at pisiform bone (distal wrist crease or proximal carpal tunnel) was the most sensitive US parameter aligning with previous studies.^{7,8}

However, determining cutoff values to increase the diagnostic yield without false positive results remains controversial with several proposed values. We identified 12 mm^2 the cutoff value which had detected 80% of our cases, a value consistent with Ting *et al.*⁹ Another study said that

11.9 mm^2 cutoff value showed AUC of 74% with 72% sensitivity and 68% specificity.¹⁰

Numerous studies have evaluated wCSA cutoff values. For a 10 mm^2 cutoff, Sonbol *et al.* reported 93.3% sensitivity and 98.3% specificity.¹¹ For a 10.5 mm^2 cutoff, a study reported sensitivity and specificity of 97% and 75%; respectively.⁹ Finally, higher thresholds of 11.05 mm^2 and 11.5 mm^2 yielded sensitivities and specificities of 87.5% and 80%, and 87% and 91%; respectively.^{11,12}

This shows that the wCSA cutoff point for diagnosing CTS may vary among different populations and that every center should establish its own reference ranges.

Regarding WFR, our study found an optimal diagnostic value of 2.1, yielding 80% sensitivity, 85.7% specificity and AUC 90.4%. Lowering the cutoff value to 1.9 increases sensitivity to 96.7% but reduces specificity to 60%.

In our study, WFR was abnormal in 80% of patients with cutoff value of 2 same as the cutoff point taken by Preston and Shapiro.⁵ By reviewing previous literature, limited studies addressed this parameter. Ting *et al.* chose < 1.5 as their cutoff point, Hobson-Webb *et al.* and Murciano *et al.* observed that values of 1.4 or higher provide a high sensitivity (97–100%) for diagnosing CTS, while values below 1.4 are effective for ruling it out, though limited to screening due to low specificity (28%).^{9,13,14} Conversely, Ratasvuori *et al.* concluded via ROC analysis that WFR does not enhance sensitivity or specificity compared to inlet area measurements alone.¹² Further studies investigating this parameter is recommended as it showed in our study same sensitivity as wCSA in diagnosing CTS.

The bowing sign demonstrated limited diagnostic accuracy, showing 80% sensitivity, 74.3% specificity, and an 80.4% AUC at a 3.75 mm cutoff. Consistent with Kanagasabai, who reported a 3.35 mm cutoff with 66.65% sensitivity, 20% specificity, and 60.23% diagnostic accuracy. Consequently, the bowing sign lacks sufficient diagnostic utility to serve as an independent criterion for diagnosing CTS.¹¹ Vascularity of median nerve was detected in 66.7% of our patients which comes in line with Smerilli *et al.* who confirmed the role of intraneural power Doppler signal as a biomarker of median nerve compression.¹⁵

Doppler has never been demonstrated intraneural blood flow in healthy subjects, therefore, seems to reflect a pathological condition. Increased interstitial pressure and continuous nerve edema increase both axonal transport and intraneural blood flow. Furthermore, venous outflow is blocked in early stages of CTS resulting in blood accumulation and increased pressure reducing the Doppler signal; however, compensatory peripheral veins dilatation may result in a net signal increase. So we recommend power Doppler for early CTS diagnosis consistent with Kudo *et al.*^{10,14}

These findings suggest that while US is a robust screening tool, it may miss subtle physiological changes that EDX captures, particularly in early-stage entrapment. And so, American Academy of Orthopedic Surgeons in its latest guidelines in 2016 categorized EDX as “moderate evidence” and US as “limited evidence”.³

For EDX, AUC values were 88%, and 73% for DML, and PSL, respectively in Kudo *et al.*'s study. Cutoff values

were 5.1ms, and 3.1ms for DML, and PSL, respectively. The most accurate diagnostic parameter in this study was the DML.¹⁰

Reviewing previous literature, we selected a one-month postoperative follow-up, the time when most patients resume daily living activities and had enough rest after surgery. Supporting this, Mallick *et al.* concluded that clinical outcomes (using BCTQ) at two weeks and six months are statistically equivalent and found no difference ($p=0.365$).¹⁶ Since most patients experience a post-surgical pain related to scar *i.e.* pillar pain, we agreed with recommendation of Pedersen *et al.* to incorporate a surgery-specific pain question into the BCTQ as pillar pain can significantly impair the postoperative scoring.¹⁷

Following OCTR, the study documented a rapid physiological response to decompression within the one-month follow-up period. A highly significant reduction in wCSA ($p<0.001$) and WFR ($p=0.036$) was observed, indicating the immediate relief of mechanical pressure and the subsequent reduction of intraneural edema similar to other studies,¹⁷⁻²⁰ and contradictory to another.²¹ The significant reduction in wCSA postoperatively supports the theory that nerve enlargement is partially reversible once compression is relieved. The lack of correlation between preoperative wCSA and symptom severity in our cohort aligns with several studies suggesting that US assesses anatomy rather than function.^{17,22} Yet, significant correlation was found between wCSA and DML ($p=0.028$) as reported in previous studies.^{8,9}

The significant improvement in the notch sign and nerve echogenicity further underscores US's utility as a tool to objectively verify the success of surgical decompression. Addressing concerns regarding postoperative surgical outcome, we assessed the functional recovery and found that EDX parameters, specifically DML and PSL, showed highly significant improvements ($p<0.001$), reflecting early remyelination and restored nerve conduction efficiency. This is consistent with previous studies that found motor and sensory improvement. Another study found only sensory improvement; Aksekili *et al.* and another one found only motor improvement; Green *et al.*^{17,18,23,24}

A critical contribution of this research is the identification of prognostic markers. Despite the marked morphological recovery seen on US and the improvement in conduction velocities, neither preoperative wCSA nor sensory latencies predicted the degree of clinical improvement (measured by BCTQ) as reported also in previous studies,^{1,22} and in contrast with others.²⁵ Instead, linear regression analysis identified CMAP amplitude as the sole preoperative parameter significantly associated with clinical improvement (BCTQ score reduction) at one-month post-surgery ($p=0.012$) as mentioned also by Coggon and colleagues who said that abnormal SCV could have predictive capacity for the identification of patients who would benefit from surgery.²⁶ This supports the "axonal integrity" hypothesis: clinical recovery is limited by the baseline state of motor axons. While Ise *et al.* argue that EDX lack predictive value or act as confounding factors,²⁷ our study suggests that patients with reduced CMAP amplitudes preoperatively (indicating axonal loss) may show "successful" decompression on US but experi-

ence slower or incomplete symptomatic recovery compared to those with preserved motor amplitudes.

One study reported that at 1 week and 6 weeks postoperatively, the EDX could not predict the clinical improvement of patients after OCTR. This may be because that the EDX analysis included in their study were fibrillations in APB and latency difference between median and ulnar nerve but did not study absolute latencies or other conduction variables.²⁸ Furthermore, we found that wCSA and DML are mutually predictive ($p=0.017$), as are WFR and CMAP ($p=0.034$). However, it is obvious that sensory parameters could not be predicted by either clinical assessment nor US and so, early cases would not be predicted using these methods. Thus, we agreed with Sonoo *et al.* that EDX could not be replaceable.²⁹

Despite others findings previously mentioned, as to low correlation of EDX studies to clinical outcomes after surgery, EDX testing is still widely used for diagnosis and is most appropriate as a baseline for monitoring unexpected outcomes or quantifying improvement objectively after surgery. Furthermore, regeneration of the median nerve after surgical decompression could be demonstrated and monitored with NCS.²¹

While US is an excellent non-invasive tool for monitoring the anatomical resolution of nerve compression, baseline axonal integrity (measured via CMAP) is the primary determinant of clinical recovery. These findings suggest that patients with preserved motor amplitudes may expect superior outcomes following OCTR, whereas those with advanced axonal loss may require a guarded prognosis regardless of the morphological resolution seen on US. And so we recommend longer follow up periods for US assessment and comparison with nonsurgical treatment options. Although US may not replace EDX testing as the gold standard for confirmation, Fowler *et al.* suggest that US could be proposed as an initial screening test, leaving EDX for definitive diagnosis.³⁰

Conclusions

EDX remains superior in CTS diagnosis. While US is an excellent, non-painful modality for the initial diagnosis of CTS and for monitoring anatomical recovery post-surgery, EDX remains indispensable for prognostication. For surgical candidates, clinicians should prioritize the assessment of CMAP amplitude to provide realistic expectations regarding the magnitude of postoperative clinical benefit.

List of abbreviations

CTS, Carpal tunnel syndrome
EDX, Electrodiagnostic studies
BCTQ, Boston Carpal Tunnel Questionnaire
SSS, Symptom severity scale
US, Ultrasound
wCSA, wrist cross-sectional area
OCTR, Open carpal tunnel release
ECTR, Endoscopic carpal tunnel release
WFR, Wrist-Forearm ratio

CTI, Carpal tunnel inlet
FR, Flattening ratio
NCS, nerve conduction studies
DML, Distal motor latency
PSL, Peak sensory latency
SCV, Sensory conduction velocity
APB, Abductor pollicis brevis
CMAP, Compound muscle action potential
SNAP, Sensory nerve action potential

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Conflict of interest

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Ethics approval and consent to participate

This study had the approval of the Ethics Committee for research of faculty of Medicine-Cairo University on 7-3-2024 with a code (MD-297-2023). A written consent was taken from each subject.

Contributions

FatemaAlZahraa Ahmad achieved the methodology, collected the data, shared in writing the manuscript and organization of results, Shahira Mahmoud Mostafa plotted the hypothesis, was the research manager, helped in general revision of the manuscript, Eman Ahmad Maher revised the practical and theoretical inputs at each step of the research, helped in organization of the results and in discussion generation, Mostafa Ezzat Mahmoud was responsible for proper selection of the patients, and progress of the clinical part of the research, Aliaa Ali Tawfeek helped in writing and editing the manuscript.

Consent for publication

Not applicable.

Availability of data and materials

The data that support the findings of this study are available on request from the corresponding author.

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