BENHA MEDICAL JOURNAL bmj

Print ISSN 1110-208X.

Online ISSN 2357-0016

Original article

Added Value of Morphological and Functional Magnetic Resonance Neurography in Assessment of Carpal Tunnel Syndrome in Correlation with Nerve Conduction Studies

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Received: 21 June 2023

Accepted: 3 September 2023

Abstract:

Background: To study the value of morphological and functional MRI criteria in diagnosis of carpal tunnel syndrome (CTS) and determine cut-off values between normal individuals and CTS patients. **Patients and methods**: Forty wrists were examined in 24 patients with CTS diagnosis confirmed by nerve conduction studies (NCS) and in 10 healthy subjects. Cross-sectional area (CSA), fractional anisotropy (FA) and apparent diffusion coefficient (ADC) were measured at three levels as well as signal intensity ratio (SIR), flattening ratio (FR) and retinacular bowing ratio. Comparison between the two groups was done. **Results:** CSA is increased in CTS patients compared to healthy controls. The cut off value for CSA at pisiform bone was little more sensitive than maximum CSA. SIR & FR showed no significant difference between CTS patients and control groups. RBR is increased in CTS patients. FA is decreased in CTS patients. A significant positive correlation was found between maximum CSA & highest ADC, and the findings of NCS. A significant negative correlation was found between lowest FA and the findings of NCS. **Conclusions:** CSA, RBR, FA & ADC are highly significant predictors of carpal tunnel syndrome. FR and SIR are not reliable for diagnosis of carpal tunnel syndrome. Maximum CSA, lowest FA & highest ADC can be used for grading of CTS severity.

Keywords: MR neurography; carpal tunnel; diffusion tensor imaging; nerve conduction studies

Introduction

Carpal tunnel syndrome (CTS) is a common medical condition that remains one of the most frequently reported forms of median nerve compression. CTS occurs when the median nerve is squeezed or compressed as it travels through the wrist. The syndrome is characterized by pain in the hand, numbness, and tingling in the distribution of the median nerve [(1)].

Many controversies have arisen regarding the necessity of nerve conduction studies (NCS) as confirmatory tests or tools contributing to patient management. These controversies emanate mainly by the rise of the time and the cost needed for the diagnosis of CTS with the use of NCS, the discomfort caused to the patients by nerve stimulation, and the high rate of false positive and false negative results of NCS along with the ease and the accuracy of clinical diagnosis in many cases with symptoms and signs typical of CTS [(2)].

When clinical assessment or NCS are somewhat equivocal regarding a diagnosis of CTS, hand surgeons may have hesitancy in undertaking surgery. At this situation, ultrasound or MRI may be helpful in supporting a diagnosis of CTS. MRI has advantages over ultrasound in being less operator-dependent, allowing clearer delineation of the carpal tunnel contents, and enabling the entire median nerve to be measured [(3)].

MRI of peripheral nerves, also referred to as MR neurography (MRN), is increasingly being used in clinical routine because of advances in MRI hardware and the development of new imaging techniques. MRN nicely depicts peripheral nerve anatomy and pathology, and studies have shown that MRN findings may substantially influence the management of patients with peripheral neuropathies [(4)].

Increased interest in functional MR neurography, based on diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI), has been seen in the literature. DWI is based on the ability to detect and quantify the movement of water molecules in the extracellular space. DTI shares the same biophysical basis as DWI, considering the presence of a dominant direction in the movement of free water in the three-dimensional (3D) space [(5)]. Peripheral nerves are highly anisotropic structures, presenting a facilitated diffusion along its longitudinal axis and a marked restriction of the free movement of water in the transverse plane [(6)].

The DTI-based parameter values of the CTS patients differ significantly from those of the healthy volunteers at the location of the carpal tunnel. As the nerve approaches the carpal tunnel, the perpendicular diffusivity significantly increases, evidenced by the decreasing FA and increasing ADC, indicating that diffusion in the tissue has become more isotropic [(7)].

Patients and methods:

Patients:

This study is a prospective case control comparative study, conducted on 24 patients and 10 control subjects in Department of Radiology, in Matareya teaching, within the period of January 2022 to May 2023. The study design was approved by the ethical committee of Benha University Hospitals, Benha University {M.S.12.12.2021}.

Written informed consent was obtained from all subjects. This study included 24 patients, 6 out of the 24 had bilateral complain and both wrists were examined with the total of 30 wrists.10 healthy individuals serving as a control group were also examined (10 wrists). Patients were diagnosed as CTS by clinical examination then confirmed by nerve conduction studies (NCS). Patients had the characteristic clinical symptoms of CTS: pain, numbness and tingling at the palmar aspect of the hand and at the lateral three and a half fingers. The findings of NCS

matched with CTS. The control subjects were not complaining from any symptoms suggesting CTS and their NCS were within normal.

Inclusion criteria:

Patient group:

Patients diagnosed (both clinically and electro-physiologically) with carpal tunnel syndrome.

Control group:

Healthy volunteers not complaining from any of the symptoms of CTS with normal NCS.

Exclusion criteria:

Exclusion criteria included patients with contraindication to MRI, like patients with cardiac pacemaker and patients with claustrophobia, and patients with previous surgery for CTS.

Clinical examination:

All patients were subjected to a full clinical examination and history. Patients were asked about their symptoms and did the most known clinical provocative tests of CTS (Phalen's and Tinel's tests). Phalen's test was done by asking the patient to hold his wrists in complete and forced flexion (pushing the dorsal surfaces of both hands together) for 1 minute. Tinel's test was done by taping along the patient's median nerve near the carpal tunnel. The tests were considered positive if the patient felt numbness in at least one of the three lateral finger**s**.

Nerve conduction studies:

Nerve conduction studies were performed using a Dantec NCV/EMG machine (Keypoint, Pleasanton, CA, USA). All patients underwent standardized motor and sensory nerve conduction studies (NCS) in accordance with the standard procedure as recommended by the American Association of Neuromuscular and Electrodiagnostic Medicine (AANEM) guidelines. Nerve conduction studies were carried for all patients and healthy volunteers according to the protocol proposed by the American Academy of Neurology. The median and ulnar nerves were stimulated at the wrist and elbow at 8 cm from the wrist to the active electrode. The upper limb was placed in a relaxed position. Skin temperature of the hands was maintained between 21– 23 °C. Application of gel under the electrode was done to decrease electrode impedance and electrode fixation with adhesive tape to the skin. For motor nerve conduction studies, the compound muscle action potentials (CMAP) were recorded using surface recording bar electrodes and were placed over the thenar eminence. Motor stimulation was applied at the palm, the wrist, then at the mid-forearm. For sensory nerve conduction studies, ring electrodes were applied where the proximal electrode was placed at the first interphalangeal joint and the distal electrode at 3 cm. The sensory responses were measured by the antidromic technique. The distal motor latency (DML) and distal sensory latency (DSL) were recorded for all subjects in the patient and control group. The cut-off upper limit of normal values used were 4.4 ms for DML and 3.5 ms for DSL [(8)].

MRI examination:

MRI was performed on 1.5 T closed MR Imager (Achieva; Philips, Netherlands) and a standard surface coil. The data were transferred to an offline workstation (extended workspace "EWS") and a special software was used for diffusion analysis.

Conventional MRI:

- Axial T1 turbo-spin-echo (T1-TSE): TR=504 ms, TE=8 ms, FOV=11 cm, slice thickness 2.5 mm, flip angle 90, matrix 128 ×128 pixels.
- Axial T2 turbo-spin-echo (T2-TSE): TR=4000 ms, TE=80 ms, FOV=11 cm, slice thickness 2.5 mm, flip angle 90, matrix 128 ×128 pixels.
- Axial, Sagittal& Coronal T2 SPAIR: TR=2900 ms, TE=30 ms, FOV=14 cm (11 for Axial), slice thickness 3 mm, flip angle 90, matrix 128 ×128 pixels.

Functional MR neurography:

- A single-shot spin-echo echo-planar DTI sequence with a b value of 1000 s/mm² in 32 directions. TR=3300 ms, TE=94 ms,

FOV=11 cm, slice thickness 3 mm, matrix 128 ×128 pixels.

- Post processing ADC map, FA map & 3D DTI median nerve tractography (when applicable).

Image analysis:

Conventional sequences assessment:

- CSA: Measurement of CSA was done at three levels as shown in figure 1.

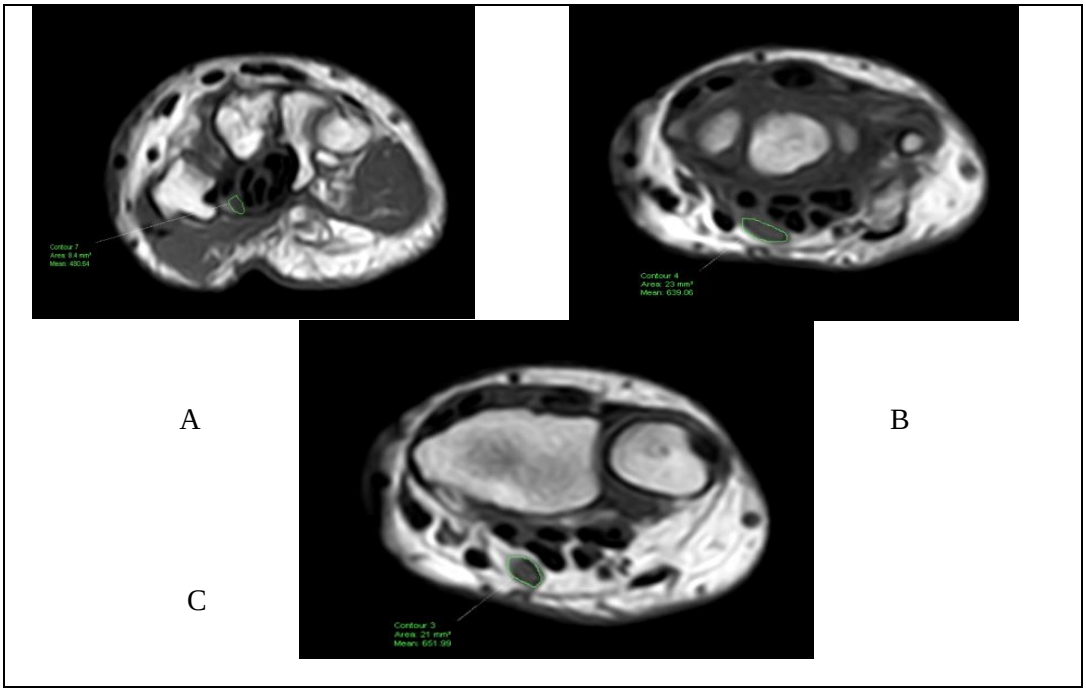

Figure (1): Measurement of cross-sectional area at three different levels by free hand technique. The free hand method is more accurate than ellipse region of interest (ROI) as the nerve may have uneven margin. A: at the level of hook of hamate, B: at the level of pisiform bone & C: at the level of distal radio-ulnar joint. The maximum CSA in this case is at the level of pisiform bone measuring 23 mm^2.

- FR: measurement of FR was done at level of maximum flattening of MN as shown in figure 2.

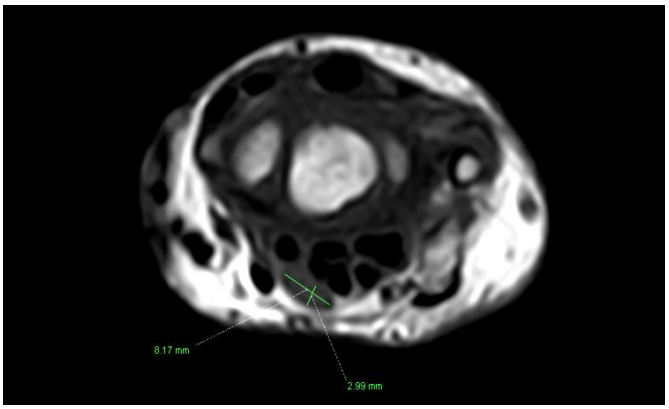

Figure (2): How to measure the flattening ratio of median nerve. The flattening ratio (FR) was calculated by dividing the major axis by the minor axis at the level of maximum flattening of median nerve. In this example the long axis measures (8.17 mm) and the short axis measures (2.9 mm), so the flattening ratio equals (2.73).

- RBR: measurement of RBR was done at the level of hook of hamate bone as shown in figure 3.

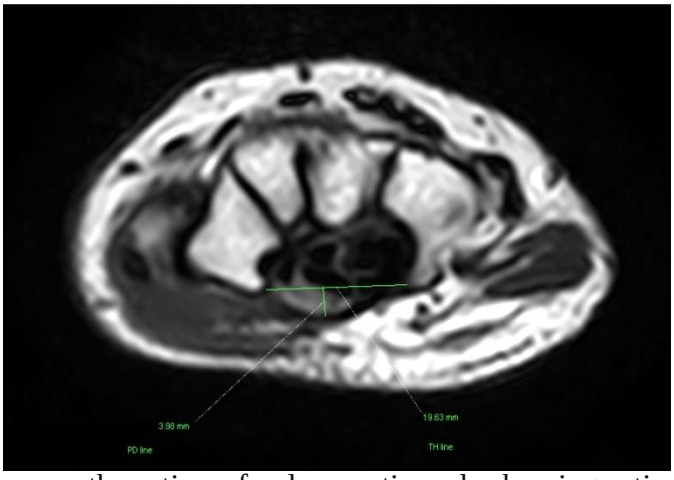

Figure 3: how to measure the ration of palmar retinacular bowing ratio. The ratio of palmar retinacular bowing ratio (RBR) was also measured by dividing the perpendicular (PD) line by the trapezium-hamate (TH) line (RBR= PD/TH ×100). First, a straight line (TH) is drawn between the attachments of the flexor retinaculum, from the tubercle of trapezium to the hook of hamate, and the length is measured. Second, the (PD) line is drawn from TH line to the apex of the flexor retinaculum perpendicularly. Here the PD line measures (3.98 mm) and the TH line measures (19.63 mm), so the ratio equals 20 %.

- SIR: Measurement of SIR was done by calculating the signal intensity of MN and that of hypothenar muscle on T2 SPAIR images as shown in figure 4.

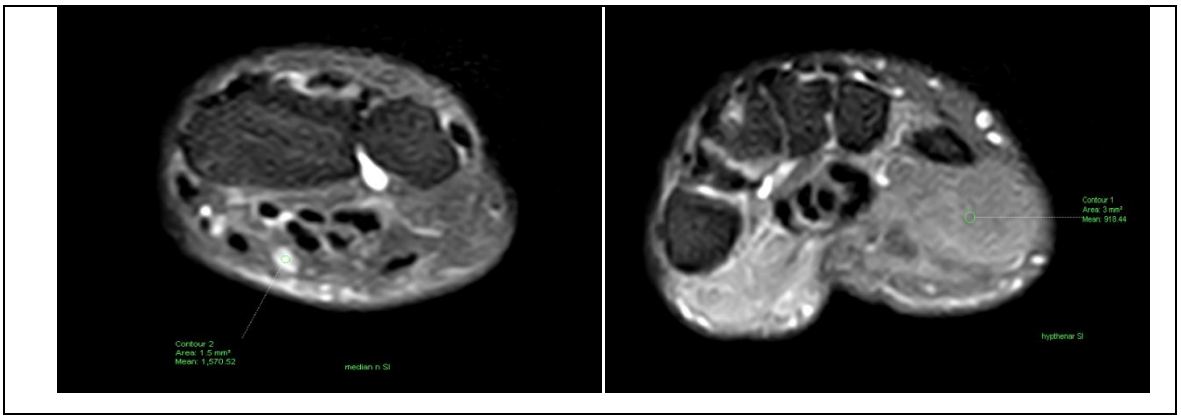

Figure 4: measurement of the signal intensity ratio by calculating the maximum signal intensity of median nerve and the hypothenar muscle. Axial T2 SPAIR images were analyzed to measure the signal intensity ratio (SIR). This was calculated by measuring the maximum signal intensity of the median nerve and dividing this value by the value of signal intensity of the hypothenar muscle to get a signal intensity ratio. Here in this example the SI of median nerve is (1570) and the SI of hypothenar muscle is (918). By dividing these values, we get a ratio of (1.71).

Functional images assessment:

The ADC and FA maps were analyzed with the guidance of T1 weighted images as anatomic reference for better localization of the median nerve accurately as reading of the ADC and FA maps alone is difficult because of their low resolution. This is shown in figure 5.

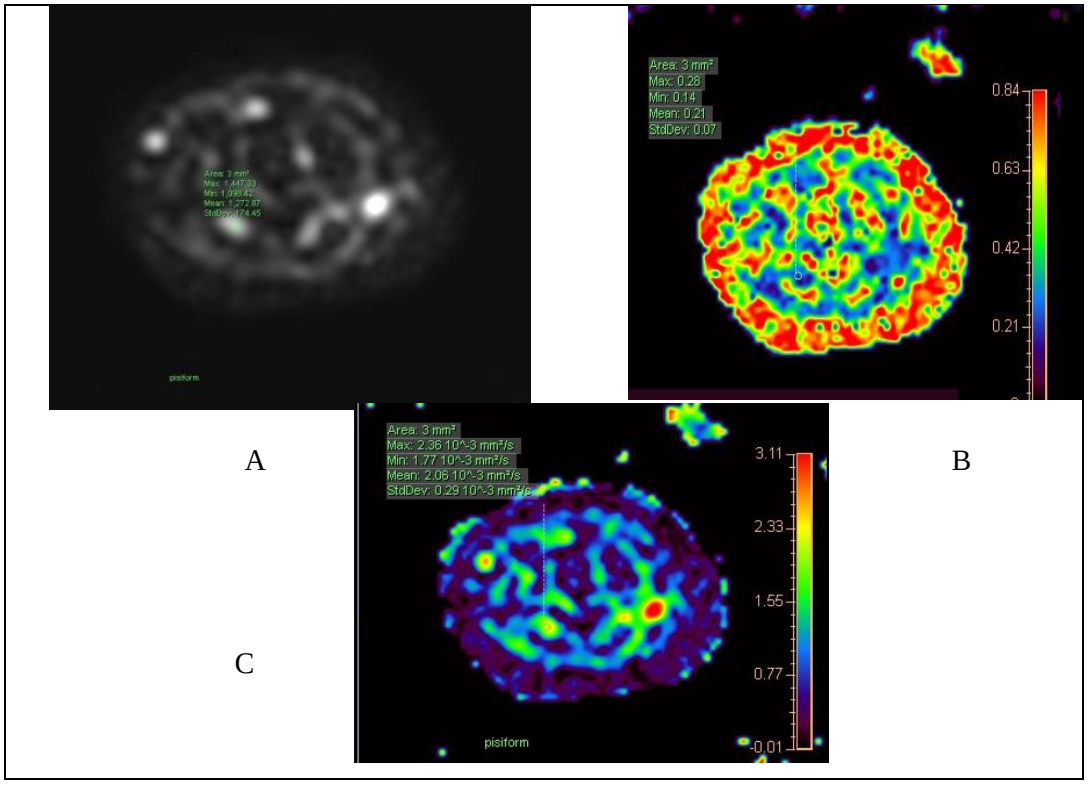

Figure 5: measurements of FA & ADC values of the median nerve at the level of pisiform bone. A circular region of interest (ROI) was drawn manually at the median nerve for calculation of FA and ADC. The ROI was smaller than the median nerve to avoid partial volume artifacts and to exclude vessels, tendons, or adjacent fat. The ADC and FA values of the median nerve were measured at the same three levels at which we measured the CSA; at DRUJ, pisiform and hook of hamate bone. A: axial DTI image with the ROI localized at the median nerve, B: FA map showing that the FA value = 0.21 & C: ADC map showing that the ADC value = 2.06 $\times 10^{-3}$ mm^2/sec.

3D tractography of the medial nerve was retrieved from the DTI images as shown in figure 6.

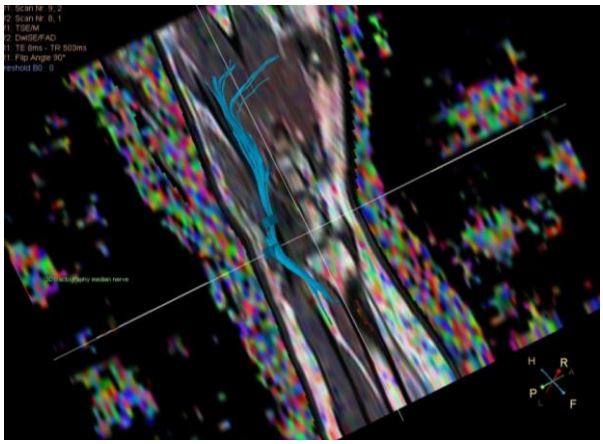

Figure 6: 3D tractography of the median nerve at the level of carpal tunnel. 3D tractography of the median nerve was done by using the overlay method of the anatomical and DTI images and choosing the multilevel ROI technique at the same forementioned three levels.

Statistical analysis

Statistical analysis was performed using the SPSS (v. 16.0). Data were represented as mean ± standard deviations and range. Mann–Whitney test was employed to compare both groups to find statistical differences in different variables. With *p* value < 0.05, the results were significant. Receiver operating characteristic curve (ROC) was performed to obtain the optimal cutoff values of different variables with their sensitivity and specificity.

Results

Regarding CTS group, the age of the studied patients ranged from 28 to 65 years old with a mean value of 46.5 ± 10.39 years. The affected wrist was on the right side in 10 (42%) patients, left in 8 (33%) patients and on both sides in 6 (25%) patients. Most of the study participants were females (21 patients representing 87.5%) and only 3 patients were males (representing 12.5 %).

Regarding the healthy controls group, their age ranged from 28 to 49 years old with a mean value of 39.9 ± 6.74. Half of them were males and the other half were females.

Morphological criteria of median nerve:

CSA, FR, RBR & FR are the morphological criteria of median nerve that have been examined in our study as shown in table 1.

Table 1: Morphological data of the studied wrists.

		CTS wrists (n =30)	Control wrists (n =10)	*p* value
CSA DRUJ (mm^2)	Mean ± S.D.	12.33 ± 4.1	6.74 ± 0.67	**<0.001****
	Range	6.7 - 21.7	5.6 - 8	
CSA Pisiform (mm^2)	Mean ± S.D.	19.93 ± 6.82	5.74 ± 1.41	**<0.001****
	Range	7.9 - 40.4	3.8 - 8.8	
CSA Hook (mm^2)	Mean ± S.D.	9.64 ± 2.75	4.08 ± 1.42	**<0.001****
	Range	5.3 - 17.1	2.5 - 6.7	
Maximum CSA (mm^2)	Mean ± S.D.	20.15 ± 6.69	7.36 ± 1.26	**<0.001****
	Range	9.7 - 40.4	6.5 - 10.3	
SIR	Mean ± S.D.	1.4 ± 0.39	1.18 ± 0.28	0.106
	Range	0.72 - 2.22	0.89 - 1.84	
FR	Mean ± S.D.	2.66 ± 0.71	2.32 ± 0.65	0.129
	Range	1.62 - 4.42	1.66 - 4	
RBR	Mean ± S.D.	12.94 ± 3.65	7.98 ± 4.51	**<0.001****
	Range	6.4 - 20.27	0 - 16	

CSA: Cross sectional area; DRUJ: Distal radioulnar joint; SIR: Signal intensity ratio; FR: Flattening ratio; RBR: Retinacular bowing ratio; S.D. = standard deviation; *Significant as *p* value ≤0.05; **Highly significant as *p* value ≤0.001. Chi square test was used for calculation of *p* value.

Regarding CTS group, CSA DRUJ ranged from 6.7 mm^2 to 21.7 mm^2 with a mean value of 12.33 ± 4.1 mm^2, CSA Pisiform ranged from 7.9 mm^2 to 40.4 mm^2 with a mean value of 19.93 ± 6.82 mm^2, CSA hook ranged from 5.3 mm^2 to 17.1 mm^2 with a mean value of 9.64 ± 2.75 mm^2, and Maximum CSA ranged from 9.7 mm^2 to 40.4 mm^2 with a mean value of 20.15 ± 6.69 mm^2.

SIR ranged from 0.72 to 2.22 with a mean value of 1.4 ± 0.39, FR ranged from 1.62 to 4.42 with a mean value of 2.66 ± 0.71, RBR ranged from 6.4 to 20.27 with a mean value of 12.94 ± 3.65.

Regarding healthy control group, CSA DRUJ ranged from 5.6 mm^2 to 8 mm^2 with a mean value of 6.74 ± 0.67 mm^2, CSA Pisiform ranged from 3.8 mm^2 to 8.8 mm^2 with a mean value of 5.74 ± 1.41 mm^2, CSA hook ranged from 2.5 mm^2 to 6.7 mm^2 with a mean value of 4.08 ± 1.42 mm^2, and Maximum CSA ranged from 6.5 mm^2 to 10.3 mm^2 with a mean value of 7.36 ± 1.26 mm^2.

SIR ranged from 0.89 to 1.84 with a mean value of 1.18 ± 0.28, FR ranged from 1.66 to 4 with a mean value of 2.32 ± 0.65, RBR ranged from 0 to 16 with a mean value of 7.98 ± 4.51.

CSA DRUJ, CSA pisiform, CSA hook, maximum CSA, and RBR were significantly higher in CTS wrists compared to Control wrists, but there was no significant difference in SIR and FR between both groups.

Functional criteria of median nerve:

The functional criteria of medial nerve that have been examined in our study are FA & ADC. Table 2 shows the FA of the studies wrists and table 3 shows the ADC.

Regarding CTS group, FA DRUJ ranged from 0.28 to 0.66 with a mean value of 0.45 ± 0.09, FA pisiform ranged from 0.2 to 0.56 with a mean value of 0.34 ± 0.09, FA hook ranged from 0.19 to 0.56 with a mean value of 0.37 ± 0.08, and lowest FA ranged from 0.19 to 0.41 with a mean value of 0.3 ± 0.06.

Regarding healthy control group, FA DRUJ ranged from 0.47 to 0.65 with a mean value of 0.58 ± 0.07, FA pisiform ranged from 0.51 to 0.78 with a mean value of 0.6 ± 0.09, FA hook ranged from 0.4 to 0.54 with a mean value of 0.48 ± 0.05, and lowest FA ranged from 0.4 to 0.52 with a mean value of 0.48 ± 0.04.

FA DRUJ, FA pisiform, FA hook, and lowest FA were significantly lower in CTS wrists compared to control wrists (*p* <0.001).

Regarding CTS group, ADC DRUJ ranged from 0.81 to 1.75×10^{-3} mm^2/sec with a mean value of $1.19 \pm 0.22\times10^{-3}$ mm^2/sec, ADC pisiform ranged from 1.04 to 2.12 $\times10^{-3}$ mm^2/sec with a mean value of $1.5 \pm 0.3\times10^{-3}$ mm^2/sec, ADC hook ranged from 1.03 to 2.16 $\times10^{-3}$ mm^2/sec with a mean value of $1.52 \pm 0.25 \times10^{-3}$ mm^2/sec, and highest ADC ranged from 1.19 to 2.16 $\times10^{-3}$ mm^2/sec with a mean value of $1.67 \pm 0.23\times10^{-3}$ mm^2/sec.

Regarding healthy control group, ADC DRUJ ranged from 0.59 to 1.2×10^{-3} mm^2/sec with a mean value of $0.86 \pm 0.18\times10^{-3}$ mm^2/sec, ADC pisiform ranged from 0.67 to 1.22 $\times10^{-3}$ mm^2/sec with a mean value of $0.92 \pm 0.19\times10^{-3}$ mm^2/sec, ADC hook ranged from 0.91 to 1.24 $\times10^{-3}$ mm^2/sec with a mean value of $1.11 \pm 0.11\times10^{-3}$ mm^2/sec, and highest ADC ranged from 0.91 to 1.24 $\times10^{-3}$ mm^2/sec with a mean value of $1.12 \pm 0.12\times10^{-3}$ mm^2/sec.

ADC DRUJ, ADC Pisiform, ADC Hook, and Highest ADC were significantly higher in CTS wrists compared to control wrists (*p* <0.001).

There was a significant negative correlation between maximum CSA and lowest FA (*r* = -0.524, *p* <0.001) and there was a significant positive correlation between maximum CSA and highest ADC (*r* = 0.705, *p* <0.001), RBR (*r* = 0.384, *p* =0.014), DSL (*r* = 0.496, *p* =0.001), and DML (*r* = 0.528, *p* <0.001)

But there was no significant correlation between maximum CSA and (FR and SIR).

A correlation between the maximum CSA and functional variable as well as to other morphological criteria was done and shown in table 4.

The diagnostic value of both morphological and functional MRN criteria for diagnosis of CTS are summarized in table 5.

Table 2: Fractional anisotropy data of the studied wrists.

		CTS wrists (n =30)	Control wrists(n =10)	*p* value
FA DRUJ	Mean ± S.D.	0.45 ± 0.09	0.58 ± 0.07	**<0.001****
	Range	0.28 - 0.66	0.47 - 0.65	
FA Pisiform	Mean ± S.D.	0.34 ± 0.09	0.6 ± 0.09	**<0.001****
	Range	0.2 - 0.56	0.51 - 0.78	
FA Hook	Mean ± S.D.	0.37 ± 0.08	0.48 ± 0.05	**<0.001****
	Range	0.19 - 0.56	0.4 - 0.54	
Lowest FA	Mean ± S.D.	0.3 ± 0.06	0.48 ± 0.04	**<0.001****
	Range	0.19 - 0.41	0.4 - 0.52	

FA: Fractional anisotropy; DRUJ: Distal radioulnar joint; *Significant as *p* value ≤0.05; **Highly significant as *p* value ≤0.001. Chi square test was used for calculation of *p* value.

Table 3: Apparent diffusion coefficient data of the studied wrists.

		CTS wrists (n =30)	**Control wrists (n =10)**	***p* value**
ADC DRUJ	Mean ± S.D.	1.19 ± 0.22	0.86 ± 0.18	**<0.001****
	Range	0.81 - 1.75	0.59 - 1.2	
ADC Pisiform	Mean ± S.D.	1.5 ± 0.3	0.92 ± 0.19	**<0.001****
	Range	1.04 - 2.12	0.67 - 1.22	
ADC Hook	Mean ± S.D.	1.52 ± 0.25	1.11 ± 0.11	**<0.001****
	Range	1.03 - 2.16	0.91 - 1.24	
Highest ADC	Mean ± S.D.	1.67 ± 0.23	1.12 ± 0.12	**<0.001****
	Range	1.19 - 2.16	0.91 - 1.24	

ADC: Apparent diffusion coefficient; DRUJ: Distal radioulnar joint; *Significant as *p* value ≤0.05; **Highly significant as *p* value ≤0.001. Chi square test was used for calculation of *p* value.

Table 4: Correlation between maximum CSA, morphological and functional variables and nerve conduction studies.

	Maximum CSA	
	r	***p* value**
Lowest FA	-0.524	**<0.001****
Highest ADC	0.705	**<0.001****
FR	0.073	0.653
RBR	0.384	**0.014***
SIR	0.098	0.547
DSL (msec)	0.496	**0.001***
DML (msec)	0.528	**<0.001****

CSA: Cross sectional area; FA: Fractional anisotropy; ADC: Apparent diffusion coefficient; FR: Flattening ratio; SIR: Signal intensity ratio; RBR: Retinacular bowing ratio; DSL: Distal sensory latency; DML: Distal motor latency; *Significant as *p* value ≤0.05; **Highly significant as *p* value ≤0.001; *r* = Pearson correlation.

Table 5: Diagnostic value of morphological and functional magnetic resonance neurography for the prediction of carpal tunnel syndrome.

	Cut-off value	**Sen.**	**Spc**	**PPV**	**NPV**	**AUC**	***p* value**
CSA DRUJ	>8	83.33	100	100	66.7	0.967	**<0.001****
CSA Pisiform	>8.8	96.67	100	100	90.9	0.997	**<0.001****
CSA Hook	>6.7	90	100	100	76.9	0.980	**<0.001****
Maximum CSA	>10.3	93.33	100	100	83.3	0.995	**<0.001****
SIR	>1.3	53.3	90	94.1	39.1	0.679	0.052
FR	>2.4	60	90	94.7	42.9	0.663	0.091
RBR	>9	80	80	92.3	57.1	0.800	**<0.001****
FA DRUJ	≤0.58	96.67	70	90.6	87.5	0.878	**<0.001****
FA Pisiform	≤0.48	96.67	100	100	90.9	0.983	**<0.001****
FA Hook	≤0.42	80	90	96	60	0.890	**<0.001****
Lowest FA	≤0.39	90	100	100	76.9	0.993	**<0.001****
ADC DRUJ	>1.02	83.33	90	96.2	64.3	0.893	**<0.001****
ADC Pisiform	>1.15	86.67	90	96.3	69.2	0.950	**<0.001****
ADC Hook	>1.24	86.67	100	100	71.4	0.920	**<0.001****
Highest ADC	>1.24	96.67	100	100	90.2	0.987	**<0.001****

CSA; Cross sectional area; SIR; signal intensity ratio; FR: Flattening ratio; RBR: retinacular bowing ratio; FA: Fractional anisotropy; ADC: Apparent diffusion coefficient; *Significant as *p* value ≤0.05; **Highly significant as *p* value ≤0.001; PPV: positive predictive value; NPV: negative predictive value; AUC: Area under curve; sen.: sensitivity; spc: specificity.

Discussion

Morphological MRI parameters in CTS diagnosis:

CSA:

In our study we measured the CSA at three different levels of carpal tunnel: just proximal to the tunnel at the DRUJ level, at the proximal part of carpal tunnel at the level of pisiform bone and at the distal part of carpal tunnel at the level of the hook of hamate bone. Also, we reported the maximum CSA for each candidate. The CSA at all the three levels and, of course, the maximum CSA, showed significant difference between the patient and control groups. In most of the cases, the maximum CSA was noted at the level of pisiform bone. Using cut off value for maximum CSA of > 10.3 mm^2, the sensitivity was 93.33 % with 100 % specificity, and using cut off value for CSA at pisiform bone of >8.8 mm^2, the sensitivity was 96.67 % with 100 % specificity. These values are less than that suggested by other studies. For example, in another study, the sensitivity was 85 % with 100 % specificity using >15 mm^2 at pisiform bone as cut off value [(3)]. In another example the cut off value of CSA at pisiform bone was 14.4 mm^2 in another study**,** with sensitivity = 90 % [(9)]. The results of our study are somewhat near to a more recent study**,** in which the use of cut off value 10.9 mm^2 for CSA at pisiform bone resulted in 97.4 % & 80 % sensitivity & specificity, respectively in diagnosis of CTS [(10)].

In our study, the mean values of CSA at pisiform bone were 19.93 ± 6.82 mm^2 & 5.74 ± 1.41 mm^2 in patient & control groups, respectively, while in another study**,** the mean values of CSA at pisiform bone were 15.58 ± 0.84 mm^2 & 9.8 ± 0.29 mm^2 in patient & control groups, respectively [(11)].

SIR:

In our study, SIR ranged from 0.72 to 2.22 with a mean value of 1.4 ± 0.39 for CTS group and ranged from 0.89 to 1.84 with a mean value of 1.18 ± 0.28 for control group, yet statistically there was no significant difference between the two groups. This is against many other studies. For example, a study found that SIR was significantly different between the two groups (1.0 ± 0.30 in control group & 1.30 ± 0.30 in patient group, *p* value < 0.0001) and with the use of 1.05 as cut off value, the sensitivity, specificity & accuracy for diagnosis of CTS were 88.4, 68.8, and 82.2%, respectively [(3)]. Also, in another study, the use of SIR > 2.4 as cut off value resulted in 70 % sensitivity and 66.7 % specificity [(10)]. However, the wide range of cut off values suggested by other studies and the relatively low specificity may indicate that the use of SIR is unreliable in diagnosing CTS.

FR:

Regarding the flattening ratio of median nerve, our study showed no significant difference between the patient and control group. In the patient group, FR ranged from 1.62 to 4.42 with a mean value of 2.66 ± 0.71 and in the control group, FR ranged from 1.66 to 4 with a mean value of 2.32 ± 0.65. We reported the maximum FR regardless of the site of flattening, yet that was at the level of proximal carpal tunnel at most of the cases. On the contrary, another study, showed significant difference in FR at the proximal carpal tunnel (2.2± 0.52 in the control group & 2.7 ± 0.9 in the patient group, *p* value < 0.0001) with 72.5 % & 65.6 % specificity using a of cut off value >2.4 [(3)]. With the use of the same cut off value, our study showed 60 % sensitivity & 90 % specificity (*p* value =0.091). Another study also showed significant difference between the patient and control groups regarding the FR only at the distal part of carpal tunnel (*p* value = 0.028), with no significant difference at the proximal part of carpal tunnel [(10)].

RBR:

Regarding the ratio of retinacular bowing, in our study we found significant difference between the patient and control

groups (in patient group, RBR ranged from 6.4 % to 20.27 % with a mean value of 12.94 ± 3.65 % and in the control group, RBR ranged from 0 % to 16 % with a mean value of 7.98 ± 4.51 %. With the use of cut off value > 9 %, both the sensitivity and specificity were 80 % (*p* value = < 0.001). This matched with other studies which found significant difference in retinacular bowing between the patients and healthy volunteers. Some of other studies calculated the degree of retinacular bowing by distance rather than ratio as in another study, in which the use of cut off value of retinacular bowing at the outlet of carpal tunnel > 1mm resulted in 69.6 % sensitivity and 96.9 % specificity [(3)]. Another study calculated the retinacular bowing by ratio, like our study, and they also found significant difference between patient and control groups with the mean value of RBR at the level of hook of hamate bone = 8 ± 2 % in patient group and 1 ± 3 % in control group. They suggested a cut off value of 4 % with 100 % sensitivity and 90 % specificity **[(10).]** In another study, the retinacular bowing ratio at the level of the hook of hamate bone was considered abnormal if more than 15 % [(12)].

Functional MRI parameters in CTS diagnosis:

The most studied peripheral nerve with DTI is the median nerve because of the potential application to CTS. In these studies, a decreased FA and increased ADC are the most commonly observed findings as in the median nerve compression, the micro-structural changes including disruption of axonal architecture and poor or lost myelination, lead to decrease of the property of anisotropy which is indicated by increased ADC and decreased FA [(13)].

FA:

We found that the FA in the patient group is significantly lower than the FA in control group at the three measured levels (DRUJ, pisiform bone & hook of hamate bone). To our knowledge this is in agreement with all the previous studies worked on the same issue and this was stated in a meta-analysis performed on 32 studies of median nerve DTI at wrist [(13)]. In our study, the largest difference between the two groups was at the level of pisiform bone and this was the same at the aforementioned meta-analysis [(13)]. In our study, the use of cut off value <0.48 at the level of pisiform bone gave the best results with 96.67 % sensitivity & 90 % specificity, which is nearly the same cut off value stated by Guggenberger et al. who reported that an FA < 0.47 at the level of the pisiform bone might be used in the diagnosis of CTS [(14).] Another study was also in agree with us, regarding that the largest difference in median nerve FA between CTS patients and healthy individuals, is at the pisiform level, however they mentioned a lower cut off value (< 0.44) with lower sensitivity (72 %) and specificity (82 %) [(15)].

ADC:

We found significant difference in ADC value between patient and control groups with the ADC in patient group higher than that of control at all the three levels of carpal tunnel. Contrary to our study, many other studies showed no significant difference regarding ADC between CTS patients and healthy controls [(16- 18)]. Nevertheless, in accordance with our study, other studies showed significant differences between CTS patients and healthy controls regarding the median nerve ADC **[(7,** 14 ,19**).]** In a systemic review and meta-analysis, they found that the ADC cut off value at the pisiform level fall within the range of 1.27 to 1.39 $\times 10^{-3}$ mm^2/sec, which is little different from our study where the cut off value for diagnosis of CTS at pisiform level is 1.15×10^{-3} mm^2/sec [(20).] Another study mentioned 1.05 $\times 10^{-3}$ mm^2/sec as a cut off value for ADC (mean value), with 83 % and 54% sensitivity and specificity, respectively [(14).] In our study, the best cut off value of ADC for diagnosis of CTS is the highest ADC value regardless of the level of

measurement. With the use of >1.24 $\times 10^{-3}$ mm^2/sec as a cut off value, the sensitivity was 96.67 % with 100 % specificity.

Correlation between maximum CSA and nerve conduction studies:

In our study we found significant positive correlation between the maximum CSA and DSL (*P* value = 0.001) and highly significant positive correlation between the CSA and DML (*p* value = < 0.001), so we suggest that CSA can be used for grading of the severity of CTS. This is in agree with another study [(3)].

Conclusions

- CSA is a highly significant predictor of carpal tunnel syndrome at the three examined levels as well as the maximum CSA.
- RBR is a highly significant predictor of carpal tunnel syndrome.
- FA is a highly significant predictor of carpal tunnel syndrome at the three examined levels as well as the lowest FA.
- ADC is a highly significant predictor of carpal tunnel syndrome at the three examined levels as well as the highest ADC.
- FR and SIR are not reliable for diagnosis of carpal tunnel syndrome.
- Maximum CSA, lowest FA & highest ADC can be used for grading of CTS severity.

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To cite this article: Mahmoud A. Abdullah, Tamer A. Kamal, Ahmed E.Shaalan, Soha S.Naby. Added Value of Morphological and Functional Magnetic Resonance Neurography in Assessment of Carpal Tunnel Syndrome in Correlation with Nerve Conduction Studies. BMFJ 2023;40(2): 553-565.