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High-resolution ultrasound findings of the median nerve in electrophysiologically severe carpal tunnel syndrome

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Abstract

Objective: Carpal tunnel syndrome (CTS) is caused by entrapment of the median nerve at the wrist. Nerve conduction studies (NCS) confirm the diagnosis and grade the severity. High-resolution ultrasound (HRUS) is useful for diagnosing CTS and excluding alternative etiologies. However, data on sonological characteristics of electrophysiologically severe CTS are limited. We aim to describe the sonological characteristics of patients with severe CTS. *Methods:* Fifty-two adults fulfilling the American Association of Neuromuscular and Electrodiagnostic Medicine practice parameters for the diagnosis of CTS and absent median nerve sensory action potential (severe CTS) were included. Cross-sectional areas (CSA) of the median nerve were obtained at the level of the carpal tunnel inlet and mid-forearm. The wrist-to-forearm ratio (WFR) was calculated. These findings were compared with 60 age- and gender-matched healthy controls. *Results:* In the patient group, the mean median nerve CSAs (in mm2) at the wrist and forearm and WFR were 15.64±3.7, 5.53±0.7 and 2.86±0.7 respectively, while in the control group, these were 7.50±0.9, 4.91±0.7 and 1.56±0.3 respectively. All parameters were significantly higher in patients compared to controls. A threshold value of 10.45 mm^2 for median nerve CSA at the wrist showed a high accuracy for severe CTS. A threshold value of WFR of 2.07 showed high sensitivity and specificity of 94.2% and 98.3%, respectively.
Conclusion: The present study provides robust data on the sonological characteristics of severe CTS. HRUS being a non-invasive tool, can be used to identify severe CTS at the point of care.

Keywords: HRUS; CTS; Peripheral nerve ultrasonography; Severe carpal tunnel syndrome; Point-of-care ultrasonography

INTRODUCTION

Carpal tunnel syndrome (CTS) is the commonest entrapment neuropathy. It is caused by entrapment of the median nerve at the level of the carpal tunnel, an osseous-fibrous canal, at the wrist and is frequently bilateral.[1] Symptoms usually consist of pain and unpleasant tingling or burning sensation in the median innervated fingers, which are usually more severe in the dominant hand and worse at night.[1,2] The diagnosis is confirmed by nerve conduction studies (NCS), which demonstrate selective and focal involvement of the median nerve at the wrist and differentiate from diffuse neuropathy and mononeuritis multiplex.[3]

High-resolution ultrasound (HRUS) provides the necessary technology for assessing the peripheral nerves non-invasively and rapidly at the point of care. HRUS is being increasingly used to complement NCS for diagnosing CTS. HRUS has also been demonstrated to be useful in diagnosing CTS in patients with typical symptoms and normal NCS.[4,5] Increased cross-sectional area (CSA) of the median nerve at the carpal tunnel inlet, bowing of the flexor retinaculum, flexor

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retinaculum thickness, flattening ratio, swelling ratio, and longitudinal compression sign are the various sonological parameters that have been described for diagnosing CTS. Some of these protocols are elaborate, and their performance, reliability and interpretation depend upon the skill of the examiner, such as optimal positioning of the hand and placement of the probe. This, in turn, determines the sensitivity, specificity, and intra- and inter-observer variability for these parameters.[6] The various techniques are not completely standardised for uniform comparison across cohorts; there is a lack of consensus regarding the optimal cut-off values of median nerve CSA at the wrist for diagnosing CTS and specifically severe CTS, particularly given the fact that the normative data varies across different populations.[7] The aim of this study is to describe the sonological characteristics in patients with electrophysiological features of severe CTS.

METHODS

This study included 52 adults with idiopathic severe CTS, and 60 matched healthy controls seen over four years between January 2018 and December 2021. Patients, aged 18 years or more, fulfilling the American Association of Neuromuscular and Electrodiagnostic Medicine (AANEM) practice parameters[8] for the diagnosis of CTS were included in this study. The presence of distal motor latency of median nerve greater than 4.5 milliseconds and absent sensory nerve action potential (SNAP) was used to diagnose severe CTS.[9] Exclusion criteria included (i) systemic inflammatory disorders such as rheumatoid arthritis, (ii) significant medical comorbidities such as uncontrolled diabetes mellitus, hypothyroidism, etc., (iii) co-existing polyneuropathy, mononeuritis multiplex or involvement of other sites of the neuraxis such as cervical radicles, anterior horn cells, etc., (iv) obesity, (v) trauma or fracture to the wrist, (vi) prior intervention for CTS in the form of carpal tunnel release surgery or injection into the carpal tunnel, and (vii) pregnant women. The clinical and demographic details were collected for all patients. The HRUS of the median nerve was performed by a single examiner (LB) using a hockey stick probe (L 15-7 MHz, CX50, Philips Medical Systems, Bothell, Washington, USA). The recording was carried out with the patient in the supine position, upper limbs abducted above the head and wrists supinated, or with the patient seated, shoulders adducted, elbows flexed to 90 to 120 degrees, forearms supported on a pillow and wrists supinated. The median nerve was traced from the wrist to the mid-forearm, with the probe oriented perpendicular to the long axis of the nerve. The CSAs of transverse sections of the median nerve were recorded within the echogenic rim surrounding the nerve with minimal pressure of the probe on the skin. The CSAs were obtained at the carpal tunnel inlet at the level of the pisiform bone and the mid-forearm. The wrist-to-forearm ratio (WFR) was calculated. The data were entered in a predesigned proforma and incorporated into a Microsoft Excel Spreadsheet for analysis. Since no identifiable patient details were revealed in this study, the need for Institutional Ethics Committee approval was waived. However, an informed verbal consent was obtained from all participants in this study.

Statistical analysis

Data was expressed as mean ± standard deviation (SD) and range for continuous variables, and number (percentage) for categorical variables. The distribution was tested for normality and logarithmically transformed when skewed. Independent t-test was used to obtain the p-value and a p-value of < 0.05 was considered statistically significant. To determine a statistically significant cut-off value for the CSA of the median nerve at the level of the wrist and the WFR, a receiver operating characteristic (ROC) curve was plotted, and a threshold value was obtained. Statistical analysis was conducted using the Statistical Package for Social Sciences (SPSS version 20.0., IBM Corporation).

RESULTS

The cohort comprised seven men (13.5%) and 45 women (86.5%) with CTS. Their mean age was 48.35±8.1 years. The electrophysiological and sonological data are summarised in Table 1. In the patient group, the mean CSA of the median nerve at the wrist was 15.64 ± 3.7 mm^2, the mean CSA of the median nerve at the mid-forearm was 5.53 ± 0.7 mm^2, and the mean WFR was 2.86 ± 0.7. Compared to normal healthy subjects, the mean CSA of the median nerve was higher among patients at the wrist (15.64 ± 3.7 vs 7.50 ± 0.9 mm2, $p < 0.0001$) and at the level of the mid-forearm (5.53 ± 0.7 vs 4.91 ± 0.7 mm^2, $p < 0.0001$). The mean WFR was significantly higher in patients with CTS than healthy controls (2.86 ± 0.7 vs 1.56 ± 0.3, $p < 0.0001$).

The plotted ROC curves provided a statistically

Table 1: Electrophysiological and sonological data of patients with carpal tunnel syndrome in the present cohort

Parameter	Patients	Controls	P value
M:F	7:45	8:52	1.00
Mean age (years)	48.35 ± 8.1	47.65 ± 10.2	0.693
Median nerve conduction studies			
Mean distal motor latency (millisec)	6.89 ± 1.6	3.08 ± 0.4	**< 0.0001**
Mean amplitude of CMAP after stimulation at wrist (milliV)	4.75 ± 3.1	8.01 ± 2.0	**< 0.0001**
Mean motor conduction velocity (m/sec)	52.38 ± 7.2	57.92 ± 2.4	**< 0.0001**
HRUS of median nerve (mm^2)			
Mean CSA at wrist (mm^2)	15.64 ± 3.7	7.50 ± 0.9	**< 0.0001**
Mean CSA at mid-forearm (mm^2)	5.53 ± 0.7	4.91 ± 0.7	< 0.0001
Mean wrist-to-forearm ratio	2.86 ± 0.7	1.56 ± 0.3	**< 0.0001**

'CMAP': compound motor action potential; 'CSA': cross-sectional area; 'F': female; 'HRUS': high-resolution ultrasound; 'M': male.

significant threshold with maximum sensitivity and specificity for a diagnosis of severe CTS. The threshold value of 10.45 mm^2 was obtained for CSA of the median nerve at the wrist. This showed sensitivity, specificity, positive predictive value, negative predictive value, and accuracy of 100%. The threshold value of WFR was 2.07, with sensitivity and specificity of 94.2% and 98.3%, respectively. Table 2 summarises the details of threshold values obtained. Figures 1 and 2 represent the plotted ROC curves for CSA at the wrist and WFR, respectively.

DISCUSSION

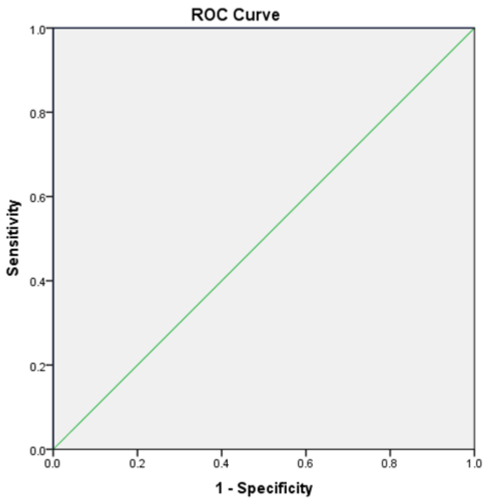
The HRUS is gaining prominence in evaluating peripheral nerve disorders, including CTS. It confirms the diagnosis of CTS and excludes alternative aetiologies such as mass lesions within the carpal tunnel and demonstrates anatomical variations such as bifid/trifid median nerve and persistent median artery, especially when the non-dominant hand is predominantly affected.[10] Moreover, HRUS guides precise injection of steroids by avoiding the neighbouring vascular and musculotendinous structures. Among the various sonological parameters, the CSA of the median nerve at the carpal tunnel inlet, i.e., pisiform level, is the most predictive of CTS. We report the two most reliable sonological parameters in patients with severe CTS, which are simple and easy to record.

The reported CSA in CTS ranges from 9.0 mm^2 to 11.0 mm^2, and sensitivity and specificity range from 70% to 94% and 65% to 97%, respectively.[6] In a large study of 207 patients with CTS, the median CSA of the median nerve at the wrist was

Table 2: Statistical results of threshold values obtained by plotting ROC curves

Parameters	Sensitivity	Specificity	Positive predictive value	Negative predictive value	False positive rate	False negative rate	Accuracy
CSA wrist > 10.45 mm^2	100%	100%	100%	100%	0	0	100%
CSA mid-forearm > 5.45 mm^2	53.8%	80%	70%	66.6%	20%	47%	67.8%
Wrist-to-forearm ratio > 2.07	94.2%	98.3%	98%	95.1%	1.7%	5.8%	96.4%

'CSA': cross-sectional area; 'ROC': receiver operating characteristic.



Area Under the Curve

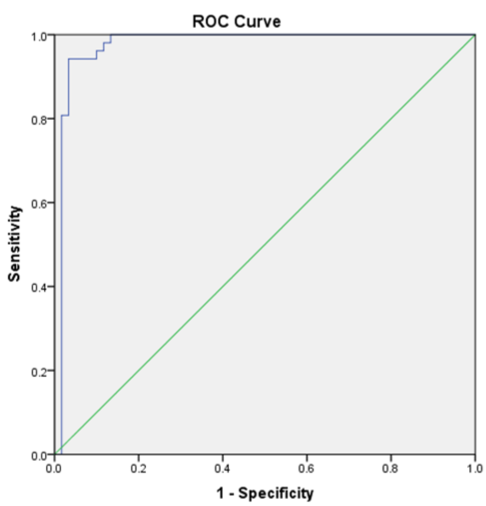
Test Result Variable(s): CSA wrist

Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
1.000	.000	.000	1.000	1.000

a. Under the nonparametric assumption

b. Null hypothesis: true area = 0.5

Figure 1: Receiver operating characteristic (ROC) curve plotted for CSA at wrist with details of area under the curve (AUC).



Area Under the Curve

Test Result Variable(s): Wrist_to_forearm_Ratio

Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
.975	.005	.000	.982	1.000

a. Under the nonparametric assumption

b. Null hypothesis: true area = 0.5

Figure 2: Receiver operating characteristic (ROC) curve plotted for ratio of median nerve CSA at wrist-to-mid forearm with details of area under the curve (AUC).

13.0 mm^2.[11] A study from India reported that the mean CSA at the inlet of carpal tunnel was 11.0 ± 2.75 mm^2.[12] However, data on HRUS findings in severe CTS is limited. The mean median nerve CSA at the level of carpal tunnel inlet in severe CTS in studies by Borire *et al*., Kang *et al*., and Klauser *et al*., were 18.2 ± 6.2 mm^2 and 18.74 ± 6.01 mm^2, and 18.5 ± 6.5 mm^2 respectively.[13,14,15] The mean CSA was 15.64 ± 3.7 mm^2 in the present study, which is lower than the previous studies. Our study found that the threshold using a ROC curve of CSA at the wrist level, for the diagnosis of severe CTS was 10.45 mm^2.

Since CTS is a focal neuropathy, swelling of the median nerve and increased CSA are expected to be present only in proximity to the site of entrapment, with normal CSA in the uninvolved segment of the nerve, such as in the forearm. This is the basis for using the CSA in the forearm segment as the internal control and WFR as a more robust parameter for the sonological diagnosis of CTS. In the present study, the cut-off WFR for distinguishing severe CTS was 2.05. Table 3 summarises the CSAs of the median nerve and the WFR in CTS vis-à-vis healthy controls as reported in different studies. While the forearm CSAs of the median nerve were comparable between patients and controls in some studies,[14,16] other studies demonstrated increased CSAs in patients even at the level of the forearm.[15,17,18] In the present study too, which included only patients with severe CTS, the mean CSA at the carpal tunnel and mid-forearm was 15.64 ± 3.7 mm^2 and 5.53 ± 0.7 mm^2, respectively, and both were significantly higher among patients with CTS as compared to the control group. In contrast, a few studies demonstrated reduced CSA of the median nerve in the forearm in patients.[19,20] This may be related to the severity of CTS, which leads to more proximal swelling of the median nerve and secondary axonal loss. Non-uniform recording protocols also contribute to the wide range of values between the studies.

Injury to the median nerve occurs due to mechanical compression within the carpal tunnel and chronic ischemia, which leads to obstruction of axoplasmic flow, demyelination, remyelination, endoneurial oedema, inflammation, and perineural thickening, and in more severe cases, to axonal loss.[21] The common conditions that predispose individuals to CTS are female gender, obesity, pregnancy, diabetes and hypothyroidism. There is no gold standard test for diagnosing CTS. The diagnosis is based on clinical symptomatology and bedside provocative signs, further supported

Table 3: Summary of key studies on high-resolution ultrasound of median nerve in CTS

Author, year	Cohort	Recording sites	Mean CSA at wrist	Mean CSA at mid-forearm	Mean WFR	Key findings
Visser *et al.*, 2008.[11]	CTS = 207 HC = 137 Severe CTS = 40	Carpal tunnel inlet Distal one-third of forearm	Median = 13 mm^2 (IQR = 11 - 15 mm^2)	Median = 5 mm^2 (IQR = 5 - 6 mm^2)	-	Accuracy of ultrasound matched electrophysiology for diagnosis of CTS. Follow up study of 161 patients showed that cut-off WFR of 2.0 had sensitivity of 69% and specificity of 90%.[18]
Hobson-Webb *et al.*, 2008.[19]	CTS = 44 HC = 18	Carpal tunnel inlet (at distal wrist crease) Mid-forearm (12 cm proximal to distal wrist crease)	14.3 ± 4.1 mm^2	6.9 ± 1.6 mm^2	2.1 ± 0.5	Cut off WFR of 1.4 has sensitivity of 100%.
Klauser *et al.*, 2009.[15]	CTS = 68 (100 hands) HC = 58 (93 hands)	Maximum CSA in carpal tunnel Distal forearm (at proximal third of pronator quadratus)	16.8 ± 5.8 mm^2	9.5 ± 1.9 mm^2	NA	Cut off CSA of 12.0 mm^2 has sensitivity of 94% and specificity of 95%. Cut off of difference between CSA of 2.0 mm^2 has sensitivity of 99% and specificity of 100%
Hunderfund *et al.*, 2011.[16]	CTS = 55 HC = 49	Carpal tunnel inlet (proximal edge of flexor retinaculum) Mid-forearm (mid-way between the ulnar styloid and elbow crease)	14.8 ± 4.9 mm^2	5.2 ± 2.0 mm^2	3.09 ± 1.46	Cut off CSA of 11.0 mm2 has sensitivity of 84% and specificity of 84%. Cut off WFR of 2.4 has sensitivity of 67% and specificity of 86%
Roll *et al.*, 2011.[23]	CTS = 47 (83 hands) HC = 44 (83 hands)	Carpal tunnel (at pisiform) Forearm (distal one-third of forearm, 6 cm proximal to wrist crease)	11.36 ± 4.33 mm^2	6.16 ± 1.28 mm^2	1.88 ± 0.67	Cut off CSA of 10.3 mm2 has sensitivity of 80.4% and specificity of 90.6%. Cut off WFR of 1.7 has sensitivity of 80.4% and specificity of 81.2%
Kang *et al.*, 2012.[14]	CTS = 110 hands HC = 38 hands	Carpal tunnel inlet (at distal wrist crease) Mid-forearm (12 cm proximal to distal wrist crease)	Mild = 13.51 ± 3.72 mm^2 Moderate = 14.67 ± 2.93 mm^2 Severe = 18.74 ± 6.01 mm^2	Mild = 7.14 ± 1.76 mm^2 Moderate = 6.57 ± 1.27 mm^2 Severe = 6.39 ± 1.46 mm^2	Mild = 1.91 ± 0.33 Moderate = 2.27 ± 0.47 Severe = 3.02 ± 0.97	Cut off CSA of 9.5 mm^2 has sensitivity of 96.4% and specificity of 92.1%. Cut off WFR of 1.34 has sensitivity of 99.9% and specificity of 100% For severe CTS: Cut off CSA of 14.15 mm^2 has sensitivity of 69.4% and specificity of 68.7%. Cut off WFR of 2.2 has sensitivity of 72.2% and specificity of 72.3%

Mhoon *et al*., 2012.[24]	CTS = 100 (192 hands) HC = 25 (50 hands)	Carpal tunnel inlet (at distal wrist crease) Mid-forearm (12 cm proximal to distal wrist crease)	13.4 ± 3.6 mm^2	6.3 ± 1.3 mm^2	2.2 ± 0.67	Cut off CSA of 9.0 mm^2 has sensitivity of 99% and specificity of 22%. Cut off WFR of 1.4 has sensitivity of 97% and specificity of 29%
Ulasli *et al*., 2012.[25]	CTS = 55 (95 hands) HC = 27 (48 hands)	Maximum CSA in carpal tunnel Mid-forearm (4 cm and 12 cm proximal to distal end of radius)	14.7 ± 4.27 mm^2	5.88 ± 1.05 mm^2 (at 4 cm) 5.88 ± 1.07 mm^2 (at 12 cm)	2.52 ± 0.66 (at 4 cm) 2.51 ± 0.64 (at 12 cm)	Cut off maximum CSA in carpal tunnel of 10.5 mm^2 has sensitivity of 91% and specificity of 81%. Cut off WFR of 1.93 (at 4 cm) has sensitivity of 93% and specificity of 98% Cut off WFR of 1.93 (at 12 cm) has sensitivity of 95% and specificity of 98%
Dejaco *et al*., 2013.[26]	CTS = 111 hands HC = 40 hands	Five points including carpal tunnel inlet (proximal border of flexor retinaculum) and forearm (proximal border of pronator quadratus)	Median = 12.0 mm^2 (range = 8.0 to 25.5 mm^2)	Median = 7.0 mm^2 (range = 5.0 to 11.0 mm^2)	NA	Cut off CSA of 9.8 mm2 has sensitivity of 90.9% and specificity of 61.2%. Cut off WFR of 1.3 has sensitivity of 90.9% and specificity of 50.6%
Borire *et al*., 2016.[13]	CTS = 101 (169 hands) HC = 20 (40 hands)	Carpal tunnel inlet (at level of pisiform) Mid-forearm (junction of mid and distal third of forearm)	Mild = 13.2 ± 3.5 mm^2 Moderate = 14.0 ± 3.0 mm^2 Severe = 18.2 ± 6.2 mm^2	NA	Mild = 1.63 ± 0.38 Moderate = 1.81 ± 0.33 Severe = 2.23 ± 0.71	Cut off CSA of 11.4 mm^2 has sensitivity of 71% and specificity of 97.5%. Cut off WFR of 1.53 has sensitivity of 60% and specificity of 92.5%
Csillik *et al*., 2016.[27]	CTS = 87 (118 hands) HC = 23 (44 hands)	Carpal tunnel inlet Mid-forearm (12 cm proximal to wrist crease)	Median = 15 mm^2 (IQR = 13 - 18.1 mm^2)	NA	Median = 2.2 (IQR = 1.9 - 3.0)	Cut off CSA of 12.6 mm^2 has sensitivity of 80.4% and specificity of 87.1%. Cut off WFR of 2.0 has sensitivity of 68.2% and specificity of 89.5%
Azman *et al*., 2017.[17]	CTS = 86 (135 hands) HC = 49 (93 hands)	Carpal tunnel inlet (at level of pisiform) Mid-forearm (10 cm proximal to wrist)	15.3 ± 5.15 mm^2	6.5 ± 1.27 mm^2	2.4 ± 0.79	Cut off CSA of 10.0 mm^2 has sensitivity of 87.4% and specificity of 94.6%. Cut off WFR of 1.7 has sensitivity of 77.8% and specificity of 91.4%
El-Habashy *et al*., 2017.[20]	CTS = 42 (72 hands) Controls = 40 (80 hands)	Carpal tunnel inlet 2-5 cm distal to mid-forearm	16.47 ± 4.28 mm^2	5.53 ± 1.23 mm^2	3.07 ± 0.89	CSA at carpal tunnel inlet increases with severity of CTS. The cut-off WFR for: Control vs mild CTS = 1.73 Mild vs moderate CTS = 3.1 Moderate vs severe CTS = 3.31

'CSA': cross-sectional area; 'CTS': carpal tunnel syndrome; 'HC': healthy controls; 'IQR': inter-quartile range; 'NR': not recorded; 'WFR': wrist-to-forearm ratio by NCS, which demonstrates selective and focal involvement of the median nerve at the level of the carpal tunnel. However, NCS has limitations, since it is false negative in 10% to 34% of CTS, particularly in mild CTS. Conversely, this may result in the misclassification of subjects into the CTS and control groups while analysing sonological data. Therefore, we included only patients with severe CTS in the present study to overcome this ambiguity.

The present study demonstrates that HRUS is a useful and well-tolerated tool for rapidly diagnosing severe CTS. This may guide the clinician to advice carpal tunnel release surgery over medical management. This may obviate the need for needle electromyography, an invasive and painful test. HRUS is a user-friendly and very smart tool and may be used by physicians without neurology speciality training for diagnosing a very common disease. Further, HRUS parameters, unlike NCS, are not influenced by ambient temperature.[22] However, it is important to have the results of the current cohort validated in a new prospective study with patients coming to the outpatient clinic with clinical signs and symptoms of CTS.

In conclusion, we provide robust data on HRUS parameters of the median nerve in severe CTS from India. This has relevance not only for diagnosis but also sets a platform for studying longitudinal alterations in the median nerve, including response to interventional therapies and correlation with the clinical course.

DISCLOSURE

Conflict of interest: None

REFERENCES

1. Ferry S, Hannaford P, Warskyj M, Lewis M, Croft P. Carpal tunnel syndrome: a nested case-control study of risk factors in women. *Am J Epidemiol* 2000;151(6):566-74. doi: 10.1093/oxfordjournals.aje.a010244.
2. Padua L, Coraci D, Erra C, *et al*. Carpal tunnel syndrome: clinical features, diagnosis, and management. *Lancet Neurol* 2016 Nov;15(12):1273-84. doi: 10.1016/S1474-4422(16)30231-9.
3. Werner RA, Andary M. Electrodiagnostic evaluation of carpal tunnel syndrome. *Muscle Nerve* 2011;44(4):597-607. doi: 10.1002/mus.22208.
4. Smidt MH, Visser LH. Carpal tunnel syndrome: clinical and sonographic follow-up after surgery. *Muscle Nerve* 2008;38(2):987-91. doi: 10.1002/mus.20982.
5. Al-Hashel JY, Rashad HM, Nouh MR, Amro HA, Khuraibet AJ, Shamov T, Tzvetanov P, Rousseff RT. Sonography in carpal tunnel syndrome with normal nerve conduction studies. *Muscle Nerve* 2015;51(4):592-7. doi: 10.1002/mus.24425.
6. Wang LY, Leong CP, Huang YC, Hung JW, Cheung SM, Pong YP. Best diagnostic criterion in high-resolution ultrasonography for carpal tunnel syndrome. *Chang Gung Med J* 2008;31(5):469-76.
7. Burg EW, Bathala L, Visser LH. Difference in normal values of median nerve cross-sectional area between Dutch and Indian subjects. *Muscle Nerve* 2014;50(1):129-32. doi: 10.1002/mus.24124.
8. American Association of Electrodiagnostic Medicine, American Academy of Neurology, and American Academy of Physical Medicine and Rehabilitation. Practice parameter for electrodiagnostic studies in carpal tunnel syndrome: summary statement. *Muscle Nerve* 2002;25(6):918-22. doi: 10.1002/mus.10185.
9. Bland JD. A neurophysiological grading scale for carpal tunnel syndrome. *Muscle Nerve* 2000;23(8):1280-3. doi: 10.1002/1097-4598(200008)23:8<1280::aid-mus20>3.0.co;2-y.
10. Chompoopong P, Preston DC. Neuromuscular ultrasound findings in carpal tunnel syndrome with symptoms mainly in the nondominant hand. *Muscle Nerve* 2021; 63(5):661-7. doi: 10.1002/mus.27148.
11. Visser LH, Smidt MH, Lee ML. High-resolution sonography versus EMG in the diagnosis of carpal tunnel syndrome. *J Neurol Neurosurg Psychiatry* 2008;79(1):63-7. doi: 10.1136/jnnp.2007.115337.
12. Kanikannan MA, Boddu DB, Umamahesh, Sarva S, Durga P, Borgohain R. Comparison of high-resolution sonography and electrophysiology in the diagnosis of carpal tunnel syndrome. *Ann Indian Acad Neurol* 2015;18(2):219-25. doi: 10.4103/0972-2327.150590.
13. Borire AA, Hughes AR, Lueck CJ, Colebatch JG, Krishnan AV. Sonographic differences in carpal tunnel syndrome with normal and abnormal nerve conduction studies. *J Clin Neurosci* 2016;34:77-80. doi: 10.1016/j.jocn.2016.05.024.
14. Kang S, Kwon HK, Kim KH, Yun HS. Ultrasonography of median nerve and electrophysiologic severity in carpal tunnel syndrome. *Ann Rehabil Med* 2012; 36(1):72-9. doi: 10.5535/arm.2012.36.1.72.
15. Klauser AS, Halpern EJ, De Zordo T, *et al*. Carpal tunnel syndrome assessment with US: value of additional cross-sectional area measurements of the median nerve in patients versus healthy volunteers. *Radiology* 2009;250(1):171-7. doi: 10.1148/radiol.2501080397.
16. Hunderfund AN, Boon AJ, Mandrekar JN, Sorenson EJ. Sonography in carpal tunnel syndrome. *Muscle Nerve* 2011;44(4):485-91. doi: 10.1002/mus.22075.
17. Ažman D, Hrabač P, Demarin V. Use of multiple ultrasonographic parameters in confirmation of carpal tunnel syndrome. *J Ultrasound Med* 2018;37(4):879-89. doi: 10.1002/jum.14417.
18. Visser LH, Smidt MH, Lee ML. Diagnostic value of wrist median nerve cross sectional area versus wrist-to-forearm ratio in carpal tunnel syndrome. *Clin Neurophysiol* 2008;119(12):2898-9; author reply 2899. doi: 10.1016/j.clinph.2008.08.022.
19. Hobson-Webb LD, Massey JM, Juel VC, Sanders DB. The ultrasonographic wrist-to-forearm median nerve area ratio in carpal tunnel syndrome. *Clin Neurophysiol* 2008;119(6):1353-7. doi: 10.1016/j.clinph.2008.01.101.
20. El Habashy HR, El Hadidy RA, Ahmed SM, El Sayed

BB, Ahmed AS. Carpal tunnel syndrome grading using high-resolution ultrasonography. *J Clin Neurophysiol* 2017;34(4):353-8. doi: 10.1097/WNP.0000000000000373.

21. Werner RA, Andary M. Carpal tunnel syndrome: pathophysiology and clinical neurophysiology. *Clin Neurophysiol* 2002;113(9):1373-81. doi: 10.1016/s1388-2457(02)00169-4.
22. Chang YW, Chen CJ, Wang YW, Chiu V, Lin SK, Horng YS. Influence of temperature on sonographic images of the median nerve for the diagnosis of carpal tunnel syndrome: a case control study. *BMC Med Imaging* 2021;21(1):163. doi: 10.1186/s12880-021-00700-6.
23. Roll SC, Evans KD, Li X, Freimer M, Sommerich CM. Screening for carpal tunnel syndrome using sonography. *J Ultrasound Med* 2011;30(12):1657-67. doi: 10.7863/jum.2011.30.12.1657.
24. Mhoon JT, Juel VC, Hobson-Webb LD. Median nerve ultrasound as a screening tool in carpal tunnel syndrome: correlation of cross-sectional area measures with electrodiagnostic abnormality. *Muscle Nerve* 2012;46(6):871-8. doi: 10.1002/mus.23426.
25. Ulaşli AM, Duymuş M, Nacir B, Rana Erdem H, Koşar U. Reasons for using swelling ratio in sonographic diagnosis of carpal tunnel syndrome and a reliable method for its calculation. *Muscle Nerve* 2013;47(3):396-402. doi: 10.1002/mus.23528.
26. Dejaco C, Stradner M, Zauner D, *et al*. Ultrasound for diagnosis of carpal tunnel syndrome: comparison of different methods to determine median nerve volume and value of power Doppler sonography. *Ann Rheum Dis* 2013;72(12):1934-9. doi: 10.1136/annrheumdis-2012-202328.
27. Csillik A, Bereczki D, Bora L, Arányi Z. The significance of ultrasonographic carpal tunnel outlet measurements in the diagnosis of carpal tunnel syndrome. *Clin Neurophysiol* 2016;127(12):3516-23. doi: 10.1016/j.clinph.2016.09.015.