Magnetic Resonance Imaging and Sonographic Features before and after Surgery in Carpal Tunnel Syndrome: Association with Clinical Findings

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Background: The interest in ultrasonography (US) and magnetic resonance imaging (MRI) assessment of the patients with carpal tunnel syndrome (CTS) is growing. This paper aimed to find the correlation of postoperative changes in these modalities’ parameters with clinical outcomes.

Methods: Boston CTS questionnaire-symptom severity (BQ-SS), Boston CTS questionnaire-functional status (BQ-FS), and visual analog scale (VAS) questionnaires (for pain, paresthesia, and grip weakness assessment) were used to evaluate clinical outcomes. Various imaging parameters of the median nerve and carpal tunnel were evaluated using US and MRI at two levels of the hook of the hamate (distal) and the pisiform (proximal) once preoperatively and then 3 months postoperatively. Corresponding US and MRI parameter measures were compared, and correlational analysis was performed between alteration of imaging findings and changes in clinical parameters postoperatively.

Results: Patients’ functional status (BQ-FS score) was positively correlated with the nerve width both in US and MRI at the proximal level ($r = 0.457$ and $r = 0.453$, respectively) and also with the MRI nerve circumference at the distal level ($r = -0.482$). Correlation between paresthesia and the nerve width was notable in MRI at the distal hook of the hamate level ($r = -0.403$). Grip weakness VAS score was correlated with the nerve width-to-height ratio (WHR) in US at the distal level ($r = 0.432$).

Conclusions: Changes in US and MRI parameters of the median nerve width, circumference, and WHR were associated with clinical changes in patients with CTS after surgery.

Keywords: Carpal tunnel syndrome, Magnetic resonance imaging, Ultrasonography, Surgery

Carpal tunnel syndrome (CTS) is the most common chronic peripheral neuropathy, which mostly affects middle-aged women. Although the etiologic factors behind the pathophysiology of CTS are not clearly known, it is evident that trapping and compression of the median nerve under the transverse carpal ligament, is the major mechanism responsible for the symptoms. Regarding changes in the nerve and carpal tunnel anatomical parameters following CTS (e.g., local swelling and flattening of the median nerve at different levels), ultrasonography (US) and magnetic resonance imaging (MRI) of peripheral nerves are also implemented as complementary diagnostic modalities for CTS patients in recent years. Not all patients with CTS respond well to surgery. In these cases,
it is important to determine the underlying anatomical pathology, if any, especially in order to decide whether there is an indication for reoperation. As the electrodiagnostic study is not accurate enough for postoperative evaluation and remains abnormal even after clinical improvement,\(^1^\) imaging studies could play a key role in assessing recurrent and persistent CTS.\(^1^\)\(^5\)-\(^1^\)\(^9\)

Most studies have evaluated the efficacy of MRI or US as a diagnostic application compared with electrophysiologic study.\(^6\) The association of some preoperative radiologic and clinical symptoms has also been previously reported,\(^2^\)\(^0\)-\(^2^\)\(^2\) but no study has dealt with the correlation of the improvements in these measures after carpal tunnel release (CTR) to find out which one is more consistent with clinical symptom improvements postoperatively. This study is a basic investigation of the link between anatomical changes and clinical parameters, which may help us to understand the major underlying anatomical pathology based on the main complaint of the patient.

In this cross-sectional study, we therefore asked (1) how US and MRI measures differ after surgery, (2) what the relationships are between corresponding measures of US and MRI, and (3) which radiologic measure changes after surgery correlate with clinical measure changes in patients with confirmed CTS.

**METHODS**

**Settings and Approval**

This prospective analytical cross-sectional study was performed in an urban tertiary hospital during 2018–2020 on patients with CTS symptoms who were referred to the orthopedic clinic. Patients signed informed written consent forms before enrollment, and their privacy rights were observed.

The study was approved by Research Ethics Committee of Mashhad University of Medical Sciences (No. IR.MUMS.fm.REC.1395.473) and was conducted in full compliance with the codes of ethical conduct from the declaration of Helsinki. Patients were provided with and signed written informed consent forms before enrollment.

**Patients**

Using a convenience sampling method, patients who were referred to our tertiary hospital orthopedic clinic and whose clinical characteristics were compatible with the diagnosis of CTS (paresthesia, numbness, motor weakness, and thenar atrophy) were investigated by a single orthopedist (AM). The participants in this study were recruited from eligible women (because of very lower CTS prevalence among men compared to women in our society\(^2^)\(^3\) with a confirmed diagnosis of CTS, according to the results of electromyography and nerve conduction velocity, who did not respond to medical therapy and, therefore, were candidates of surgical treatment. Exclusion criteria were as follows: patients with peripheral neuropathies (e.g., diabetic neuropathy), previous wrist surgery or intra-canal corticosteroid injection, rheumatoid arthritis, hypothyroidism, recent hand or wrist trauma, median nerve anomalies, and pregnant women. Three individuals were excluded from the study on the basis of corticosteroid injection and diabetic neuropathy. The median nerve was released in all of the patients using a mini-open technique. The skin was incised using a 2.5-cm incision, 5-mm ulnar side to the thenar crease and above the transverse carpal ligament. We ensured complete release by passing a dissector across the wrist to feel for any remnants of the transverse carpal ligament. The sutures were removed in 3 weeks and a compression dressing was applied for 1 week. There was no usage of a splint.

**Tools**

**Boston CTS questionnaire**

The Boston CTS questionnaire was developed for the purpose of measuring the severity of CTS symptoms. Each item is scored from 1 (normal) to 5 (very serious/difficult). It comprises two different subscales: Boston CTS questionnaire-symptom severity (BQ-SS) and Boston CTS questionnaire-functional status (BQ-FS). BQ-SS contains 11 items, which assess wrist pain episodes, weakness, numbness, and difficulty in grasping. BQ-FS includes 8 questions, which evaluate daily manual functions. We applied a valid and reliable Persian version of the questionnaire.\(^2^)\(^3\)

**Visual analog scale**

Visual analog scale (VAS) is a simple scale that can be scored from 0 (no symptom) to 10 (worst symptom) on a continuous basis. We used this scale to quantify the subjective severity of CTS symptoms including pain, paresthesia, and weakness.

**Study Design**

**Clinical assessment**

Demographic parameters including age and sex, as well as basic clinical data such as duration of symptoms, dominant hand, involved side, history of previous medical treatment, and history of comorbidities, were gathered in checklists. To assess the main clinical parameters, i.e., severity of symptoms and hand function, we used BQ-SS, BQ-FS, and VAS
US examination
A single radiologist (BA) with expertise in musculoskeletal US carried out ultrasound exams on all subjects using an Aplio 300 ultrasound machine and a 12-MHz linear probe (Canon Medical Systems, Otawara, Japan) under the same standard conditions while the patient’s forearm was lying on a table with the palm in supine position (Fig. 1).

MRI evaluation
MRI of the wrist was performed by a single expert MRI technician (BA) using a 1.5 T MRI scanner (Siemens Medical System, Erlangen, Germany). Axial 3-mm sections of T1-weighted and proton density-fat saturated sequences were used to measure the median nerve dimensions (Fig. 2). Both US and MRI of the median nerve were performed at two levels: (1) slightly before the median nerve entrance to the carpal tunnel at approximately pisiform level (proximal) (Figs. 1C, D, and 2A, B) and (2) inside the carpal tunnel at the hook of the hamate level (distal) (Figs. 1E, F, and 2C, D) to measure the width, height, circumference, and cross-sectional area of the median nerve, as well as its distance from the skin. We also calculated the flattening ratio of the median nerve by dividing the transverse diameter of the nerve (width) by the anteroposterior diameter (height) of the nerve (WHR). Cross-sectional area proximal/distal ratio of the median nerve was also calculated. Pisiform level is actually the middle of the tunnel and hook of the hamate level is the tunnel outlet. The measurement method is briefly shown in Figs. 1 and 2. MRI and US measures were interpreted by a radiologist (FK) who was not part of the study team and blinded regarding the study conduction. All clinical questionnaires, US, and MRI measurements mentioned above were performed before the operation (the day before surgery) and then 3 months postoperatively.

Patient Demographics
Overall, 26 patients with CTS were studied, all of whom were women (100%). The mean age of the patients was 46.15 years (standard deviation, 10.96 years; range, 28–67 years). Table 1 shows some of the main characteristics of the population. Of note, diabetes mellitus was the most common comorbidity (19%), followed by hypertension (11%).

Statistical Analysis
Data were analyzed using IBM SPSS ver. 22 (IBM Corp., Armonk, NY, USA). The distribution of data was checked using Kolmogorov-Smirnov test. Paired samples t-test and Wilcoxon test were used to compare data before and after
the intervention. Significance level was set at \( p < 0.05 \). The compatibility between US and MRI corresponding parameter measurements before and after was analyzed using Pearson correlation test. Pearson correlation test was also used to assess the correlations between clinical and radiologic parameters. Significant level of correlational analysis was \( r > 0.4 \) and \( p < 0.005 \).

**RESULTS**

**Radiological Outcome Changes after Surgery**

The first set of analyses examined the US parameter changes after intervention. US examination of the median nerve at the hook of the hamate and pisiform levels showed significant improvement after surgery in all the measured parameters including the width, height, cross-sectional area, and width/height ratio of the median nerve as well as its distance from the skin \( (p < 0.05) \) except for the nerve circumference at the pisiform level whose changes were not significant. The cross-sectional area increased at the hook of the hamate level, but decreased at the pisiform level, resulting in significant reduction in the proximal (pisiform) to distal (hook of the hamate) ratio.

The next question dealt with the impact of surgery on MRI parameters. Assessment at the hook of the hamate showed that the measured values for the width, circumference-
ence, and cross-sectional area of the median nerve significantly increased after surgery ($p < 0.05$), while the width/height ratio decreased ($p = 0.012$). However, no significant changes were evident in the median nerve’s height and distance from the skin. Measurements of the median nerve in MRI at the pisiform level showed that the nerve’s height, circumference, and cross-sectional area were significantly decreased while its distance from the skin was significantly increased ($p < 0.05$). On the other hand, no significant change was observed with regard to the nerve’s width and its width/height ratio at the pisiform level in MRI (Table 2).

**Correlation of Corresponding US and MRI Measures**

At the proximal level, all the measured parameters of the two modalities were correlated except for the nerve-to-skin distance before surgery. However, at the distal hook of the hamate level, the nerve height and WHR before surgery and most of the measures after surgery were not correlated (Tables 3 and 4).

**Intervariable Radiological/Clinical Correlation**

We performed bivariate correlation tests to identify possible correlations between the preoperative and postoperative mean changes in clinical and radiological outcomes.

**US hook of the hamate level**

Mean difference of BQ-SS score was correlated with that of the median nerve’s distance from skin ($r = 0.419$). Mean difference of weakness score was significantly correlated with the mean changes in the median nerve width/height ratio ($r = 0.432$) (Table 5).

**US pisiform level**

The mean difference of BQ-FS score and weakness was correlated with that of the median nerve width ($r = 0.457$ and $r = 0.428$, respectively). Paresthesia was related to nerve circumference ($r = 0.441$). Pain score changes were associated with the nerve distance ($r = 0.436$) and proximal/distal cross-sectional area ratio ($r = −0.439$) (Table 5).

**Table 2. Comparison of Preoperative and Postoperative Radiological Measurements of the Median Nerve**

| Parameter | Before surgery | After surgery | p-value (US) | p-value (MRI) |
|-----------|----------------|---------------|--------------|---------------|
|           | US | MRI | US | MRI | | |
| Hook of the hamate level | | | | | | |
| Nerve width (mm) | 4.75 ± 0.51 | 4.97 ± 0.79 | 5.21 ± 0.52 | 5.76 ± 0.64 | < 0.001 | < 0.001 |
| Nerve height (mm) | 1.90 ± 0.34 | 2.08 ± 0.34 | 2.27 ± 0.33 | 3.54 ± 4.36 | < 0.001 | 0.117 |
| Nerve circumference (mm) | 11.23 ± 1.42 | 12.22 ± 1.95 | 12.51 ± 0.98 | 14.01 ± 1.59 | < 0.001 | < 0.001 |
| Nerve cross-sectional area (mm$^2$) | 7.64 ± 1.14 | 9.14 ± 1.19 | 10.13 ± 1.30 | 12.12 ± 1.91 | < 0.001 | < 0.001 |
| Nerve-to-skin distance (mm) | 7.78 ± 1.40 | 10.70 ± 1.58 | 8.84 ± 1.32 | 10.92 ± 1.80 | < 0.001 | 0.406 |
| Nerve width/height ratio$^{16}$ | 2.55 ± 0.39 | 2.47 ± 0.72 | 2.33 ± 0.42 | 2.11 ± 0.51 | 0.012 | 0.035 |
| Pisiform level | | | | | | |
| Nerve width (mm) | 6.21 ± 1.09 | 6.15 ± 0.98 | 5.94 ± 0.97 | 5.98 ± 0.73 | 0.003 | 0.117 |
| Nerve height (mm) | 2.59 ± 0.31 | 2.82 ± 0.38 | 2.33 ± 0.25 | 2.63 ± 0.39 | < 0.001 | 0.009 |
| Nerve circumference (mm) | 13.93 ± 3.46 | 14.90 ± 2.20 | 13.15 ± 2.56 | 14.32 ± 1.61 | 0.171 | 0.021 |
| Nerve cross-sectional area (mm$^2$) | 12.92 ± 2.91 | 14.27 ± 2.55 | 11.40 ± 2.61 | 12.96 ± 1.97 | < 0.001 | < 0.001 |
| Nerve-to-skin distance (mm) | 3.52 ± 0.69 | 4.09 ± 0.61 | 4.46 ± 0.67 | 4.66 ± 0.86 | < 0.001 | 0.004 |
| Nerve width/height ratio$^{16}$ | 2.41 ± 0.40 | 2.20 ± 0.42 | 2.55 ± 0.38 | 2.30 ± 0.35 | 0.023 | 0.134 |
| Nerve cross-sectional area pisiform/hamate level (proximal/distal) ratio (mm$^2$) | 1.70 ± 0.34 | 1.56 ± 0.23 | 1.12 ± 0.21 | 1.07 ± 0.11 | < 0.001 | < 0.001 |

Values are presented as mean ± standard deviation. US: ultrasonography, MRI: magnetic resonance imaging.
MRI hook of the hamate level
BQ-FS was negatively correlated with the median nerve circumference \( (r = -0.482) \), and paresthesia score was negatively correlated with the median nerve width \( (r = -0.403) \) and width/height ratio \( (r = -0.477) \) (Table 6).

MRI pisiform level
BQ-FS was correlated with the median nerve width \( (r = 0.453) \) (Table 6).

**DISCUSSION**
Considering anatomical changes of the median nerve and carpal tunnel in CTS pathophysiology, we hypothesized that imaging studies could be associated with CTS patients’ clinical symptoms. The experimental work presented here provides one of the first basic investigations into evaluation of the correlation between clinical and radiologic parameters’ changes after CTR surgery. With respect to the first research question, the median nerve measures of US and MRI examination, whose improvement was significant at the hook of the hamate and at the pisiform levels, are consistent with results from similar studies.\(^{26,27}\)

The second question of this research was to determine MRI and US modality compatibility in measuring the same radiologic parameters. Considering that WHR at the hook of the hamate level was not correlated between US and MRI, while the WHR parameter was correlated with the grip weakness score in US, we can argue that we probably cannot substitute US with MRI for assessing WHR parameter changes in cases of remaining weakness postoperatively. On the other hand, at the MRI hook of the hamate level, paresthesia and BQ-FS score were correlated with the nerve width and circumference, respectively, while these two parameter measures were not correlated in US and MRI after surgery; as a result, for patients with remaining paresthesia and high BQ-FS score, it is better to use MRI while looking for the nerve width and circumference.

Regarding the main objective of the study to identify the MRI and US modality correlation with clinical outcomes, generally, we did not find any strong correlation...
between clinical and radiologic measures. One hypothesis for this may be that clinical symptoms improve immediately after open surgery, but it takes several months for nerve swelling to improve. One study also stated that decreased postoperative nerve swelling was not associated with reduced postoperative symptoms and functional disabilities.\(^28\)

We found that BQ-FS score improvement positively correlated with US and MRI nerve width decrease, which may reflect the reduction of swelling at the proximal level. With respect to MRI at the distal level, BQ-FS score had correlation with increased nerve circumference, perhaps because of pressure removal at this level. Paresthesia score mostly correlated with nerve width and WHR. Grip weakness and WHR at the distal hook of the hamate level also significantly correlated in US. One unanticipated finding at this level was that the nerve-to-skin distance parameter positively correlated with BQ-SS score, which probably is because of postoperative skin thickening due to scar formation.

Although there is no identical study to compare these findings with, previous studies have explored the relationships between imaging (US or MRI) and clinical or electro-myographic outcomes after surgery. Regarding the postoperative median nerve cross-sectional area, some studies reported that the reduction in the nerve’s cross-sectional area at the inlet of the carpal tunnel significantly correlated with improvement in the symptom severity and function scores.\(^25,29\) We could not find a significant correlation between clinical scores and cross-sectional area, perhaps due to the shorter duration of follow-up. Some reports showed the association of the radiologic changes with favorable outcomes on electromyography after surgery.\(^30\) Moreover, the results of one study support the idea of using MRI in addition to electromyography for postoperative evaluation.\(^24\)

Despite clinical improvements, postoperative electrodiagnostic studies show abnormalities even after 4
months of surgery. As a result, studying postoperative nerve conduction is not sensitive enough in determining an individual's clinical course. On the other hand, intraoperative MRI is a recent technology, which can be applied real time intraoperatively. Identification of MRI parameters' association with clinical symptoms becomes more significant as this technology becomes more practical and widespread. Moreover, electrodiagnostic studies are partially invasive, and some patients may prefer to be evaluated with imaging modalities.

While conducting this research, we faced a few potential limitations. Due to the prospective nature of our study and the need for long-term follow-up, some patients (3 patients) left the study. As a result, the numbers of patients examined before and after surgery were not equal. In addition, our sample size was small and included only women (because of the imbalanced gender distribution in our society referral centers) with CTS, which can be addressed in future studies. The operator-dependent nature of US is also among the limitations.

The study findings suggest that there may be an association between clinical symptoms and imaging parameters of median nerve width at proximal level, nerve circumference, and WHR. These results may facilitate a better understanding of each CTS symptom pathophysiology. This study will pave the way for future studies on CTS and investigation of changes in the median nerve dimensions and their relationship with clinical manifestations, particularly with larger sample sizes in a more detailed study of the carpal tunnel and its contents including a simultaneous review of other factors involved in the occurrence of CTS. These findings could also be of interest to physicians for choosing a more accurate method for visualizing the details of the carpal tunnel during patient follow-up.

Table 6. Correlations between the Mean Changes in Clinical and MRI Radiological Outcomes

| Radiological outcome | Clinical outcome | BQ-SS | BQ-FS | Pain | Paresthesia | Weakness |
|----------------------|------------------|-------|-------|------|-------------|---------|
| Hook of the hamate   |                  |       |       |      |             |         |
| Width                |                  | 0.019 (–0.41 to 0.37) | 0.302 (–0.66 to 0.13) | 0.215 (–0.16 to 0.58) | 0.403 (–0.68 to –0.04) | 0.185 (–0.29 to 0.63) |
| Height               |                  | 0.155 (–0.36 to 0.42) | 0.086 (–0.29 to 0.62) | 0.078 (–0.27 to 0.26) | 0.219 (0.03 to 0.57) | 0.068 (–0.56 to 0.06) |
| Circumference        |                  | 0.095 (–0.27 to 0.42) | 0.482 (–0.79 to –0.04) | 0.298 (–0.09 to 0.63) | 0.335 (–0.63 to 0.00) | 0.129 (–0.39 to 0.62) |
| Cross-sectional area |                  | 0.026 (–0.27 to 0.37) | 0.057 (–0.45 to 0.41) | 0.252 (–0.11 to 0.57) | 0.095 (–0.45 to 0.30) | 0.383 (0.01 to 0.73) |
| Distance from skin   |                  | 0.248 (–0.21 to 0.61) | 0.167 (–0.42 to 0.38) | 0.214 (–0.66 to 0.23) | 0.288 (–0.69 to 0.22) | 0.030 (–0.37 to 0.39) |
| WHR                  |                  | 0.037 (–0.42 to 0.52) | 0.214 (–0.57 to 0.20) | 0.179 (–0.13 to 0.47) | 0.477 (–0.72 to –0.12) | 0.330 (–0.07 to 0.62) |
| Pisiform             |                  |       |       |      |             |         |
| Width                |                  | 0.172 (–0.19 to 0.53) | 0.453 (0.06 to 0.70) | 0.137 (–0.32 to 0.59) | 0.143 (–0.44 to 0.21) | 0.051 (–0.39 to 0.47) |
| Height               |                  | 0.206 (–0.20 to 0.55) | 0.145 (–0.29 to 0.54) | 0.200 (–0.17 to 0.55) | 0.291 (–0.62 to 0.09) | 0.136 (–0.55 to 0.28) |
| Circumference        |                  | 0.016 (–0.33 to 0.34) | 0.155 (–0.26 to 0.56) | 0.025 (–0.32 to 0.31) | 0.105 (–0.27 to 0.46) | 0.130 (–0.52 to 0.23) |
| Cross-sectional area |                  | 0.265 (–0.55 to 0.10) | 0.141 (–0.18 to 0.58) | 0.074 (–0.43 to 0.38) | 0.210 (–0.55 to 0.23) | 0.139 (–0.51 to 0.27) |
| Distance from skin   |                  | 0.148 (–0.20 to 0.49) | 0.164 (–0.26 to 0.51) | 0.115 (–0.52 to 0.43) | 0.034 (–0.33 to 0.36) | 0.144 (–0.31 to 0.56) |
| WHR                  |                  | 0.083 (–0.41 to 0.31) | 0.158 (–0.38 to 0.54) | 0.089 (–0.47 to 0.31) | 0.124 (–0.14 to 0.44) | 0.079 (–0.44 to 0.65) |
| Hamate/pisiform      |                  |       |       |      |             |         |
| Cross-sectional area | proximal/distal ratio | 0.275 (–0.59 to 0.09) | 0.146 (–0.27 to 0.59) | 0.275 (–0.58 to 0.14) | 0.022 (–0.44 to 0.46) | 0.230 (–0.58 to 0.16) |

Values are presented as r coefficient (95% confidence interval).

MRI: magnetic resonance imaging, BQ-SS: Boston CTS questionnaire-symptom severity, BQ-FS: Boston CTS questionnaire-functional status, WHR: width-to-height ratio.
CONFLICT OF INTEREST
No potential conflict of interest relevant to this article was reported.

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REFERENCES
1. Atroshi I, Gumnessson C, Johnsson R, Ornstein E, Ranstam J, Rosen I. Prevalence of carpal tunnel syndrome in a general population. JAMA. 1999;282(2):153-8.
2. Aboonq MS. Pathophysiology of carpal tunnel syndrome. Neurosciences (Riyadh). 2015;20(1):4-9.
3. Gelfman R, Melton LJ 3rd, Yawn BP, Wollan PC, Amadio PC, Stevens JC. Long-term trends in carpal tunnel syndrome. Neurology. 2009;72(1):33-41.
4. Middleton SD, Anakwe RE. Carpal tunnel syndrome. BMJ. 2014;349:g6437.
5. 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.
6. Keberle M, Jenett M, Kenn W, et al. Technical advances in ultrasound and MR imaging of carpal tunnel syndrome. Eur Radiol. 2000;10(7):1043-50.
7. Roomizadeh P, Eftekharsadat B, Abedini A, et al. Ultrasonographic assessment of carpal tunnel syndrome severity: a systematic review and meta-analysis. Am J Phys Med Rehabil. 2019;98(5):373-81.
8. Wiesler ER, Chloros GD, Cartwright MS, Smith BP, Rushing J, Walker FO. The use of diagnostic ultrasound in carpal tunnel syndrome. J Hand Surg Am. 2006;31(5):726-32.
9. Alp NB, Akdag G, Macunluoglu AC. Median nerve and carpal tunnel volume changes after two different surgical methods: a comparative magnetic resonance imaging study of mini-open and endoscopic carpal tunnel release. Eklem Hastalik Cerrahisi. 2019;30(3):212-6.
10. Fujita K, Kimori K, Nimura A, Okawa A, Ikuta Y. MRI analysis of carpal tunnel syndrome in hemodialysis patients versus non-hemodialysis patients: a multicenter case-control study. J Orthop Surg Res. 2019;14(1):91.
11. Kumari A, Singh S, Garg A, Prakash A, Sural S. Tingling hand: magnetic resonance imaging of median nerve pathologies within the carpal tunnel. Pol J Radiol. 2019;84:e484-90.
12. Mesgarzadeh M, Triolo J, Schneck CD. Carpal tunnel syndrome. MR imaging diagnosis. Magn Reson Imaging Clin N Am. 1995;3(2):249-64.
13. Vogelin E, Nuesch E, Juni P, Reichenbach S, Eser P, Ziswiler HR. Sonographic follow-up of patients with carpal tunnel syndrome undergoing surgical or nonsurgical treatment: prospective cohort study. J Hand Surg Am. 2010;35(9):1401-9.
14. Vogt T, Scholz J. Clinical outcome and predictive value of electrodiagnostics in endoscopic carpal tunnel surgery. Neurosurg Rev. 2002;25(4):218-21.
15. Wong SM, Griffith JF, Hui AC, Lo SK, Fu M, Wong KS. Carpal tunnel syndrome: diagnostic usefulness of sonography. Radiology. 2004;232(1):93-9.
16. Park GY, Kwon DR, Seok JJ, Park DS, Cho HK. Usefulness of ultrasound assessment of median nerve mobility in carpal tunnel syndrome. Acta Radiol. 2018;59(12):1494-9.
17. Wessel LE, Marshall DC, Stepan JG, et al. Sonographic findings associated with carpal tunnel syndrome. J Hand Surg Am. 2019;44(5):374-81.
18. Vazquez-Alonso MF, Abdala-Dergal C. Principal causes for recurrent carpal tunnel syndrome. Acta Ortop Mex. 2016;30(1):17-20.

19. Omar NN, Hassan GS, Galal MA, Abdelwahab WA. Diagnosis of carpal tunnel syndrome using ultrasonography. J Curr Med Res Pract. 2020;5(2):126.

20. Kaymak B, Ozcakar L, Cetin A, Candan Cetin M, Akinci A, Hascelik Z. A comparison of the benefits of sonography and electrophysiologic measurements as predictors of symptom severity and functional status in patients with carpal tunnel syndrome. Arch Phys Med Rehabil. 2008;89(4):743-8.

21. Karadag YS, Karadag O, Cicekli E, et al. Severity of carpal tunnel syndrome assessed with high frequency ultrasonography. Rheumatol Int. 2010;30(6):761-5.

22. Tajika T, Kobayashi T, Yamamoto A, Kaneko T, Takagishi K. Diagnostic utility of sonography and correlation between sonographic and clinical findings in patients with carpal tunnel syndrome. J Ultrasound Med. 2013;32(11):1987-93.

23. Hassankhani GG, Moradi A, Birjandinejad A, Vahedi E, Kachooei AR, Ebrahimzadeh MH. Translation and validation of the Persian version the Boston Carpal Tunnel Syndrome Questionnaire. Arch Bone Jt Surg. 2018;6(1):71-7.

24. Campagna R, Pessis E, Feydy A, et al. MRI assessment of recurrent carpal tunnel syndrome after open surgical release of the median nerve. AJR Am J Roentgenol. 2009;193(3):644-50.

25. Oh WT, Kang HJ, Koh IH, Jang JY, Choi YR. Morphologic change of nerve and symptom relief are similar after mini-incision and endoscopic carpal tunnel release: a randomized trial. BMC Musculoskelet Disord. 2017;18(1):65.

26. Abicalaf CA, de Barros N, Sernik RA, et al. Ultrasound evaluation of patients with carpal tunnel syndrome before and after endoscopic release of the transverse carpal ligament. Clin Radiol. 2007;62(9):891-6.

27. Beck JD, Jones RB, Malone WJ, Heimbach JL, Ebbitt T, Kleina JC. Magnetic resonance imaging after endoscopic carpal tunnel release. J Hand Surg Am. 2013;38(2):331-5.

28. Kim JK, Koh YD, Kim JO, Choi SW. Changes in clinical symptoms, functions, and the median nerve cross-sectional area at the carpal tunnel inlet after open carpal tunnel release. Clin Orthop Surg. 2016;8(3):298-302.

29. Tran TA, Williams LM, Bui D, Anthonisen C, Paltavskiy E, Szabo RM. Prospective pilot study comparing pre- and postsurgical CTSAQ and Neuro-QoL questionnaire with median nerve high-resolution ultrasound cross-sectional areas. J Hand Surg Am. 2018;43(2):184.

30. Crnkovic T, Trkulja V, Bilic R, Gaspar D, Kolundzic R. Carpal tunnel and median nerve volume changes after tunnel release in patients with the carpal tunnel syndrome: a magnetic resonance imaging (MRI) study. Int Orthop. 2016;40(5):981-7.

31. Laochamroonvorapongse D, Theard MA, Yahanda AT, Chicoine MR. Intraoperative MRI for adult and pediatric neurosurgery. Anesthesiol Clin. 2021;39(1):211-25.