

MRI of the Median Nerve in Carpal Tunnel Syndrome

Vaishali Upadhyaya¹ Divya Narain Upadhyaya² Surendra Deo Pandey³

¹Department of Radiology, Vivekananda Polyclinic and Institute of Medical Sciences, Lucknow, Uttar Pradesh, India

²Department of Plastic Surgery, King George's Medical University, Lucknow, Uttar Pradesh, India

³Department of Plastic Surgery, Vivekananda Polyclinic and Institute of Medical Sciences, Lucknow, Uttar Pradesh, India

Address for correspondence Divya Narain Upadhyaya, MCh, FACS, Department of Plastic Surgery, King George's Medical University, B-2/128, Sector-F, Janakipuram, Lucknow 226021, Uttar Pradesh, India (e-mail: dnu1@hotmail.com).

J Peripher Nerve Surg:2020;4:15–21

Abstract

Background and Aim Carpal tunnel syndrome (CTS) is the commonest compressive peripheral neuropathy, which occurs due to the compression of median nerve in a fibro-osseous tunnel at the level of the wrist. It has traditionally been diagnosed by history, clinical examination, and electrodiagnostic tests. Multiple studies have also described MRI findings in CTS, and MRI is indicated in specific conditions. The aim of this study is to describe the spectrum of MRI findings in patients diagnosed with CTS in a tertiary care hospital.

Methods A total of 35 patients with as many affected wrists, and a diagnosis of CTS based on history, clinical examination and NCV (nerve conduction velocity) results were included in the study. The median nerve at the level of the wrist was evaluated as per a predefined MRI protocol. Findings were recorded at the level of the distal radioulnar joint, pisiform and hamate and assessed.

Results The MR study revealed T2 hyperintense signal in the median nerve in 20% of patients at the level of the distal radioulnar joint and 80% of patients each at the level of the pisiform and hamate. The mean cross-section area of the nerve measured 11.8 mm², 16.2 mm² and 10.7 mm² at the level of the distal radioulnar joint, pisiform and hamate, respectively. The flattening ratio at the level of the distal radioulnar joint, pisiform and hamate was 1.7, 2.2, and 3.4, respectively. The nerve was compressed due to isolated flexor tenosynovitis in 34.3% patients, due to flexor tenosynovitis in rheumatoid arthritis in 22.85% patients and due to ganglion cyst in 2.85% patients. No obvious cause of nerve compression was detected in 40% of patients and these were classified as idiopathic.

Conclusion MRI findings in patients with CTS include T2 hyperintense signal in the median nerve, enlargement at the level of the pisiform and flattening at the level of the hamate. There was no obvious cause of median nerve compression in the majority of patients, and the commonest identified cause was isolated flexor tenosynovitis.

Keywords

- ▶ carpal tunnel syndrome
- ▶ median nerve
- ▶ magnetic resonance imaging
- ▶ MRI

Introduction

Carpal tunnel syndrome (CTS) is the commonest compressive peripheral neuropathy, which occurs due to compression of the median nerve in a fibro-osseous tunnel at the level of the wrist.¹ The cause of compression is often idiopathic but may also be due to flexor tenosynovitis and rheumatoid

arthritis. Traditionally, CTS has been diagnosed by history, clinical examination and electrodiagnostic tests. However, in recent times, MRI has been increasingly used to image the median nerve in CTS, document its compression, assess the cause and severity of compression, and detect any additional pathologies.²⁻⁸

Earlier studies by Jarvik and Pasternack described a wide range of sensitivity and specificity of MRI in the diagnosis of CTS, ranging from 45 to 88% and 33 to 95%, respectively, based on the imaging criteria used in their studies.^{2,4} However, a recent study by Ng et al showed a sensitivity of 100%, specificity of 94% and an overall accuracy of 98% in the evaluation of CTS by MRI.⁹ These studies indicate that MRI can facilitate appropriate patient management in specific conditions. In this paper, the authors will describe the spectrum of MRI findings in patients diagnosed with CTS in a tertiary care hospital.

Anatomy

The carpal tunnel is a cone-shaped fibro-osseous tunnel through which the median nerve passes along with the flexor tendons of the fingers and the thumb. The carpal bones form the floor and the walls of the tunnel. The roof is formed by the flexor retinaculum, which is constituted by the antebrachial fascia, transverse carpal ligament (TCL) proper, and palmar aponeurosis between the thenar and hypothenar muscles. The flexor tendons which accompany the median nerve include four flexor digitorum superficialis tendons, four flexor digitorum profundus tendons, and the flexor pollicis longus tendon. In the neutral position, the nerve usually lies ventral to the flexor digitorum superficialis tendon of index finger or between this tendon and the flexor pollicis longus tendon. However, the position of the nerve may change with wrist movements.^{10,11}

Materials and Methods

This was a single institution, prospective, observational study which was approved by the Institutional Ethics Committee. A total of 35 patients of CTS with as many affected wrists were included in the study. The study was conducted from April 2017 till December 2019. These patients were diagnosed on the basis of history, clinical examination and nerve conduction velocity (NCV), and were referred from the Department of Plastic Surgery to the Department of Radiology for MRI of the median nerve at the level of the carpal tunnel. Informed consent was taken from all the patients who participated in the study. Those patients in whom MRI was contra-indicated,

such as those with pacemakers or cochlear implants, or those who were severely claustrophobic, were excluded from the study. Such patients were also excluded who did not provide consent for participating in the study.

Imaging Parameters

All the patients were imaged in a 1.5T scanner (Magnetom Essenza; Siemens, Erlangen, Germany). The patients were scanned in the prone position with the arm over the head (superman position). The wrist was placed at the center of the scanner. A small surface coil was used for imaging. The MR protocol consisted of a combination of two-dimensional (2D) and three-dimensional (3D) sequences in multiple planes. In the axial plane, T1-weighted (T1W) and T2-weighted (T2W) SPAIR (spectral adiabatic inversion recovery) sequences were acquired. In the coronal plane, T1W and proton density (PD) fat-saturated (FS) sequences were obtained. The 3D PD SPAIR SPACE (sampling perfection with application optimized contrasts using variable flip angle evolutions) sequence was acquired in the sagittal plane (►Table 1). No intravenous contrast was used.

Image Interpretation

The MR study was interpreted by an experienced radiologist with more than 15 years' experience in reading MR scans. The signal intensity, area and flattening ratio of the median nerve was assessed at three levels: distal radioulnar joint, pisiform and hamate. The signal intensity of the median nerve was compared with that of the hypothenar muscles in T2W FS images. If it was similar to muscles, it was recorded as normal, and if the nerve appeared brighter than muscles, it was recorded as hyperintense (►Fig. 1). The cross-section area of the nerve was then measured at the above-mentioned levels (►Fig. 2). Finally, the flattening ratio was calculated at all three levels as a ratio of major axis of the nerve to its minor axis (►Fig. 3).

Also, noted were any findings suggestive of the cause of nerve compression in the carpal tunnel such as flexor tenosynovitis, erosions in the carpal bones, adjacent fractures or dislocated bone fragments, bony spurs, solid or cystic mass lesions, anomalous muscle, or a persistent median artery.

In patients with tenosynovitis, MRI revealed T2 hyperintense synovial thickening which showed intermediate signal

Table 1 MRI protocol

Sequence	FOV (mm)	Slice thickness (mm)	Slice gap (mm)	TR (msec)	TE (msec)	Acquisition duration (min)	Voxel size (mm)
Axial T1W	224x320	3.0	0.3	718	11	4:43	0.6x0.4x3.0
Axial T2W SPAIR	192x256	3.0	0.3	5370	80	6:23	0.7x0.5x3.0
Coronal T1W	224x320	3.0	0.3	646	14	4:36	0.5x0.4x3.0
Coronal PD FS	174x256	3.0	0.3	2800	27	3:27	0.6x0.5x3.0
Sagittal 3D PD SPAIR SPACE	198x320	0.9	–	1100	41	4:52	1.0x0.8x0.9

Abbreviations: FOV, field of view; FS, fat-saturated; PD, proton density; SPACE, sampling perfection with application optimized contrasts by using varying flip angle evolutions; SPAIR, spectral adiabatic inversion recovery; T1W, T1-weighted; T2W, T2-weighted; TE, time of echo; TR, repetition time.

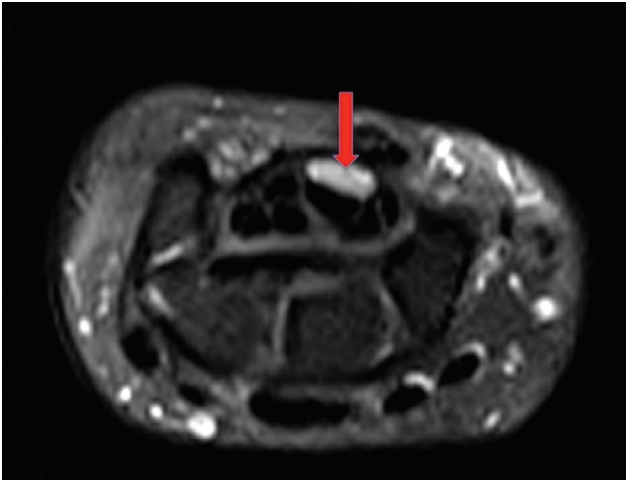


Fig. 1 Axial T2W SPAIR image showing a hyperintense median nerve in a patient with CTS. CTS, carpal tunnel syndrome; SPAIR, spectral adiabatic inversion recovery; T2W, T2-weighted.

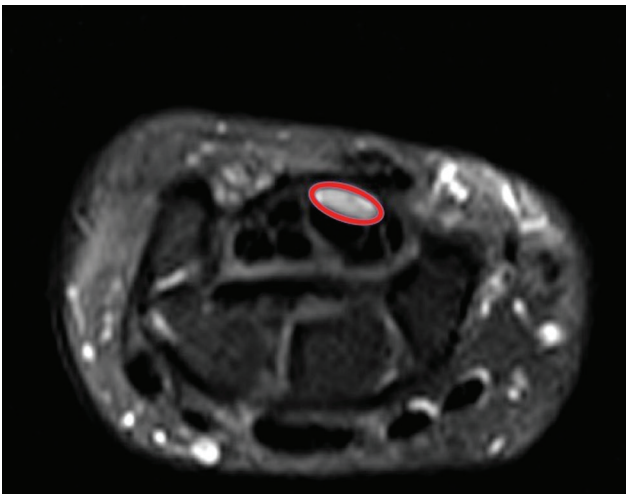


Fig. 2 Axial T2W SPAIR image at the level of the pisiform demonstrating measurement of the area of the nerve. SPAIR, spectral adiabatic inversion recovery; T2W, T2-weighted.

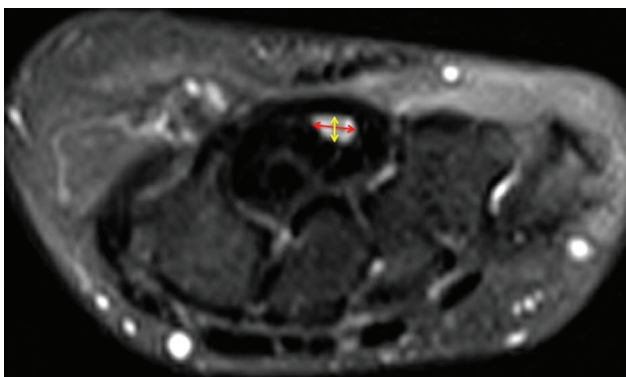


Fig. 3 Axial T2W SPAIR image at the level of the hamate showing measurement of the flattening ratio of the nerve which is a ratio of its major axis (red line) to minor axis (yellow line). SPAIR, spectral adiabatic inversion recovery; T2W, T2-weighted.

intensity in T1W images and presence of fluid within the tendon sheath.¹² Fluid appeared hypointense in T1W images and hyperintense in T2W images. The carpal bones, distal radius and ulna were evaluated for the presence of any erosions, fractures or spurs. Bone defects with sharply defined margins were interpreted as erosions.¹³ Fractures, on the other hand, produce hypointense linear signal in T1W and T2W images with surrounding edema which is hyperintense in T2W images.¹⁴

Different types of mass lesions, arising either from the median nerve or from other structures, can be visualized in the carpal tunnel as a possible cause of nerve compression. Tumors affecting the median nerve include schwannoma, neurofibroma and fibrolipomatous hamartoma. Schwannomas and neurofibromas appear isointense to muscle in T1W images and heterogeneous in T2W images, with a surrounding rim of fat which is called the “split fat” sign. A fibrolipomatous hamartoma shows signal intensity corresponding to fat, with interspersed hypointense signal due to neural and fibrous tissue.^{10,11}

Extrinsic mass lesions include lipomas, hemangiomas and ganglion cysts. Lipomas show signal intensity corresponding to fat in all sequences with suppression of signal in FS sequences. Hemangiomas show heterogeneous signal intensity with interspersed fat signal, serpentine flow voids and phleboliths. Ganglion cysts are well defined lesions which show signal intensity similar to muscle in T1W images and are hyperintense in T2W images.^{10,11}

Sometimes, a mass lesion can be seen in the carpal tunnel which shows signal intensity similar to muscle in all sequences and appears to be causing nerve compression. Such a mass lesion could be an accessory palmaris longus muscle, proximal origin of an index lumbrical muscle, or an anomalous muscle belly of the flexor digitorum superficialis muscle of the index finger.¹⁵

A persistent median artery (PMA) can also cause compression of the median nerve if it is enlarged, calcified, thrombosed, or in case of an aneurysm. This artery is an anatomical variant, seen in approximately 10% of the population, and arises from the ulnar artery or anterior interosseous artery. It is often associated with a high-division of the median nerve or bifid median nerve.^{16,17} On MRI, the artery is seen as a circular structure close to the median nerve with higher signal intensity than the nerve.

Results

There were 7 males and 28 females in this study with male:female ratio of 1:4. The age range of the patients was 30 to 65 years with a mean age of 44.57 years (► **Table 2**).

The MR study revealed evidence of median nerve compression within the carpal tunnel in all the 35 patients (100%). Isolated flexor tenosynovitis was identified as the cause of nerve compression in the carpal tunnel in 12 of 35 patients (34.3%) (► **Fig. 4**). Eight of 35 patients (22.85%) were diagnosed as having rheumatoid arthritis. These patients had both flexor and extensor tenosynovitis (► **Fig. 5**). Among these eight patients, small erosions in the carpal bones were

Table 2 Demographics

Male	7
Female	28
Sex ratio (M:F)	1:4
Age range	30–65 years
Mean age	44.57 years

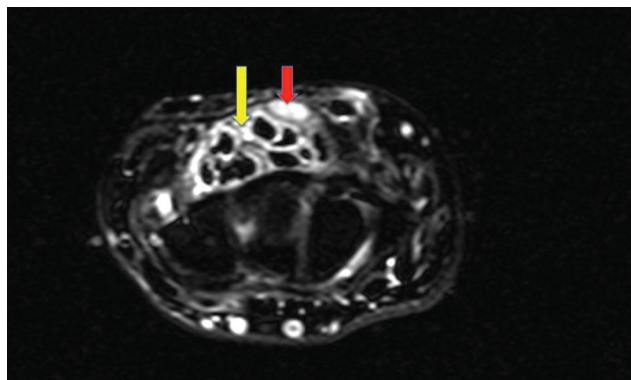


Fig. 4 Axial T2W SPAIR image showing synovial proliferation (yellow arrow) around the flexor tendons with median neuropathy (red arrow). SPAIR, spectral adiabatic inversion recovery; T2W, T2-weighted.

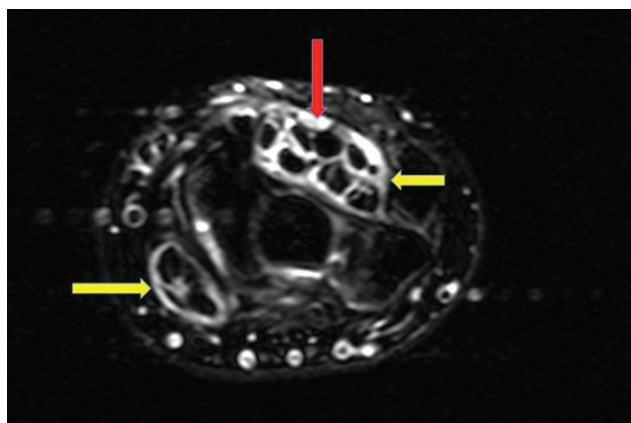


Fig. 5 Axial T2W SPAIR image in a patient with rheumatoid arthritis showing both flexor and extensor tenosynovitis (yellow arrows) with median neuropathy (red arrow). SPAIR, spectral adiabatic inversion recovery; T2W, T2-weighted.

seen in three patients (37.5%), synovial proliferation in the distal radioulnar and radiocarpal joints was seen in one patient (12.5%), and small distal radioulnar joint effusion was noted in one patient (12.5%). One of the 35 patients (2.85%) had a ganglion cyst in the carpal tunnel (►Fig. 6). No obvious cause of nerve compression was detected in 14 of 35 patients (40%) and these were classified as idiopathic (►Figs. 7, 8). Thus, in our study, we found that the idiopathic variety was the commonest cause (40%), followed by flexor tenosynovitis (34.3%) (►Table 3).

At the level of the distal radioulnar joint, the signal intensity of the nerve was isointense to muscle in T2W FS images

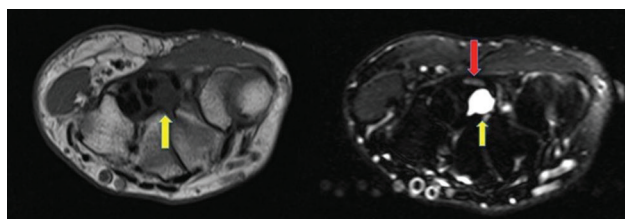


Fig. 6 Axial T1W image to the left showing a hypointense ganglion cyst (yellow arrow). Axial T2W SPAIR image to the right in which the ganglion cyst appears hyperintense (yellow arrow), and it is compressing the median nerve (red arrow). SPAIR, spectral adiabatic inversion recovery; T1W, T1-weighted; T2W, T2-weighted.

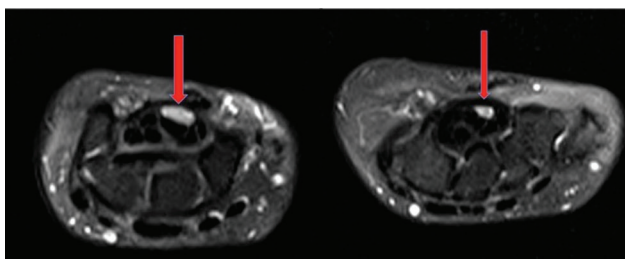


Fig. 7 Axial T2W SPAIR image to the left at the level of the pisiform in a patient with idiopathic CTS, showing an enlarged median nerve (red arrow). Axial T2W SPAIR image to the right in the same patient showing flattening of the median nerve (red arrow) at the level of the hamate. CTS, carpal tunnel syndrome; SPAIR, spectral adiabatic inversion recovery; T2W, T2-weighted.

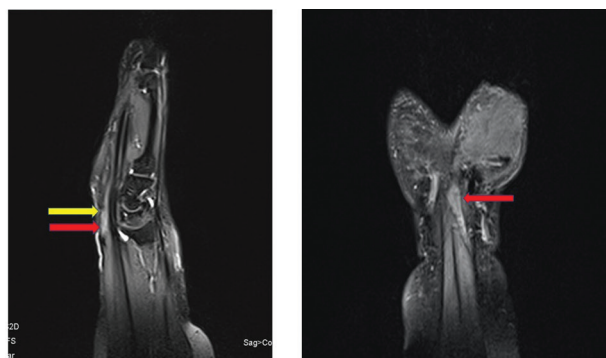


Fig. 8 Sagittal 3D PD SPAIR SPACE image (to the left) and coronal PD FS image (to the right) showing compression of the median nerve in the carpal tunnel (yellow arrow) with proximal enlargement (red arrows) in a case of idiopathic CTS. CTS, carpal tunnel syndrome; FS, fat-saturated; PD, proton density; SPACE, sampling perfection with application optimized contrasts by using varying flip angle evolutions; SPAIR, spectral adiabatic inversion recovery.

Table 3 Causes of nerve compression

Cause	Number	Percentage
Idiopathic	14/35	40
Isolated flexor tenosynovitis	12/35	34.3
Rheumatoid arthritis	8/35	22.85
Ganglion cyst	1/35	2.85

in 28 of 35 patients (80%) which was interpreted as normal. Hyperintense signal was seen in the nerve in 7 of 35 patients (20%). At the level of the pisiform, it was the reverse. Only 7 of 35 patients (20%) showed normal neural signal intensity, whereas 28 of 35 patients (80%) had nerves which showed hyperintense signal. Similarly, at the level of the hamate, normal neural signal intensity was seen in 7 of 35 patients (20%), while the median nerve showed hyperintense signal in 28 of 35 patients (80%) (► **Table 4**). This showed that with nerve compression, there was alteration in the signal intensity of the nerve. This change in signal intensity was most prominent at the level of compression and distal to it.

The mean cross-section area of the median nerve measured 11.8 mm², 16.2 mm² and 10.7 mm² at the level of the distal radioulnar joint, pisiform and hamate, respectively. This indicated that when the nerve was compressed in the carpal tunnel, there was proximal enlargement, which was most prominent at the level of the pisiform (► **Table 4**).

The flattening ratio of the median nerve was 1.7, 2.2, and 3.4 at the level of the distal radioulnar joint, pisiform and hamate, respectively. This showed that with nerve compression, its contour changed, and it became flatter in appearance. Thus, the flattening ratio measured as ratio of major axis to minor axis of the nerve increased. This ratio was maximum at the level of the hamate (► **Table 4**).

Discussion

The diagnosis of CTS is usually based on the patient's history, clinical examination, and electrophysiological tests such as NCV. Imaging supplements the traditional methodology by documenting the compression of the nerve in the carpal tunnel, assessing its severity, and also detecting the cause of CTS which, if unaddressed, may lead to a failure of surgical treatment and relapse of symptoms.

Commonly used imaging modalities for evaluation of the median nerve in CTS include ultrasonography (USG) and MRI. USG is cheaper and more widely available than MRI, however, it is operator-dependent. It is also not able to assess signal intensity changes in nerves, associated changes in muscles and adjacent bony structures as well, as MRI can.¹⁸ MRI enables complete evaluation of the median nerve as well as its surrounding structures. However, since it is an expensive procedure, it should be used judiciously in selected cases of CTS. These include patients in whom there is clinical suspicion of causes other than idiopathic such as a mass lesion, inflammatory arthropathy, or congenital anomaly. It may

also be indicated in patients who fail to respond to conservative or surgical treatment.

MR imaging can be done on 3T or 1.5T scanners. Today, 3T magnets are preferred as they have higher signal to noise ratio and provide better resolution. However, meticulous planning, knowledge of sequences to be used, and thorough understanding of the anatomy have enabled good results on 1.5T scanners as well. A combination of 2D and 3D sequences is used to evaluate the median nerve. These sequences include T1W and T2W FS sequences such as T2W SPAIR. Other sequences include 3D SPAIR SPACE and 3D diffusion-weighted (DW) reversed steady-state free precession (PSIF). These sequences enable excellent depiction of the nerve in multiple planes, so that any changes in nerve contour, signal intensity and size can be appreciated.^{19,20}

In the present study, only patients who were already diagnosed with CTS on the basis of clinical findings and NCV results were included. The authors then proceeded to image them according to a predefined MR protocol for the median nerve. The authors evaluated the condition of the nerve by assessing its signal intensity, cross-section area and flattening ratio at specified levels, and have tried to identify the cause of nerve compression.

In this study, most of the patients were females in the age group of 30 to 65 years. This is an established fact that women suffer from CTS more than males and most patients are between 35 to 65 years of age.²¹

CTS is often idiopathic, although it can be due to multiple other causative factors such as inflammatory and infective synovitis, rheumatoid arthritis, granulomatous infections, adjacent fractures and dislocations, repetitive flexion and extension movements at the wrist, infiltrative diseases such as amyloidosis or acromegaly, and neurogenic and non-neurogenic neoplasms such as schwannomas, hamartomas, ganglia and lipomas. Other factors include anatomic causes such as anomalous muscles, small carpal canal, pregnancy, and use of oral contraceptives.^{10,18,21}

In majority of the patients in this study, no cause of nerve compression was identified on MRI, and these were labeled as the idiopathic variety (40%). Other than this, the most frequently identified cause in this group of patients was isolated flexor tenosynovitis (34.3%), followed by rheumatoid arthritis (22.85%). There was one case in which a ganglion cyst was causing compression of the median nerve in the carpal tunnel (2.85%).

In this study, the first important variable studied was the change in the signal intensity of the median nerve in MR

Table 4 Other MRI findings

Variable		Distal radioulnar joint	Pisiform	Hamate
Signal intensity	Isointense to muscle	28/35 (80%)	7/35 (20%)	7/35 (20%)
Signal intensity	Hyperintense	7/35 (20%)	28/35 (80%)	28/35 (80%)
Cross-section area (mean)		11.8 mm ²	16.2 mm ²	10.7 mm ²
Flattening ratio		1.7	2.2	3.4

images. The normal nerve appears similar or minimally hyperintense to muscle in T2W FS sequences, whereas in patients with CTS, the nerve appears prominently hyperintense in T2W FS sequences. This finding is due to venous congestion in the compressed nerve with edema, ischemia and interruption in the flow of axoplasm.²² Persistent ischemia, more than about eight hours, can lead to loss of axons and Wallerian degeneration.²³ The finding of isolated T2 hyperintense signal may be spurious and change in signal intensity should be considered significant only when associated with other findings of nerve compression, such as enlargement of the median nerve at the level of pisiform and distal flattening. In this study, only 20% of the nerves showed hyperintense signal in T2W FS images at the level of the distal radioulnar joint, but at the level of the pisiform and hamate, 80% of the nerves showed prominent hyperintense signal. This reflects the fact that the altered signal intensity is seen near the point of entrapment.

The second variable studied was the change in the size of the median nerve. The normal range of cross-section area of the median nerve is 6.1 to 10.4 mm².²⁴ At the level of the pisiform, the average area is 7 mm² with a range of 5.3 to 9.7 mm² and at the level of the hamate, the average area is 8 mm² with a range of 4.2 to 10.8 mm².²⁵ In patients with CTS, the nerve is enlarged at the level of the pisiform and flattened at the level of the hamate. It can be about two to three times larger at the level of the pisiform than that at the level of the distal radioulnar joint.^{10,11} In this study, the authors found that the average area of the nerve at the level of the distal radioulnar joint, pisiform and hamate was 11.8 mm², 16.2 mm², and 10.7 mm², respectively. Thus, the enlargement was most at the level of the pisiform, and the nerve appeared compressed at the level of the hamate. Similar to change in signal intensity, change in size also reflects the proximity to the site of entrapment.

The third variable was the flattening ratio of the nerve, which is a ratio of its major axis to its minor axis. As the median nerve gets compressed, its contour is deformed, and it becomes flattened. This finding is best assessed at the level of the hamate. Patients with CTS usually demonstrate flattening ratio of more than 3 at this level.^{10,11} In this study, the authors found a ratio of 1.7 at the level of the distal radioulnar joint and 3.4 at the level of the hamate.

The present study was performed in Indian patients who were already diagnosed with CTS on the basis of clinical evaluation and electrophysiological tests, and thus this study has a truly representative sample of the desired patient population. Also, all the measurements were performed at specified levels which included the distal radioulnar joint, pisiform and hamate. This makes the study systematic and reproducible. A search of relevant, current medical literature has revealed no similar studies with detailed measurements of the median nerve in the Indian population.

There were, however, a few limitations of the study. First, the sample size is small. So, studies with a larger patient population would be needed to further elaborate upon the findings of this study. Second, there was a selection bias as the authors included only those patients in the study who were already diagnosed with CTS based on clinical and electrophysiological findings.

Conclusion

This study was done to evaluate the median nerve by MRI in patients diagnosed with CTS in a tertiary care hospital in India. MRI findings in these patients included T2 hyperintense signal in the median nerve, enlargement at the level of the pisiform, and flattening at the level of the hamate. There was no obvious cause of median nerve compression in the majority of patients and the commonest identified cause was isolated flexor tenosynovitis.

Funding

None.

Conflict of Interest

None declared.

References

- 1 Kothari MJ. Carpal tunnel syndrome: Etiology and epidemiology. Shefner JM, Eichler AF, eds. UpToDate. Waltham, MA: UpToDate Inc. Available at: <https://www.uptodate.com/contents/carpal-tunnel-syndrome-treatment-and-prognosis>.
- 2 Jarvik JG, Yuen E, Haynor DR, et al. MR nerve imaging in a prospective cohort of patients with suspected carpal tunnel syndrome. *Neurology* 2002;58(11):1597–1602
- 3 Cudlip SA, Howe FA, Clifton A, Schwartz MS, Bell BA. Magnetic resonance neurography studies of the median nerve before and after carpal tunnel decompression. *J Neurosurg* 2002;96(6):1046–1051
- 4 Pasternack II, Malmivaara A, Tervahartiala P, Forsberg H, Vehmas T. Magnetic resonance imaging findings in respect to carpal tunnel syndrome. *Scand J Work Environ Health* 2003;29(3):189–196
- 5 Uchiyama S, Itsubo T, Yasutomi T, Nakagawa H, Kamimura M, Kato H. Quantitative MRI of the wrist and nerve conduction studies in patients with idiopathic carpal tunnel syndrome. *J Neurol Neurosurg Psychiatry* 2005;76(8):1103–1108
- 6 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):644–650
- 7 Oge HK, Acu B, Gucer T, Yanik T, Savlarli S, Firat MM. Quantitative MRI analysis of idiopathic carpal tunnel syndrome. *Turk Neurosurg* 2012;22(6):763–768
- 8 Onen MR, Kayalar AE, Ilbas EN, Gokcan R, Gulec I, Naderi S. The role of wrist magnetic resonance imaging in the differential diagnosis of the carpal tunnel syndrome. *Turk Neurosurg* 2015;25(5):701–706
- 9 Ng AWH, Griffith JF, Tong CSL, et al. MRI criteria for diagnosis and predicting severity of carpal tunnel syndrome. *Skeletal Radiol* 2020;49(3):397–405
- 10 Stoller DW, Li AE, Lichtman DM, Brody GA. The wrist and hand. In: Stoller DW, ed. *Magnetic Resonance Imaging in Orthopaedics and Sports Medicine*. 3rd ed. Baltimore, Philadelphia: Lippincott Williams & Wilkins; 2007
- 11 Berquist TH. Hand and wrist. In: Berquist TH, ed. *MRI of the Musculoskeletal System*. 6th ed. Philadelphia: Lippincott Williams & Wilkins; 2013
- 12 Plotkin B, Sampath SC, Sampath SC, Motamedi K. MR Imaging and US of the Wrist Tendons. *Radiographics* 2016;36(6):1688–1700
- 13 Peterfy CG. MRI of the wrist in early rheumatoid arthritis. *Ann Rheum Dis* 2004;63(5):473–477
- 14 Peh WC, Gilula LA, Wilson AJ. Detection of occult wrist fractures by magnetic resonance imaging. *Clin Radiol* 1996;51(4):285–292

- 15 Mitchell R, Chesney A, Seal S, McKnight L, Thoma A. Anatomical variations of the carpal tunnel structures. *Can J Plast Surg* 2009;17(3):e3–e7
- 16 Salter M, Sinha NR, Szmigielski W. Thrombosed persistent median artery causing carpal tunnel syndrome associated with bifurcated median nerve: A case report. *Pol J Radiol* 2011;76(2):46–48
- 17 Gassner EM, Schocke M, Peer S, Schwabegger A, Jaschke W, Bodner G. Persistent median artery in the carpal tunnel: color Doppler ultrasonographic findings. *J Ultrasound Med* 2002;21(4):455–461
- 18 Linda DD, Harish S, Stewart BG, Finlay K, Parasu N, Rebello RP. Multimodality imaging of peripheral neuropathies of the upper limb and brachial plexus. *Radiographics* 2010;30(5):1373–1400
- 19 Chalian M, Behzadi AH, Williams EH, Shores JT, Chhabra A. High-resolution magnetic resonance neurography in upper extremity neuropathy. *Neuroimaging Clin N Am* 2014;24(1):109–125
- 20 Howe BM, Spinner RJ, Felmlee JP, Frick MA. MR imaging of the nerves of the upper extremity: elbow to wrist. *Magn Reson Imaging Clin N Am* 2015;23(3):469–478
- 21 Resnick D, Kransdorf MJ. Neuromuscular disorders. In: Resnick D, Kransdorf MJ, eds. *Bone and Joint Imaging*. 3rd ed. Philadelphia: Elsevier; 2005
- 22 Subhawong TK, Wang KC, Thawait SK, et al. High resolution imaging of tunnels by magnetic resonance neurography. *Skeletal Radiol* 2012;41(1):15–31
- 23 Nadi M, Midha R. Entrapment neuropathies and peripheral nerve tumors. In: Ellenbogen RG, Sekhar LN, Kitchen ND, da Silva HB, eds. *Principles of Neurological Surgery*. 4th ed. Philadelphia: Elsevier; 2018
- 24 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):171–177
- 25 Middleton WD, Kneeland JB, Kellman GM, et al. MR imaging of the carpal tunnel: normal anatomy and preliminary findings in the carpal tunnel syndrome. *AJR Am J Roentgenol* 1987;148(2):307–316