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Original Article

Diffusion tensor imaging combined with the dual-echo steady-state (DESS) protocol for the evaluation of the median nerve in the carpal tunnel: A preliminary study

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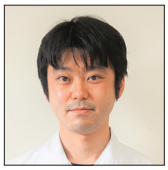

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Received: 03 March 2024
Accepted: 08 March 2024
Published: 29 March 2024

DOI
10.25259/SNI_156_2024

Quick Response Code:

ABSTRACT

Background: Carpal tunnel syndrome (CTS) is diagnosed based on neurological, electrophysiology, and radiological findings. Due to the technical development of magnetic resonance imaging (MRI), the median nerve is evaluated with several MRI protocols. However, diffusion tensor imaging (DTI) combined with a dual-echo steady-state (DESS) protocol is not frequently used to evaluate the median nerve of CTS. This study aimed to evaluate the median nerve in the carpal tunnel using DTI combined with a DESS protocol.

Methods: Five healthy volunteers and seven patients with CTS were enrolled. The patients underwent MRI for CTS pre- and post-operatively. The median nerve was evaluated using a 3-T MRI scanner. The parameters of the DESS protocol were as follows: Repetition time (TR)/echo time (TE) = 10.83/3.32 ms, slice thickness = 0.45 mm, field of view (FoV) = 350 × 253 × 350 mm, and 3D voxel size = 0.5 × 0.5 ×0.4 mm. The parameters of the DTI sequence were as follows: TR/TE = 4000/86 ms, slice thickness = 3 mm, FoV = 160 × 993 × 90 mm, 3D voxel size = 1.2 × 1.2 ×3.0 mm, and b value = 0.1000 s/mm^2. The apparent diffusion coefficient (ADC) and fractional anisotropy (FA) values of the median nerve were statistically analyzed. Statistical significance was set at $P< 0.05$.

Results: The FA value of healthy volunteers was 0.576 ± 0.058, while those of the patients were 0.357 ± 0.094 and 0.395 ± 0.062 pre-and post-operatively, respectively. Statistically significant differences were identified between the FA values of healthy volunteers and pre-operative/post-operative patients. The ADC values of healthy volunteers and pre-operative patients were 0.931 ± 0.096 and 1.26 ± 0.282 (10^{-3} mm^2/s), respectively ($P< 0.05$).

Conclusion: This MRI protocol may be useful for evaluating the median nerve in the carpal tunnel.

Keywords: Apparent diffusion coefficient, Diffusion tensor imaging, Dual-echo in the steady-state, Fractional anisotropy, Median nerve

INTRODUCTION

Carpal tunnel syndrome (CTS) is an entrapment neuropathy that irritates the median nerve.[6,10] The clinical diagnosis of CTS is based on the presence of symptoms such as nocturnal paresthesia and triggered pain of the wrist with Phalen and/or Tinel's tests.[12] However, there is some uncertainty regarding the reliability of these findings for the diagnosis of CTS.[20] Peripheral

nerve conduction examination and ultrasonography may be useful for the diagnosis of CTS; however, the results of these examinations may be affected by factors such as the age and sex of the patient's background and the examiner's technique. Magnetic resonance diffusion tensor imaging (DTI) can be used as an objective examination to evaluate the median nerve in patients with CTS. In addition, representative DTI metrics, such as fractional anisotropy (FA) and apparent diffusion coefficient (ADC), are also usually analyzed.[1,10,11] The previous studies have evaluated the ADC and FA values of the median in healthy populations and patients.[2,8-10,16,19] However, to the best of our knowledge, literature regarding the comparison of the ADC and FA values of a healthy population with those of perioperative patients with CTS remains scant.[13]

Several magnetic resonance imaging (MRI) protocols have been utilized to evaluate the median nerve in the carpal tunnel; however, the evaluation of the median nerve in the carpal tunnel with a dual-echo in the steady-state (DESS) protocol has not been described in detail.[5,14,16,17]

This study aimed to evaluate the ADC and FA values of the median nerve using the DESS protocol in healthy volunteers and patients with CTS. Changes between the pre-operative and post-operative ADC and FA values of patients with CTS were also analyzed.

MATERIALS AND METHODS

This study enrolled five healthy volunteers and seven patients with CTS after obtaining informed consent. MRI examination was performed according to the protocol described below. Healthy volunteers underwent MRI examination only once; in contrast, the patients with CTS underwent MRI examination twice, preoperatively and postoperatively (within three months after the surgery).

Protocol of MRI examination

MRI was performed using a 3-T MRI scanner (SIEMENS MAGNETOM Trio Tim Syngo MR B17). The wrist undergoing examination was slightly elevated, and a head coil was placed distal to the wrist joint. A single loop-coil of 7 cm diameter was set on the palm to increase the signal intensity. A DESS[16] with fat suppression protocol with the following parameters was used in this study: Repetition time (TR)/echo time (TE) = 10.83/3.32 ms, slice thickness = 0.45 mm, field of view (FoV) = 350 × 253 × 350 mm, and 3D voxel size = 0.5 × 0.5 ×0.4 mm. DTI of the median nerve was performed with the following sequence: TR/TE = 4000/86 ms, slice thickness = 3 mm, FoV = 160 × 993 × 90 mm, 3D voxel size = 1.2 × 1.2 ×3.0 mm, and b value = 0.1000 s/mm^2. The ADC and FA values of the median nerve in the carpal tunnel at the level of the hook of the hamate bone were calculated.

Statistical analysis

The ADC and FA values of the key slices of the median nerves were evaluated, and the data of the healthy volunteers were statistically compared with the pre-operative and post-operative data of the patients with CTS. The pre-operative and post-operative patient data were also compared. SPSS Statistics software (version 24; Chicago, Illinois, USA) was used to perform the statistical analyses. Student's t-test was used to analyze the collected data. The power and effect size was evaluated using G* power (version 3.1.9.6, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). A power ≥0.8 was defined as significant. A significant effect size was defined as a $d > 0.8$. Statistical significance was set at $P < 0.05$.

RESULTS

Data of healthy volunteers

In healthy volunteers, the median nerve in the carpal tunnel could be clearly identified as superior to the tendons of the flexor muscle tendons on MR images [Figure 1a]. The median nerve was visualized using fiber tractography [Figures 1b and c]. Color and FA maps of the diffusion tensor images were used to calculate the ADC and FA values of the median nerve [Figures 1d and e]. The ADC and FA values of the median nerve in healthy volunteers are summarized in Table 1.

Data of patients with CTS

The median nerve in the carpal tunnel could be identified vaguely in patients with CTS. Moreover, it could not be visualized clearly with fiber tractography [Figure 2]. However, the median nerve in the carpal tunnel was well visualized after surgery. The median nerve was visualized using fiber tractography [Figure 3]. The ADC and FA values of the median nerve in patients with CTS are summarized in Table 2. Independent Student's t-test detected a statistically significant difference between the ADC and FA values of the healthy volunteers and the pre-operative ADC and FA values of the patients with CTS ($P< 0.05$). The d values of the ADC and FA values were 1.34 and 2.53, respectively. The powers of the ADC and FA values were 0.54 and 0.97, respectively. Independent Student's t-test detected a statistically significant difference only between the FA values of the healthy volunteers and the post-operative FA values of the patients with CTS ($P< 0.05$).

No statistically significant difference was identified between the ADC values of the healthy volunteers and the post-operative FA values of the patients with CTS ($P = 0.124$). The d values of the ADC and FA values were 0.87 and 2.86, respectively. The powers of the ADC and FA values were 0.27 and 0.99, respectively. The paired samples t-test did

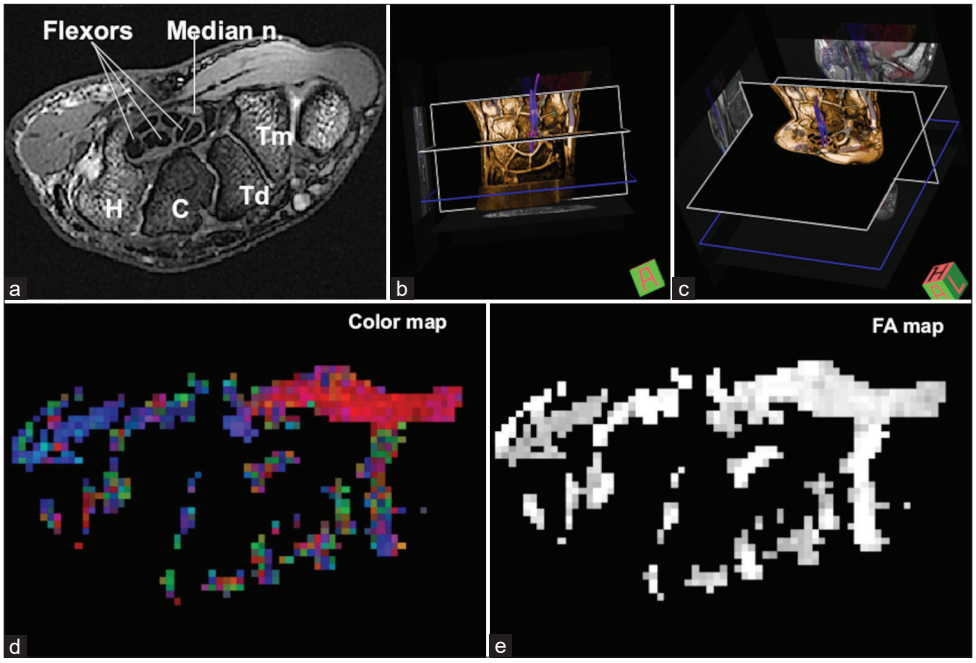

Figure 1: Representative data of a healthy volunteer (a) the median nerve can be observed on an image acquired using transversal DESS with fat suppression. (b and c) The median nerve can be visualized with fiber tractography. (d and e) Color map and FA map images were extracted to calculate the ADC and FA values of the median nerve. C: Os capitatum, H: Os hamatum, n.: Nerve, Td: Os trapezoideum, Tm: Os trapezium, FA: Fractional anisotropy, ADC: Apparent diffusion coefficient, DESS: Dual-echo in the steady-state.

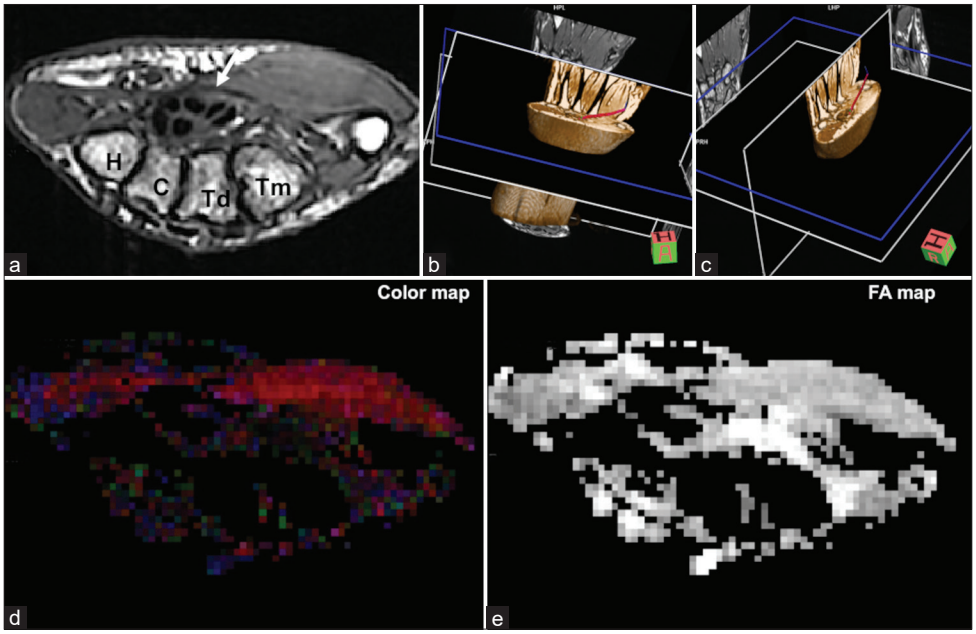

Figure 2: Representative pre-operative data of a patient with carpal tunnel syndrome (a) the median nerve is not clearly visible compared with that of the healthy volunteer (white arrow). (b and c) The median nerve could not be detected with fiber tractography. (d and e) The color map and FA map images are not clear compared with those of the healthy volunteers. C: Os capitatum, H: Os hamatum, n.: Nerve, Td: Os trapezoideum, Tm: Os trapezium, FA: Fractional anisotropy.

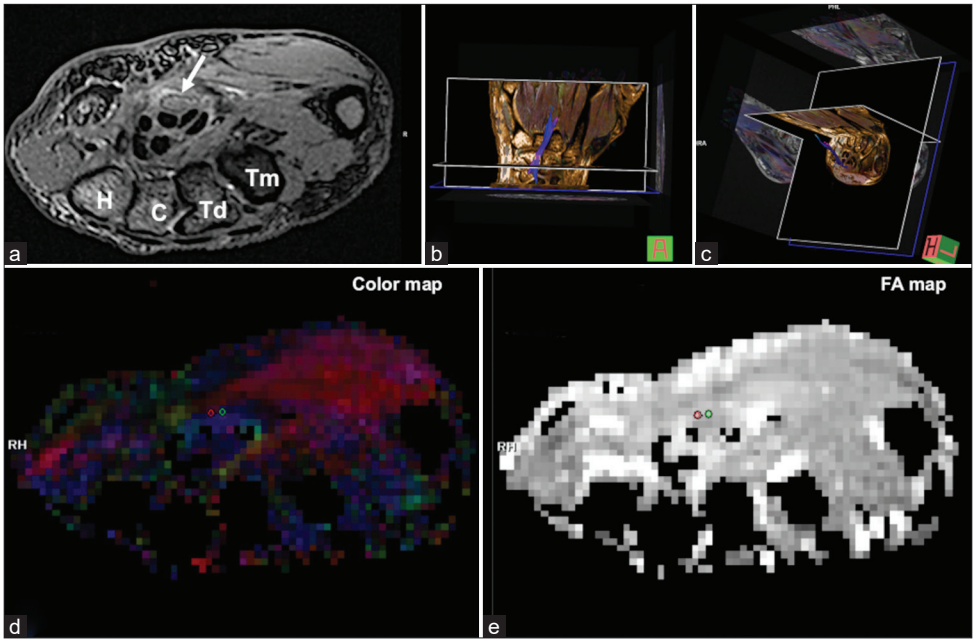

Figure 3: Representative post-operative data of a patient with carpal tunnel syndrome (a-c) Postoperatively, the median nerve could be identified on an image acquired using DESS with fat suppression and fiber tractography. (d and e) A lesion on the median nerve to extract ADC and FA values was easily identified. C: Os capitatum, H: Os hamatum, n.: Nerve, Td: Os trapezoideum, Tm: Os trapezium, ADC: Apparent diffusion coefficient, FA: Fractional anisotropy, DESS: Dual-echo in the steady-state.

Table 1: ADC and FA values of the healthy volunteers.

	Age (years)	Sex	FA value	ADC value (10^{-3} mm^2/s)
Case 1	30	Man	0.524	1.008
Case 2	23	Man	0.644	0.863
Case 3	25	Man	0.63	0.797
Case 4	28	Man	0.523	0.98
Case 5	30	Woman	0.561	1.009
Mean±standard deviation	27.2±3.1		0.576±0.058	0.931±0.096

FA: Fractional anisotropy, ADC: Apparent diffusion coefficient.

Table 2: ADC and FA values of the patients with carpal tunnel syndrome.

	Age (years)	Sex	Preoperative FA value	Pre-operative ADC value (10^{-3} mm^2/s)	Post-operative FA value	Post-operative ADC value (10^{-3} mm^2/s)
Case 1	52	Woman	0.257	1.54	0.332	1.515
Case 2	41	Woman	0.345	1.661	0.412	1.327
Case 3	64	Woman	0.464	1.251	0.481	1.076
Case 4	49	Woman	0.447	1.175	0.484	1.009
Case 5	52	Woman	0.454	1.143	0.381	0.889
Case 6	54	Woman	0.211	1.308	0.353	1.358
Case 7	70	Man	0.319	0.718	0.321	0.729
Mean±standard deviation	54.5±21.1		0.357±0.094	1.26±0.282	0.395±0.062	1.129±0.261

FA: Fractional anisotropy, ADC: Apparent diffusion coefficient

not detect a statistically significant difference between the pre-operative and post-operative ADC and FA values of the patients with CTS (ADC values: $P = 0.057$, FD values: $P = 0.184$). The *d* values of the ADC and FA values were 1.91 and 1.22, respectively. The powers of the ADC and FA values were 0.99.

DISCUSSION

In this study, the median nerve in healthy volunteers and patients with CTS was objectively evaluated using DTI combined with a DESS protocol. The median nerve could be visualized clearly in healthy volunteers, whereas the median nerve could be visualized only vaguely in patients with CTS preoperatively. However, the median nerve could be visualized clearly postoperatively. The ADC and FA values of the median nerve at the level of the hook of the hamate were also analyzed. The pre-operative ADC and FA values of the patients with CTS were significantly higher than those of the healthy volunteers. Although no statistically significant differences were detected, the median ADC values decreased, and the median FA values increased postoperatively. The previous studies evaluating the median nerve in the carpal tunnel utilized MRI sequences, such as read-out segment echo-planar imaging and single-shot echo-planar imaging.[5,14,16,17] DESS was performed to evaluate the median nerve in our study. The DESS protocol is a combination sequence of fast imaging with steady-state precession and time-reversed fast imaging with steady-state precession. This sequence can provide high-resolution, heavily T2*-weighted images.[4] The DESS protocol can be used to evaluate the cartilage in the knee or wrist ligament.[4,15] However, to the best of our knowledge, it has not been used to evaluate the median nerve in the carpal tunnel previously. Since the median nerve is compressed in patients with CTS, we hypothesized that it could be identified vaguely in the images. DESS protocol with fat suppression was used to minimize the signal effect due to fat tissue, which is present around the median nerve in the carpal tunnel.[7,18] Therefore, this sequence was used to identify the median nerve on pre-operative magnetic resonance images. The FA and ADC values are commonly used parameters in DTI. FA measures the directionality of water diffusion along a particular axis, and the FA value can vary from 0 (isotropy) to 1 (infinite anisotropy).[3,15,16] Peripheral nerves show a high degree of anisotropic diffusion since the running pathway of the axons and myelin sheath defines water diffusion. However, in patients with CTS, neural edema due to chronic nerve compression can lead to a breakdown of the blood-nerve barrier and venous congestion. Demyelination and Wallerian degeneration due to chronic nerve compression can also limit the random movement of water molecules.[15] The increased water content in extracellular space creates an isotropic condition, which leads to a decrease in the FA value of the median nerve in patients with CTS. In the previous reports, the FA values of the patients with CTS were lower than those of the healthy volunteers.[2,8,16] In a meta-analysis by Rojoa *et al*., the normal FA value was 0.58, which was similar to the median FA value obtained in our study.[16] Although only a limited number of healthy volunteers were recruited in our study, the DESS protocol used in our study seems appropriate. The pre-and post-operative FA values of patients with CTS were significantly lower than those of the healthy volunteers. This finding may be attributed to altered water diffusion resulting from compression of the median nerve. Although no statistically significant differences were detected between the pre-operative and post-operative FA values in patients with CTS, the median post-operative FA values increased. We speculate that the increased post-operative FA values could be representative of an increase in the anisotropic water diffusion due to the release of the median nerve through surgery. The ADC value signifies the molecular diffusivity in a three-dimensional tissue space. The ADC values of patients with CTS are typically higher than those of healthy people.[2,8,16] This finding was also identified preoperatively in our study. No statistically significant difference was detected between the post-operative ADC values of patients with CTS and those of healthy volunteers. This may be attributed to the statistical power for the comparison of the ADC values of healthy volunteers and post-operative patients not being sufficiently strong. The mean post-operative ADC value was lower than the mean pre-operative ADC value. This may also be attributed to the decompression of the median nerve through surgery. As observed in this study, DTI combined with a DESS protocol may contribute to the evaluation of the median nerve in CTS. As the literature related to this topic remains scarce, further research is warranted.

Limitations

Only a limited number of healthy volunteers and patients with CTS were recruited in this study. The distribution of the age and sex in those groups was not equivalent. This limitation could have been a confounding factor and could have affected the statistical results, such as the insufficient power of the ADC values in our study. A DESS protocol with fat suppression was used to collect clinical data in our study. However, reports on the use of this sequence for the evaluation of the medial nerve in the carpal tunnel are scarce. Thus, the optimal parameters of the DESS protocol with fat suppression for evaluating the median nerve in patients with CTS should be investigated in future studies. In addition, the ADC and FA values were compared between healthy volunteers and patients with CTS. However, these values were not evaluated based on subjective and objective clinical findings from questionnaires or nerve conduction studies. The correlation between the ADC and FA values and clinical

symptoms should also be addressed in future studies. Finally, patients with CTS were followed up for a limited period postoperatively in this study. Due to the patient's wishes, the timing of the post-operative MRI examination was not completely standardized, which may have affected the post-operative ADC and FA values. It is also necessary to evaluate whether the ADC and FA values of the median nerve in patients with CTS chronologically shift to those of healthy volunteers.

CONCLUSION

DESS with fat-suppression protocol may be useful for evaluating the median nerve in the carpal tunnel. Further research is required to optimize this sequence for clinical use.

Ethical Approval

The Institutional Review Board approval is not required.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation:

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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How to cite this article: Maki Y, Takayama M, Okawa T, Goda A, Miyakoshi A. Diffusion tensor imaging combined with the dual-echo steady-state (DESS) protocol for the evaluation of the median nerve in the carpal tunnel: A preliminary study. Surg Neurol Int. 2024;15:110. doi: 10.25259/SNI_156_2024