The effect of carpal tunnel release on wrist anatomical characteristics

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Abstract

Introduction and purpose: Carpal tunnel syndrome (CTS) is the most common compressive neuropathy. Clinically it is present as tingling in the first three and radial half of the fourth finger of the hand. Symptoms are usually relieved by shaking or changing the position of the hand, and worsened by repetitive movements of the wrist and fingers or holding the objects. The aim of the present study was to determine the effect of surgical decompression on the anatomical characteristics of the carpal tunnel and median nerve. Methods: We enrolled 25 patients with electrophysiologically (EDx) confirmed moderate CTS and surgical decompression of the median nerve at wrist. Clinical, EDx and ultrasonographical (US) studies were done before, 2 and 6 weeks, and 3 and 6 months after the surgical decompression. Results: Surgical decompression of the median nerve at wrist significantly improved symptoms, nerve conduction studies, flattening ratio and carpal tunnel width. However, it has no impact on median nerve cross-sectional area, median nerve distance from carpal bones or bowing. Usability: Results could be used as a background in further research on physiotherapeutic modalities in patients with CTS. Limitations: Relatively small number of subjects with CTS. Follow-up at 12-months after surgical decompression should also be informative. Key words: carpal tunnel syndrome, surgical decompression, ultrasonographic examination, anatomy, median nerve, carpal tunnel

Vpliv operativne sprostitve medianega živca na anatomske značilnosti zapestnega prehoda

Povzetek

Uvod in namen: Sindrom zapestnega prehoda (SZP) je najpogostejša utesnitvena nevropatija, ki se klinično kaže kot mravljinčenje v prvih treh in radialni polovici četrtega prsta rok. Simptome običajno ublaži otresanje rok in zapestja ali sprememba položaja rok, poslabša pa ponavljajoči se gibi zapestja in prstov ter držanje predmetov. Namen študije naloge je bil določiti vpliv operativne sprostitve na anatomske značilnosti zapestnega prehoda in medianega živca. Metode: V raziskavo smo vključili 25 pacientov z elektrofiziološko potrjenim SZP zmerne stopnje in operativno sprostitvijo medianega živca v zapestnem prehodu. Usmerjen klinični pregled, elektrofiziološke in ultrasonografske meritve smo opravili pred operativnim posegom ter 2 in 6 tednov ter 3 in 6 mesecev po njem. Rezultati: Rezultati raziskave so pokazali, da operativna sprostitev medianega živca v zapestnem prehodu značilno zmanjša simptome, izboljša rezultate elektrofiziološke preiskave, vpliva na sploščenost medianega živca in širino zapestnega prehoda. Ne vpliva pa na ploščino prečnega preseka medianega živca in na njegovo oddaljenost od spodaj ležečih zapestnih kosti in izbočenje. Uporabnost: Rezultati raziskave so uporabni kot podlaga za nadaljnje raziskave o vplivih fizioterapevtskih metod in tehnik na SZP. Omejitve: Omejitev raziskave je pogojevalo relativno majhno število preiskovancev. Prav tako bi bilo smiselno opraviti kontrolni pregled 12 mesecev po operativni sprostitvi medianega živca v zapestnem prehodu. Ključne besede: sindrom zapestnega prehoda, operativna sprostitev, ultrasonografska preiskava, anatomija, mediani živec, zapestni prehod

INTRODUCTION

Carpal Tunnel Syndrome (CTS) is the most common compressive neuropathy, with an electrophysiologically proven incidence of 139 in women and 67 in men per 100.000 annually (Bland and Rudolfer, 2003). The incidence is highest between 50-54 and 75-84 years of age, and is more severe in men and older adults. In Slovenia, approximately 2.718 cases are recorded annually, with the highest number between 45-60 years of age (Bilban, 2011).

The compression of the median nerve in the carpal tunnel (CT) is clinically present as CTS with (1) tingling in the first three fingers and the radial half of the fourth finger, (2) which is more pronounced during the night and in the morning, and (3) alleviates by shaking of the hand and wrist, or changing the position of the hand (Gomes et al., 2006; Bilban, 2011). One study showed that a large majority of patients with CTS (97%) have at least two of the three aforementioned clinical features (Rigler and Podnar, 2009). Repetitive wrist and finger movements and holding the objects usually worsen the symptoms. Typical symptoms and clinical signs arise from the compression of the median nerve in the CT, where the median nerve runs through a narrow anatomical space together with the long tendon of the flexor pollicis longus and deep tendons of the fingers flexor muscles. With continuous use of the hands, thickening of the tendons and tendon sheaths occurs, leading to narrowing of the CT and increased pressure within (Prise-Phillips 1984; Practice parameter 1993; Katz and Simmons 2002; Gomes et al., 2006; Bilban, 2011). Advanced CTS causes altered sensory perception in the innervation area of the median nerve or atrophy of the thenar muscles (Bland and Rudolfer 2003). Symptoms of CTS affect productivity and diminish quality of life (Bilban, 2011). CTS most commonly occurs in professions with a high prevalence of manual work (Chammas et al., 2014). Risk factors may also include pregnancy, wrist fracture, and diabetes (Practice parameter, 1993).

The diagnosis of CTS is based on symptoms, and is confirmed by ultrasound (US) examination and nerve conduction studies (NCSs) (Podnar, 2009, 2015). Conduction in the sensory is more sensitive (74-91%) compared to motor fibers (59-63%). Among tests for measuring the conduction in the sensory fibers, comparative measurements of latency for median and ulnar nerve with stimulation at the wrist and detection from ring finger at a distance of 14 cm has shown good characteristics (sensitivity 87%, specificity 89%, positive predictive value of 93% and negative predictive value of 79%) (Podnar, 2009), making it suitable for monitoring treatment outcomes due to its simplicity and speed (Tahririan et al., 2012). A pathological finding in asymptomatic patients with preserved sensory perception in the area innervated by the median nerve generally does not require intervention. Contrary, a negative finding with a characteristic clinical picture does not exclude the possibility that symptoms are actually due to mild compression of the median nerve at wrist (Boniface et al., 1994; Bland and Rudolfer, 2003).

Treatment can be conservative or surgical (Ibrahim et al., 2012). For patients with mild or moderate CTS, conservative treatment is usually the first choice (Padua et al., 2016; Shi et al., 2020). When conservative treatment with wrist and finger splints, electrotherapy, thermotherapy, kinesiotherapy or manual therapy fails, and typical symptoms persist for at least 6 months (Podnar, 2008; Tsujii et al., 2009; Padua et al., 2016; Genova et al., 2020), surgery is advised. If the patient is not willing to undergo surgery or refuses it, treatment remains conservative, and referral for neurophysiological measurements is not meaningful. Furthermore, neurophysiological measurements are not performed if symptoms have lasted less than 6 months, as there is a high chance of spontaneous recovery in the early stages of disease (Podnar, 2008; Tsujii et al., 2009). For long-term effectiveness (>12 months), surgical treatment is still recommended (Padua et al., 2016; Shi et al., 2020).

The surgical techniques include classical open surgery, endoscopic surgery, and ultrasound (US) guided minimally invasive method. All methods involve cutting the transverse carpal ligament, which relieves pressure within the CT, and has high and comparable effectiveness (Chen et al., 2014; Newington et al., 2015; Zhang et al., 2015; Wipperman and Goerl, 2016; Alp et al., 2019; Smith et al., 2020; Li et al., 2020). The techniques differ mainly in the invasiveness of the approach, recovery time, and the possibility of surgical complications. The trend in choosing a surgical technique is moving towards minimal invasiveness and excellent visibility of anatomical structures during the procedure, which reduces both the duration and recovery time, as well as the risk of complications. Thus, due to numerous advantages, US-guided minimally invasive release of the median nerve in the carpal tunnel is becoming the most rapidly adopted method (Petrover et al., 2017; Loizides et al., 2021).

Recovery after surgery mainly depends on the degree of damage of the median nerve (Chammas et al., 2014). Symptoms improves in 95% of patients. Cutting the transverse carpal ligament and relieving pressure inside the CT has numerous consequences on the anatomical characteristics of the CT, median nerve, function and symptoms. After cutting the transverse carpal ligament, the volume and cross-sectional area of the CT increase (Alp et al., 2019; Ng et al., 2021). Study results also show a reduction in the cross-sectional area of the median nerve after surgery, but this typically does not return below the upper normal value (Inui et al., 2016; Ng et al., 2021a; Ng et al., 2021b). Symptoms and clinical presentation improves in most patients (Schmid et al., 2012; Izhodi, 2013; Li et al., 2020), as do conduction measurements (Ise et al., 2021). A deeper understanding of the impact of operative release of the median nerve on the anatomical characteristics of the CT would provide a solid theoretical basis for further research on the effects of various conservative methods and techniques on CTS and for comparing results with operative treatment.

METHODS AND MATERIALS

Participants

The study was performed on patients suspected of having CTS, referred to the Institute of Clinical Neurophysiology, UKC Ljubljana. Inclusion criteria included (1) at least two affirmative responses to three questions regarding tingling in at least two of the first four fingers, more pronounced symptoms during the night or at the morning, and improvement upon shaking the hands; (2) symptoms duration of at least 6 months; (3) electrophysiologically confirmed moderate CTS; and (4) patient consent with surgical intervention. Exclusion criteria included (1) fracture or dislocation of the wrist; (2) previous surgical release of the median nerve in the CT; (3) traumatic injury to the median nerve; (4) associated diseases, including: polyneuropathy, cervical radiculopathy, cubital tunnel syndrome, thoracic outlet syndrome, diabetes, hypothyroidism, arthritis, Buerger's disease, myelopathy, hormonal, rheumatic, or cancer diseases; and (5) pregnancy.

Before inclusion, patients were thoroughly informed about the study procedure, and written informed consent was taken. The research was approved by the Medical Ethics Committee of the Republic of Slovenia. Each participant underwent a directed clinical examination, electrodiagnostic testing, and US examination.

Clinical examination

We assessed atrophy (1 – present, 2 – absent), muscle strength of the thumb abduction using the MRC (Medical Research Council) scale (Geere et al., 2007), and the sense of touch in the innervation area of the median nerve using a cotton wool (1 – normal, 2 – impaired). We evaluated the symptoms and function of the affected hand using the Boston CTS questionnaire (Leite et al., 2006; Izhodi, 2013).

EDx examination

In patients with a clinical diagnosis of CTS who provided at least two affirmative responses to three questions regarding tingling in at least two of the first four fingers, more pronounced symptoms during the night or at the morning, and improvement upon shaking the hands, and with a symptom duration of at least 6 months, we performed an EDx examination according to an established protocol (Podnar, 2009). If there was a suspicion of the associated conditions, we extended the examination to needle electromyography. According to the established protocol, the EDx examination also allows for the determination of the severity of nerve damage. In case of mild damage, the CMAP latency is normal, but there is a difference in the latency of SNAP for the median and ulnar nerve >0.4ms. In cases of moderate damage, the CMAP latency is prolonged, and the difference in latency of SNAP for the median and ulnar nerve is >0.4ms. In case of severe damage, the CMAP latency is prolonged, and the SNAP is absent. In cases of complete damage, both the CMAP and SNAP for the median nerve are absent (Podnar, 2008).

US examination

Ultrasound measurements were performed using an US machine (ProSound Alpha 7, Hitachi Aloka Medical, Ltd, Tokyo, Japan) and a 13 MHz linear probe (Hitachi Aloka, UST-5412). The assessment of morphological changes in the median nerve was based on (1) measurements of the cross-sectional area in the proximal part of the CT (PZP – line between the pisiform and scaphoid bones), 1 cm (PZP-1) and 10 cm proximal (PZP-10 – forearm) and in the distal part of the CT (DZP – line between the hamate and trapezium bones) and 1 cm distal (DZP1), (2) calculating the ratio of cross-sectional area between PZP-1 and PZP-10 (Area ratio = area PZP-1/area PZP-10), and (3) calculating the flattening ratio in PZP-1 and PZP-10 based on measurements of the width and perpendicular depth within the hyperechoic ring (Flattening ratio = d1/d2) (El Miedany et al., 2015). The greater the value of the flattening ratio, the more pronounced the flattening in the shape of an ellipse, and the smaller the value of the flattening index, the less pronounced the flattening in the shape of a circle. The cross-sectional area was measured using a built-in measuring instrument and by outlining the median nerve within the hyperechoic ring (mm^2). Minimal possible pressure of the probe on the skin was ensured.

The assessment of morphological changes in the CT was based on measurements of (1) the width of the CT (Lee et al., 2020) in the proximal part at the distance between the tip of the pisiform bone and the scaphoid bone, and in the distal part at the distance between the tip of the hamate bone and the trapezium bone, (2) the bulging of the transverse carpal ligament (Ng et al., 2021), and (3) the distance of the median nerve from the underlying carpal bones in the proximal (PZP) and distal (DZP) parts.

Before the surgical procedure, we also measured the thickness of the transverse palmar ligament in PZP and DZP.

Surgical procedure

All patients included in the study were operated by the same surgeon, a specialist in plastic, reconstructive, and aesthetic surgery, with more than 20 years of experience in the field of median nerve release in CTS using traditional open techniques (Siegmeth and Hopkinson-Woolley, 2006; Oh et al., 2017).

Follow-Up examinations

All patients were invited for follow-up examinations at 2 and 6 weeks, as well as 3 and 6 months after the surgical release of the median nerve in the CT. At that time, we repeated the measurements from the initial examination. We completed the Boston CTS questionnaire and performed NCSs and US. The EDx examination included measuring the CMAP terminal latency for the median nerve, as well as a comparative measurement of the SNAP latencies for the median and ulnar nerve when stimulated at the wrist and detected at the ring finger at a distance of 14 cm. The US examination included measurements of cross-sectional areas, width of the CT, bulging of the transverse palmar ligament, and the distance between the median nerve and the underlying carpal bones.

Outcome variables

The outcome variable for assessing the impact of surgical release on the anatomical characteristics of the CT will be the width of the CT in the proximal and distal part. The outcome variables for assessing the impact of surgical release on the anatomical characteristics of the median nerve are cross-sectional areas, flattening, bulging, and the distance of the median nerve from the underlying carpal bones. We also compared the results of the Boston CTS questionnaire, terminal CMAP latencies, and comparative measurements of SNAP for the median and ulnar nerve. We calculated the correlation between the measured parameters and the duration of symptoms.

Statistical analysis

Data were entered into Microsoft Office Excel 365 (Microsoft, Albuquerque, New Mexico, USA) and analyzed using GraphPad Prism (Windows, GraphPad Software, San Diego, California, USA). Differences in outcome variables between the individual time intervals (before surgical release of the median nerve in the CT, at 2 and 6 weeks, and at 3 and 6 months after the operation) were calculated using the Kruskal-Wallis test. For analyzing differences between individual measurements, we used Dunn's comparison. To calculate the differences in the thickness of the transverse palmar ligament between PZP and DZP, we used the Mann-Whitney test. Graphs display the median, first and third quartiles, as well as the minimum and maximum values. The significance level α was set at 5 percent.

RESULTS

We included 25 patients (22 women) with an average of 61 years of age (SD 15 years, range 36 – 84 years). The surgical procedure was performed on the right hand in 18 subjects. We analyzed the differences in (1) severity of symptom occurrence, (2) latencies and amplitudes of SNAP for the median and ulnar nerve, (3) cross-sectional areas of the median nerve, (4) flattening ratio of the median nerve, (5) distance of the median nerve from the underlying carpal bones, (6) bulging, and (7) CT width before the surgical procedure and at 2 weeks, 6 weeks, 3 months, and 6 months post-operatively. In addition, we also analyzed the differences in the thickness of the transverse palmar ligament between the proximal and distal parts of the CT before the surgical procedure.

Analysis of symptom severity

The analysis of symptom severity using the Boston CTS questionnaire showed statistically significant differences between the scores obtained before the surgical procedure, and at 2 weeks, 6 weeks, 3 months, and 6 months post-operatively (Table 1, Figure 1).

Table 1: Comparison of the total score of the Boston CTS questionnaire before the surgical procedure (Before) and at 2 weeks (2W), 6 weeks (6W), 3 months (3M), and 6 months (6M) post-operatively. Results are presented as mean values with standard deviation.

	Before	2W	6W	3M	6M	p-value
Boston CTS	35.2 (6.8)	13.0 (3.9)	18.6 (6.4)	20.5 (6.4)	18.6 (8.1)	<0.0001

Note: The maximum possible score for the symptoms assessment using the Boston questionnaire is 55 (Max) and the minimum is 11 (Min).

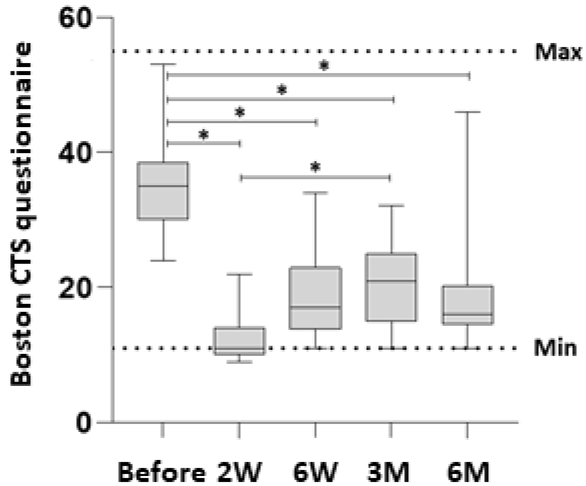

Figure 1: Comparison of the total score of the Boston questionnaire (BQ) before the surgical procedure (Before) and at 2 weeks (2W), 6 weeks (6W), 3 months (3M), and 6 months (6M) post-operatively. The maximum possible score for the symptoms assessment using the Boston questionnaire is 55 (Max) and the minimum is 11 (Min). Statistically significant differences between individual pairs are indicated with *.

Analysis of latencies and amplitudes of SNAP for the ulnar and median nerve

The analysis of the SNAP latency of the ulnar nerve did not show statistically significant differences between the scores obtained before the surgical procedure and at 2 weeks, 6 weeks, 3 months, and 6 months after the procedure. In contrast, the analysis of the SNAP latency of the median nerve demonstrated statistically significant differences between the scores obtained before the surgical procedure and at 3 and 6 months after (Table 2, Figure 2). Furthermore, the analysis of differences in SNAP latencies between the ulnar and median nerves showed statistically significant differences between the scores obtained before the surgical procedure and at 6 months after (Table 2). We did not find statistically significant differences in the SNAP amplitudes for the ulnar and median nerve (Table 2).

Table 2: Comparison of the SNAP latencies and amplitudes of the ulnar and median nerve, as well as the differences in the SNAP latency between the ulnar and median nerve (Δ latency) before the surgical procedure (Before) and at 2 weeks (2W), 6 weeks (6W), 3 months (3M), and 6 months (6M) after. Results are presented as mean values with standard deviation.

	Before	2W	6W	3M	6M	p-value
Latency [ms]						
Ulnar	2.6 (0.3)	2.5 (0.2)	2.5 (0.3)	2.4 (0.3)	2.5 (0.3)	0.4857
Median	4.0 (0.7)	3.5 (0.5)	3.4 (0.5)	3.3 (0.4)	3.3 (0.4)	**0.0191**
Δ lat	1.5 (0.7)	1.1 (0.5)	1.0 (0.5)	0.9 (0.4)	0.8 (0.3)	**0.0310**
Amplitude [µV]						
Ulnar	13.4 (7.9)	15.2 (8.4)	13.8 (8.0)	14.6 (7.8)	17.6 (9.3)	0.4668
Median	6.4 (5.7)	6.8 (5.8)	8.4 (7.6)	8.2 (6.4)	8.4 (6.0)	0.6673

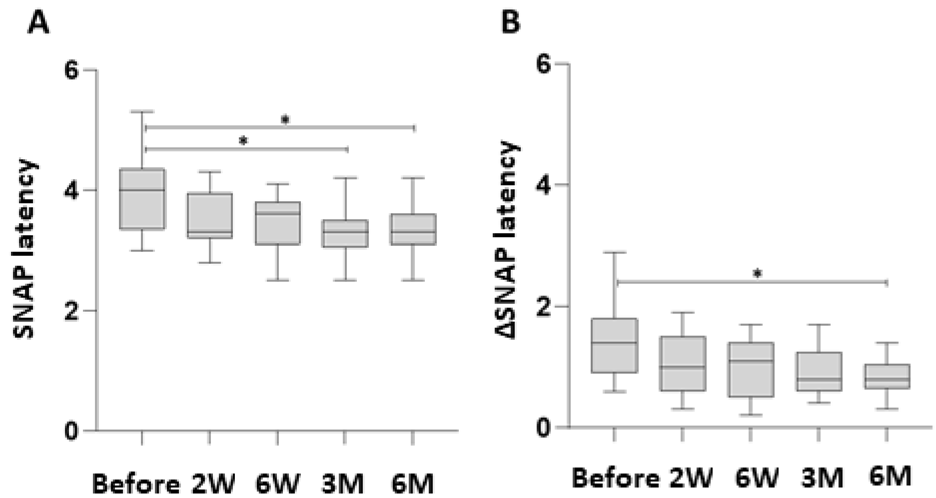

Figure 2: SNAP latency for the median nerve (A) and differences in the SNAP latencies between the ulnar and median nerves (B). Statistically significant differences between individual pairs are indicated with *.

Analysis of the cross-sectional area of the median nerve

The analysis of the cross-sectional area of the median nerve did not show statistically significant differences between the scores obtained before the surgical procedure and at 2 weeks, 6 weeks, 3 months, and 6 months after at any of the measured levels (Table 3, Figure 3).

Table 3: Cross-sectional area (mm^2) of the median nerve at different levels before the surgical procedure (Before) and at 2 weeks (2W), 6 weeks (6W), 3 months (3M), and 6 months (6M) after the procedure. Results are presented as mean values with standard deviation.

	Before	2W	6W	3M	6M	p-value
PZP-10	6.5 (1.3)	6.5 (1.7)	6.5 (1.6)	6.6 (1.0)	6.6 (1.1)	0.9772
PZP-1	13.8 (5.0)	12.0 (4.9)	11.2 (4.7)	11.7 (4.5)	12.9 (3.6)	0.2324
PZP	14.8 (5.9)	12.3 (3.8)	11.9 (4.1)	12.5 (3.6)	12.4 (3.9)	0.4565
DPZ	11.1 (4.8)	13.8 (4.3)	10.5 (3.8)	10.1 (3.2)	11.7 (4.7)	0.0531
DPZ1	14.4 (4.6)	14.9 (3.7)	13.6 (4.9)	14.4 (3.2)	13.4 (3.7)	0.7063

PZP-10 – 10 cm proximal to CT; PZP-1 – 1 proximal to CT; PZP – line os pisiforme and os scaphoideum; DPZ – line os hamatum and os trapezium; DPZ1 – 1 cm distal to CT.

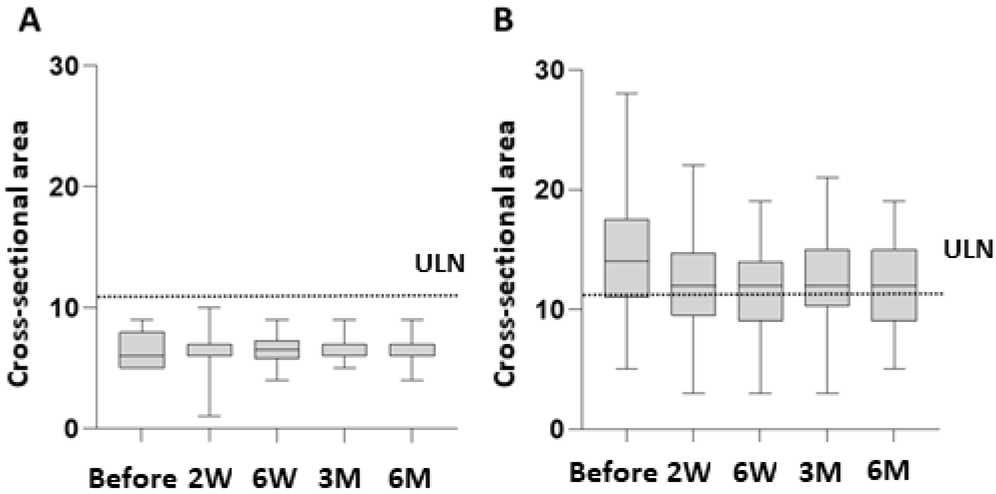

Figure 3: Cross-sectional area of the median nerve 10 cm proximal to the wrist (A) and cross-sectional area of the median nerve at the wrist (B). Statistically significant differences between individual pairs are indicated with *. ULN – upper limit of normal is 11 mm².

Analysis of the flattening ratio of the median nerve

The analysis of the flattening ratio of the median nerve showed statistically significant differences at the levels of PZP, PZP-1, DZP, and DZP1 (Table 4, Figure 4).

Table 4: Flattening ratio of the median nerve at different levels before the surgical procedure (PRE) and at 2 weeks (2W), 6 weeks (6W), 3 months (3M), and 6 months (6M) after the procedure. Results are presented as mean values with standard deviation.

	Before	2W	6W	3M	6M	p-value
PZP-10	1.7 (0.3)	1.6 (0.3)	1.7 (0.4)	1.7 (0.6)	1.8 (0.4)	0.9025
PZP-1	2.8 (0.7)	2.7 (0.6)	2.8 (0.9)	3.0 (0.8)	3.4 (0.9)	0.0506
PZP	3.1 (0.6)	2.6 (0.7)	2.8 (0.7)	3.2 (0.7)	3.4 (1.3)	0.0141
DPZ	2.9 (0.9)	2.2 (0.7)	2.5 (0.7)	2.7 (0.9)	2.8 (0.8)	0.0347
DPZ1	3.4 (0.7)	2.5 (0.7)	3.3 (0.7)	3.2 (0.8)	3.6 (1.0)	0.0097

PZP-10 – 10 cm proximal to CT; PZP-1 – 1 proximal to CT; PZP – line os pisiforme and os scaphoideum; DPZ – line os hamatum and os trapezium; DPZ1 – 1 cm distal to CT. A higher value of the flattening ratio indicates a more pronounced flattening (elliptical shape), while a lower value of the flattening index indicates a less pronounced flattening (circular shape).

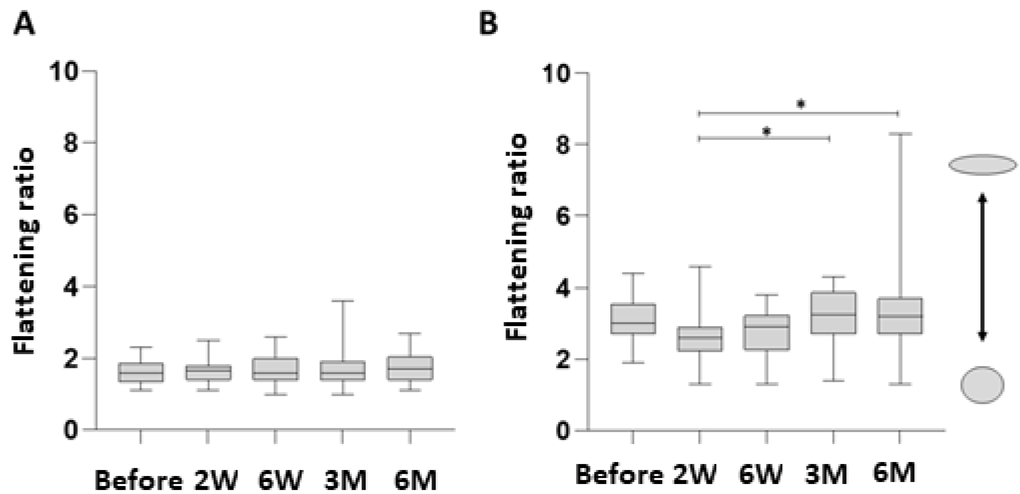

Figure 4: Flattening ratio of the median nerve 10 cm proximal to the wrist (A) and at the wrist (B). Statistically significant differences between individual pairs are indicated with *. A higher value of the flattening ratio indicates a more pronounced flattening (elliptical shape), while a lower value of the flattening index indicates a less pronounced flattening (circular shape).

Analysis of the distance of the median nerve from the underlying carpal bones and protrusion

Both the analysis of the distance of the median nerve from the underlying carpal bones and the protrusion did not show statistically significant differences between the results obtained before the surgical procedure and at 2 weeks, 6 weeks, 3 months, and 6 months after the procedure (Table 5).

Table 5: Distance (mm) of the median nerve from the underlying carpal bones and protrusion (mm) in the proximal (PZP) and distal (DZP) parts of the CT. Results are presented as mean values with standard deviation.

	Before	2W	6W	3M	6M	p-value
PZP						
Distance	11.7 (2.8)	9.5 (1.5)	9.5 (2.0)	10.2 (1.4)	10.2 (1.5)	0.1030
Bowing	4.7 (1.2)	4.0 (1.2)	4.0 (1.6)	4.0 (1.5)	3.8 (1.1)	0.1833
DPZ						
Distance	9.3 (1.5)	9.6 (1.0)	9.3 (0.7)	9.1 (1.2)	9.2 (1.0)	0.7999
Bowing	2.3 (0.9)	2.1 (0.9)	1.8 (0.8)	2.4 (0.7)	2.1 (0.6)	0.3124

PZP – line os pisiforme and os scaphoideum; DPZ – line os hamatum and os trapezium

Analysis of the width of the CT

The analysis of the width of the CT showed statistically significant differences in the distal part of the CT before the surgical procedure and also at 2 weeks, 6 weeks, 3 months, and 6 months after the procedure (Table 6, Figure 5). In the proximal part of the CT, the analysis of width did not show statistically significant differences (Table 6).

Table 6: Width (mm) of the CT in the proximal (PZP) and distal (DZP) parts. Results are presented as mean values with standard deviation.

	Before	2W	6W	3M	6M	p-value
PZP	30.8 (2.4)	31.7 (2.4)	31.0 (4.8)	32.6 (2.5)	32.4 (3.2)	0.0836
DPZ	17.1 (2.8)	20.1 (5.0)	22.6 (3.8)	25.3(2.6)	25.3 (2.8)	<0.0001

PZP – line os pisiforme and os scaphoideum; DPZ – line os hamatum and os trapezium

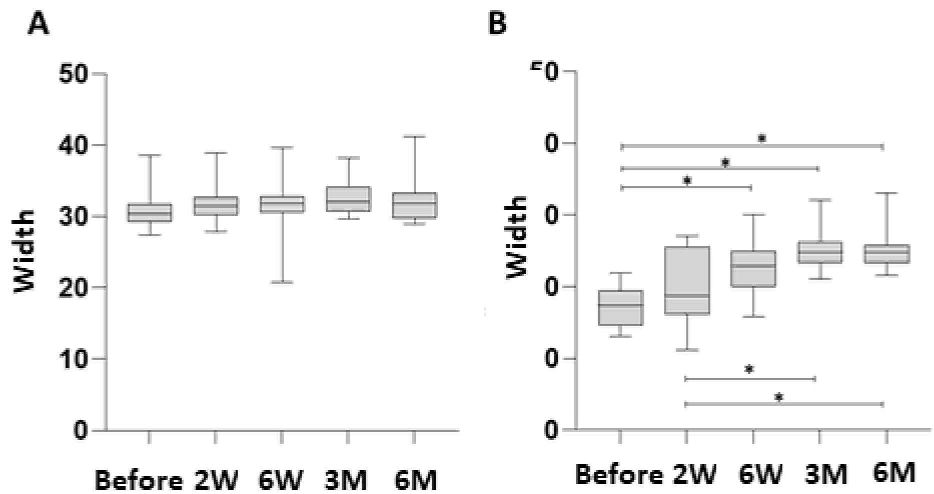

Figure 5: Width of the CT in the proximal (A) and distal (B) parts of the CT. Statistically significant differences between individual pairs are indicated with *.

Analysis of the thickness of the transverse carpal ligament before the surgical procedure

The thickness of the transverse carpal ligament was measured before the surgical procedure. The analysis showed a statistically significant difference between the proximal and distal parts of the CT. The transverse carpal ligament is thicker in the distal part of the CT (Table 7).

Table 7: Thickness (mm) of the transverse carpal ligament in the proximal (PZP) and distal (DZP) parts of the CT. Results are presented as mean values with standard deviation.

	PZP	DZP	p-value
Thickness of the transverse carpal ligament	0.9 (0.2)	1.2 (0.2)	0.0002

PZP – line os pisiforme and os scaphoideum; DPZ – line os hamatum and os trapezium

DISCUSSION

The CT is a connective tissue-bone structure passage at wrist containing 9 finger flexor tendons and the median nerve. Increased pressure inside the CT leads to the entrapment of the median nerve and the appearance of typical symptoms of tingling in the first four fingers, which are more pronounced during the night and in the morning, and is relieved by shaking of the hand. In advance stage, atrophy of the thenar muscles also appears. Treatment can be conservative or surgical. In conservative management, the use of wrist and finger splints during the night is recommended. In cases of significant impairment of the median nerve at wrist, or ineffectiveness of conservative therapy, surgical release is advised. Regardless of the technique, the goal of every surgery is to cut the transverse carpal ligament, which reduces pressure in the CT and allows the median nerve to regenerate. Cutting the transverse carpal ligament has numerous anatomical consequences for both the CT and the median nerve.

Before the surgical procedure, we measured the thickness of the transverse carpal ligament in the proximal and distal part of the CT and found a statistically significant difference. The transverse carpal ligament is thicker at the distal part of the CT compared to the proximal, measuring 1.2 mm versus 0.9 mm. Bartolome Villar et al. (2018) and Shen et al. (2012) state that the average thickness of the transverse carpal ligament ranges from 1.3 to 3 mm, depending on the measurement location. The most probable site of median nerve entrapment is therefore at the distal part of the CT, since at this location, along with the thicker transverse carpal ligament, there is also a smaller cross-section of the CT. Results from one of the studies indicate that the thickness of the transverse carpal ligament does not have a direct influence on the incidence of CTS, however only on pain (Shen et al., 2012). Marquardt et al. (2016) explain that local changes in stiffness of the transverse carpal ligament can reduce the lumen of the CT, which conditions the entrapment of the median nerve and the onset of pain. Throughout the study, they found that thickening of the transverse carpal ligament was present only in patients with CTS, while thickening was not present in healthy individuals. They concluded that the thickness of the transverse carpal ligament is not the cause of the CTS (Bartolome Villar et al., 2018). Shen et al. (2012) conducted an investigation on cadavers and found the presence of thickening of the transverse carpal ligament and validated US as a legitimate diagnostic technique for measuring the thickness of the transverse carpal ligament. This finding is also supported by Marquardt et al. (2016), who claim that patients with CTS have a thicker transverse carpal ligament, especially in the central region. Later, Lee et al. (2020) concluded that the thickness of the transverse carpal ligament is related to the cross-sectional area and the duration of symptom severity. They also found that for patients with an average transverse carpal ligament thickness of 2.28 mm have a 67.7% probability of surgical intervention. The thickness of the transverse carpal ligament is believed to be a measure for deciding between surgical and conservative treatment, at a threshold value of 1.5 mm. One of the limitations of our study is that we measured the thickness of the transverse carpal ligament only before the surgical release of the median nerve at wrist. By measuring the thickness of the transverse carpal ligament at different time intervals after surgery, we could compare the results with the expression of symptoms and the muscle strength of thumb abduction. Marquardt et al. (2016) explain that there is a correlation between the transverse carpal ligament and muscle strength of the thumb abduction. When squeezing the thumb and index finger, the thenar muscles contract and pull the transverse carpal ligament in the volar direction. The transverse carpal ligament also shifts volarly when the flexor tendons are tense under finger load. Repetition of such movements is believed to cause thickening of the transverse carpal ligament. Kilinc et al. (2021) also note that it is important to monitor the thickness of the transverse carpal ligament after the surgical release.

The analysis of symptom expression using the Boston CTS questionnaire showed significant differences between the results before the surgical procedure and 2 weeks, 6 weeks, 3 months, and 6 months after the surgery. The average values of symptom occurrence significantly decrease in the first two weeks after the surgical procedure, and most patients practically no longer report typical symptoms. After 3 months post-surgery, the severity of symptom occurrence significantly increases, but does not reach the levels observed before the surgical procedure during the duration of the study. Most studies report significant improvement in symptoms immediately following the release of the median nerve at the wrist (Ball et al., 2011; Kim et al., 2012; Izhodi, 2013; De Kleermaeker et al., 2019; Chappell et al., 2020; Multanen et al., 2020; Mozaffarian et al., 2022; Nguyen et al., 2022). At the same time, results of one study also show a significant improvement in symptoms at eight months (De Kleermaeker et al., 2019) and 12 months (Multanen et al., 2020; Mozaffarian et al., 2022) after the surgery. The results of the studies also show that symptoms after three months post-surgery are unlikely to improve further (Ball et al., 2011). The rate of symptom recurrence and reoperation is low, estimated at only 5% (de Roo et al., 2022).

Neurophysiological measurements of conduction in peripheral nerves are used to confirm the diagnosis of CTS, to define the degree of nerve damage, and to monitor the improvement after surgery. The analysis of SNAP latency of the ulnar nerve did not show significant differences before and at 2 weeks, 6 weeks, 3 months, and 6 months after surgery. The result is expected and indicates the reliability of measurements under controlled conditions of temperature, stimulation parameters, and agreed distance, since the ulnar nerve traverses through Guyon's tunnel at the wrist, and not through the CT. On the contrary, the analysis of SNAP latency of the median nerve showed significant differences before and 3 months and 6 months after surgery. Furthermore, the analysis of differences in SNAP latencies between the ulnar and median nerve also showed significant differences before and 6 months after surgery. The difference in average SNAP latency for the median nerve before and 6 months after the surgery was 0.7 ms. The difference in average SNAP latency between the ulnar and median nerve was also 0.7 ms. Neurophysiological changes thus require significantly more time compared to symptoms. The immediate improvement of paresthesia (especially nighttime tingling) is explained by the absence of ischemia of the sensory fibers of the median nerve at the wrist. Typical nighttime issues in CTS are indeed related to the flexion of the wrist and fingers, increased pressure in the CT, and ischemia of nerve fibers. The use of wrist and finger splints prevents the flexion of the wrist and fingers. After surgical release, the pressure inside the CT decreases. It is likely that patients are also more mindful of the operated hand or using a splint in the initial days post-surgery. After a certain period, symptoms may worsen again, as patients begin to perform manual work, and the transverse carpal ligament re-fuses in a new position. The improvement in conduction velocity through sensory fibers is associated with remyelination, a restorative process that requires 3-6 months. This is about the time that has elapsed in our research for a significant improvement in the latency of the median nerve SNAP across the wrist. No significant differences were found between the amplitudes of the SNAP between the ulnar and median nerve.

Measurements of the width of the CT showed that CT is approximately 30 mm wide in the proximal part (line between the pisiform and scaphoid bone), and approximately 20 mm in the distal part (line between the hamate and trapezium bone). The study by Rotman and Donovan (2002) also states that the width of the CT is greater in the proximal compared to distal part (25 vs 20 mm). The conical shape of the CT is believed to be a predictive factor for CTS in both men and women (Shiri, 2015). It is also suggested that the shape of the hand differs between patients with CTS and healthy individuals. The distance between the thumb and the third metacarpal bone is believed to be a true measure for determining hands prone to CTS (Sahebalam et al., 2021). The analysis of the width of the CT showed significant differences in the distal part of the CT prior to the surgery and at 2 weeks, 6 weeks, 3 months, and 6 months post-surgery. The width of the distal CT thus increased on average by 8 mm 6 months after the surgery. In the proximal part of the CT, the analysis of width did not show significant differences. Opinions among other authors regarding anatomical changes in the width of the CT vary. Brooks et al. (2003) in their study following the surgical release of the median nerve report a significant increase in the width of the CT in both the proximal and distal parts by an average of 7%. Garcia-Elias et al. (1992) also report an increase in the width of the distal CT by 11%. They have found that the ligaments connecting the carpal bones play a crucial role in ensuring the stability of the carpal arch, not the transverse carpal ligament. Kwon et al. (2016) found a 7.4% increase in the width of the distal CT 6 months post-surgery. Conversely, Xiu et al. (2010) and Marquardt et al. (2015) report reduced widths of the distal CT. Xiu et al. (2010) also studied the effect of external force on the width of the CT on cadavers. They found that with an inward force of 10N, the width of the CT in the distal part decreased by 10.6% and by 37.9% in the proximal part. When an outward force of 10N was applied, the width of the CT in the distal part increased by 9.6% and in the proximal part by 33.9%. Therefore, cutting the transverse carpal ligament may have minimal effects on the anatomical characteristics of the unburdened carpal arch, but significantly increases its flexibility under load. This state may also be a source of problems for some patients after the surgical release of the median nerve in the CT, who report pain and a sense of instability.

Based on the results, we can conclude that the release of the median nerve at wrist does not affect the width of the proximal and distal parts of the CT. The results of the study indicate that the width of the distal part of the CT increases after surgical release, while the width of the proximal part remains unchanged. Measurements of the cross-sectional area of the median nerve at the wrist are an important diagnostic criterion (Podnar, 2015). A positive correlation was found between US examination and the degree of CTS. Additionally, the combination of US examination and neurophysiological measurements showed greater sensitivity compared to using US measurements alone or neurophysiological measurements alone to confirm the degree of CTS (Badger et al., 2008; Rao et al., 2012). The upper limits of normal for the cross-sectional area of the median nerve in the CT vary among authors and range from 4 to 10mm² (Rao et al., 2012; Tahririan et al., 2012; Podnar, 2015; Lim et al., 2022). It is recommended that each laboratory independently determine reference values. Thus, at the Institute of Clinical Neurophysiology, the upper limit of normal is set at 11mm² (Podnar, 2015). The average cross-sectional area of the median nerve in the proximal part of the CT before the surgical release was 14.8mm². After surgical release, the cross-sectional area of the median nerve decreased, but the differences were not statistically significant. Additionally, 6 months post-surgical release, the cross-sectional area of the median nerve at the wrist decreased below the upper limit of normal (11mm²) in only 7 patients, with only one patient measuring exactly 11mm². Tahririan et al. (2012) also did not find a characteristic decrease in the cross-sectional area. However, significant reductions in cross-sectional area were shown in the research conducted by Chappell et al. (2020) between 6 and 10 weeks post-surgery. Ng et al. (2021) also proved the significant reduction of the cross-sectional area of the median nerve in the proximal part of the CT at 1, 3, and 12 months post-surgical release. The reason for a reduction in the cross-sectional area within 1 month post-surgical release lies, as noted by the author, in decreased venous flow due to inflammation. Thus, the median nerve remains thickened (edematous) even up to 12 months post-surgical release. In cases of recurrent symptoms post-surgery, neurophysiological examination is recommended (El-Hajj et al., 2010), as US is practically useless for assessing recurrent entrapment due to the increased cross-sectional area of the median nerve even in patients without symptoms (Ng et al., 2021). Nevertheless, US examination is a suitable diagnostic method for assessing incomplete release of the transverse carpal ligament, which is most often recognized in the distal part of the CT in a small percentage of patients (Tulipan et al., 2020).

The ratio of the largest to the smallest rectangular diameter of the median nerve provides an estimate of flattening. The larger the flattening index, the more the median nerve resembles an ellipse; the smaller the flattening index, the more the median nerve resembles a circle. The analysis of the flattening ratio of the median nerve showed significant differences only within the CT (proximal CT, distal CT, and distal CT1). The results indicate a decrease in the flattening ratio of the median nerve within the CT during the first week after surgery, when the median nerve begins to take on an elliptical shape again. Similar results are cited by Ng et al. (2021); the flattening of the median nerve is expected to decrease in the first month post-surgical release, then increase between 3 and 12 months, most significantly in the distal part of the CT. Changes in the shape of the median nerve can easily be correlated with changes in pressure within the CT. El Miedany et al. (2015) indicate that patients with CTS have elevated pressure within the CT. The degree of median nerve impairment is related to pressure, with mild entrapment associated with slight increases in pressure and significant entrapment associated with strong increases in pressure (Ahn et al., 2009). When discussing chronic CTS, pressure increases in relation to structural changes within the CT, associated with the duration of symptoms. Increased pressure within the CT predominantly affects the median nerve superficially, causing it to assume an elliptical shape primarily in the proximal part of the CT. After cutting the transverse carpal ligament, pressure within decreases (Ahn et al., 2009; El Miedany et al., 2015; Snarrenberg et al., 2018; Ng et al., 2021), while the nerve retains its original circular shape, observable at all non-entrapment locations. Eventually, the transverse carpal ligament heals in its new position and pressure within the CT rises again, forcing the median nerve to take on a more flattened

shape. Ng et al. (2021) note that 3 months after surgical release, the transverse carpal ligament heals in 10% of patients, and in one year in 70% of patients.
Cutting the transverse carpal ligament causes a reduction in pressure within the CT (Snarrenberg et al., 2018), which hypothetically should lead to a superficial shift of the median nerve. We aimed to verify this hypothesis by measuring the distance of the median nerve from the underlying carpal bones and its protrusion, but the analysis of significant differences before the surgical intervention and at 2 weeks, 6 weeks, 3 months, and 6 months post-operation showed no differences in either the proximal or distal part of the CT (Table 5). Our study results contradict the findings of Schmid et al. (2012), who found statistically significant protrusion occurring in the first month post-surgery, which then progressively decreases to the 12th month. An increased protrusion in the first month post-surgery is also confirmed by Ng et al. (2021). Additionally, it is expected that the protrusion of the median nerve begins to decrease in the time interval from 3 to 12 months. They also found that the protrusion of the median nerve after surgical release is more pronounced in the distal part of the CT compared to the proximal part, at 68% (Ng et al., 2021).
Based on our results, we can partially confirm that surgical release of the median nerve at wrist affects the cross-sectional area, flattening, protrusion, and the distance of the median nerve from the underlying carpal bones. The results indicate that the release of the median nerve in the CT does not affect the cross-sectional area, the distance of the median nerve from the underlying structures, or protrusion. According to our findings, surgical release of the median nerve in the CT primarily affects flattening, which is expected to decrease in the initial weeks and then increase again.

CONCLUSION

Cutting the transverse carpal ligament has numerus consequences on morphology of the CT and functioning of the median nerve. Surgical decompression significantly and immediately improves symptoms, while the improvement in nerve conduction studies takes more time. The procedure also affects flattening ratio and CT width, however, it has no impact on median nerve cross-sectional area, median nerve distance from carpal bones or bowing.

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