Carpal Tunnel Syndrome and Related Median Neuropathies

Challenges and Complications

Scott F. M. Duncan
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Editors
Scott F.M. Duncan
Department of Orthopedic Surgery
Boston University/Boston Medical Center
Boston, MA, USA

Ryosuke Kakinoki
Department of Orthopaedic Surgery
Kindai University Hospital
Osaka, Japan

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We wish to dedicate this book to all those with hand surgery expertise that continue to write book chapters. Some in our profession feel that the effort of writing a book chapter is wasteful and that all of their time and energy should be focused on research. While we respect this opinion, we value the authors of this book who selflessly dedicated themselves to contributing to the teaching and education of others through the dissemination of information that this book offers. This form of self-sacrifice is getting harder to find in our profession given the ever more demanding schedules that we all face.

Preface

Historically, there have been several useful references created on topics related to carpal tunnel syndrome. The publications that we have reviewed during our careers in hand surgery have certainly contributed to our knowledge and understanding of carpal tunnel syndrome. Despite previous excellent publications on this subject matter, we felt that many aspects of previous publications might be improved. This conclusion was reached not only by our own personal opinion but also from comments made by colleagues in practice, as well as residents and fellows in training. The chapters of this book are all written by surgeons whom we hold in the highest regard as teachers and mentors of our generation.

Our target readership is for anyone who has an interest in caring for and treating patients with carpal tunnel syndrome. We believe this update, to what has previously existed as a reference on carpal tunnel syndrome, will be of use to residents, fellows, practicing clinicians, and perhaps even patients afflicted with the disease. The book has been organized to allow for easy searching of specific subject matter related to carpal tunnel syndrome. It reviews many contemporary surgical techniques and treatments for challenging issues related to carpal tunnel syndrome. We wish to thank all of those who helped bring this project to completion.

Boston, MA, USA — Scott F.M. Duncan
Osaka, Japan — Ryosuke Kakinoki

Contents

Contributors

Julie E. Adams, MD Orthopedic Surgery, Mayo Clinic Health System, Austin, MN, USA

Department of Orthopedics, Mayo Clinic, Rochester, MN, USA

Irfan H. Ahmed, MD Orthopedic Surgery, Rutgers NJMS University Hospital, Newark, NJ, USA

Mark E. Baratz, MD Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, USA

Omkar Baxi, MD Orthopedic Surgery, Rutgers NJMS University Hospital, Newark, NJ, USA

Oam Bhate, MD Boston University School of Medicine, Boston, MA, USA

Philip E. Blazar, MD Brigham and Women's Hospital, Boston, MA, USA

Kevin C. Chung, MD, MS Section of Plastic Surgery, Department of Surgery, University of Michigan Medical School, Ann Arbor, MI, USA

Margaret E. Cooke, MD Orhtopaedic Surgery, Boston Medical Center, Boston, MA, USA

Alda Cossi, MD Department of Radiology, Boston University School of Medicine, Boston Medical Center, Boston, MA, USA

Aaron Daluiski, MD Department of Hand and Upper Extremity Surgery, Hospital for Special Surgery, New York, NY, USA

Edward Diao, MD Orthopaedic Surgery and NeuroSurgery, University of California, San Francisco, CA, USA

California Pacific Medical Center, San Francisco, CA, USA

Scott F.M. Duncan, MD, MPH, MBA Department of Orthopedic Surgery, Boston University/Boston Medical Center, Boston, MA, USA

Scott G. Edwards, MD Department of Orthopedics, University of Arizona College of Medicine-Phoenix, Phoenix, AZ, USA

Center for Orthopedic Research and Education, Phoenix, AZ, USA

Brady T. Evans, MD, MBA Department of Orthopaedic Surgery, Harvard Medical School, Beth Israel Deaconess Medical Center, Boston, MA, USA

Brian J. Evanson, MD Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, WI, USA

Jeffrey B. Friedrich, MD Plastic and Reconstructive Surgery and Orthopedic Surgery, University of Washington, Seattle, WA, USA

Michael G. Galvez, MD Division of Plastic and Reconstructive Surgery, Stanford Hospital and Clinics, Stanford, CA, USA

Steven I. Grindel, MD Department of Orthopaedic Surgery, Froedtert and the Medical College of Wisconsin, Milwaukee, WI, USA

Ali Guermazi, MD, PhD Department of Radiology, Boston University School of Medicine, Boston Medical Center, Boston, MA, USA

Warren C. Hammert, MD Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, Rochester, NY, USA

Division of Hand Surgery, Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, Rochester, NY, USA

Lindsay Hess Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, USA

Joshua W. Hustedt, MD, MHS Department of Orthopedics, University of Arizona College of Medicine-Phoenix, Phoenix, AZ, USA

Ryosuke Ikeguchi, MD, PhD Department of Orthopaedic Surgery and Rehabilitation Medicine, Kyoto University Graduate School of Medicine, Kyoto, Japan

Katherine A. Impastato, MD University of Washington, Seattle, WA, USA

Jonathan E. Isaacs, MD Division of Hand Surgery, Department of Orthopaedic Surgery, Virginia Commonwealth University Health System, Richmond, VA, USA

Loree K. Kalliainen, MD, MA, FACS Division of Plastic Surgery, University of North Carolina, Chapel Hill, NC, USA

F. Thomas D. Kaplan, MD Indiana Hand to Shoulder Center, Indianapolis, IN, USA

Andrew Kompel, MD Department of Radiology, Boston University School of Medicine, Boston Medical Center, Boston, MA, USA

Laura Lewallen, MD Department of Orthopedic Surgery, Mayo Clinic, Rochester, MN, USA

Scott D. Lifchez, MD Plastic Surgery, Johns Hopkins Bayview Medical Center, Baltimore, MD, USA

Joseph Lopez, MD, MBA Plastic and Reconstructive Surgery, Johns Hopkins Hospital, Baltimore, MD, USA

Susan E. Mackinnon, MD Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, St. Louis, MO, USA

Bilal Mahmood, MD Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, Rochester, NY, USA

Elham Mahmoudi, PhD, MS Department of Family Medicine, The University of Michigan Health System, Ann Arbor, MI, USA

University of Michigan, Ann Arbor, MI, USA

Regina Meis, MD Department of Orthopaedic Surgery, Boston University Medical Center, Boston, MA, USA

Anthony Montanez, MD Department of Orthopaedic Surgery, University of Utah, Salt Lake City, UT, USA

Akira M. Murakami, MD Department of Radiology, Boston University School of Medicine, Boston Medical Center, Boston, MA, USA

Hatim Mustaly, MS Boston University School of Medicine, Boston, MA, USA

Takashi Noguchi, MD, PhD Department of Orthopaedic Surgery, Boston Medical Center, Boston University School of Medicine, Boston, MA, USA

O. Kenechi Nwawka, MD Department of Radiology and Imaging, Hospital for Special Surgery, Weill Medical College of Cornell University, New York, NY, USA

Maureen A. O'Shaughnessy, MD Department of Orthopedics, Mayo Clinic, Rochester, MN, USA

Souichi Ohta, MD, PhD Department of Orthopaedic Surgery, Kyoto University, Kyoto, Japan

Rick F. Papandrea, MD Orthopaedic Associates of Wisconsin, Pewaukee, WI, USA

Loukia K. Papatheodorou, MD, PhD Department of Orthopaedic Surgery, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA

Shaun P. Patel, MD Department of Orthopaedic Surgery, Harvard Medical School, Beth Israel Deaconess Medical Center, Boston, MA, USA

J. Megan M. Patterson, MD Department of Orthopaedic Surgery, University of North Carolina, Chapel Hill, NC, USA

Marco Rizzo, MD Department of Orthopedic Surgery, Mayo Clinic, Rochester, MN, USA

Tamara D. Rozental, MD Department of Orthopaedic Surgery, Harvard Medical School, Beth Israel Deaconess Medical Center, Boston, MA, USA

A. Sakellariou, MD, DMD Department of Anesthesiology and Pain, Boston Medical Center, Boston University Medical School, Boston, MA, USA

Julie Balch Samora, MD, PhD Nationwide Children's Hospital, Columbus, OH, USA

Cameron W. Schick, MD Indiana Hand to Shoulder Center, Indianapolis, IN, USA

Yaron Sela, MD Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, USA

Anthony A. Smith, MD Department of Surgery, Mayo Clinic Hospital, Phoenix, AZ, USA

Dean G. Sotereanos, MD Department of Orthopaedic Surgery, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA

Scott Swanson, MD Department of Surgery, Maricopa Medical Center, Phoenix, AZ, USA

Samir K. Trehan, MD Department of Hand and Upper Extremity Surgery, Hospital for Special Surgery, New York, NY, USA

E. Vaynberg, MD Department of Anesthesiology and Pain, Boston Medical Center, Boston University Medical School, Boston, MA, USA

David R. Veltre, MD Orthopaedic Surgery, Boston University Medical Center/Boston Medical Center, Boston, MA, USA

Angela Wang, MD Department of Orthopaedic Surgery, University of Utah, Salt Lake City, UT, USA

Christina M. Ward, MD Department of Orthopaedics, University of Minnesota, Regions Hospital, Saint Paul, MN, USA

Jeffrey Yao, MD Department of Orthopaedic Surgery and Surgery, Robert A. Chase Hand and Upper Limb Center, Stanford Hospital and Clinics, Redwood City, CA, USA

Andrew Yee, BSc Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, St. Louis, MO, USA

Shuhao Zhang, MD Division of Plastic Surgery, Department of Surgery, Virginia Commonwealth University Health System, Richmond, VA, USA

1 Anatomy of the Median Nerve: Anatomic Variations and Anomalies

Samir K. Trehan and Aaron Daluiski

Introduction

In this chapter, anatomic variations and anomalies of the median nerve in or adjacent to the carpal tunnel are described. Relevant branches of the median nerve in this region include the palmar cutaneous branch, thenar motor branch, recurrent motor branch, and common digital nerves. In addition, there may be an anomalous branching pattern and/or accessory branches of the median nerve in this region. Finally, an anastomosis between branches of the median and ulnar nerves may be present.

Intraoperative observations have provided data regarding the incidence and clinical relevance of median nerve anatomic variations. Lindley and Kleinert reported that the overall rate of median nerve anatomic variations or anomalies was 1% in their series of 526 carpal tunnel releases [1]. Tountas et al. reported a 9.8% rate of median nerve anomalies in a series of 821 carpal tunnel releases [2]. Beris et al. reported a 10% rate of median nerve anomalies in a series of 110 carpal tunnel releases [3]. However, it is important to note that clinical observations may be limited by selection bias since patients undergoing carpal tunnel release may not have an anatomy that is generalizable to the general population. For example, it has been hypothesized that clinical studies may overestimate the incidence of transligamentous branching of the thenar motor branch since this anomaly may predispose to nerve compression and consequent thenar atrophy [4]. In addition, clinical studies are restricted by more limited exposure and surgical technique, as compared to cadaveric studies. Not surprisingly, the incidence of median nerve anomalies in or adjacent to the carpal tunnel is higher in cadaveric studies—ranging from 18% in 92 specimens reported by Tountas et al. to 78% in 60 specimens reported by Alizadeh et al. [2, 5].

Palmer and Toivonen reported humbling survey results of American Society for Surgery of the Hand members performing open (616 respondents) or endoscopic (708 respondents) carpal tunnel release over a 5-year period. Among respondents performing open and endoscopic surgeries, there were 147 and 100 median nerve lacerations, 29 and 88 ulnar nerve lacerations, 54 and 77 digital nerve lacerations, 34 and 121 vessel lacerations, and 19 and 69 tendon lacerations, respectively [6]. Thus, understanding the anatomic variations and anomalies of the median nerve in proximity to the carpal tunnel is essential to minimizing risk of nerve injury (i.e., the most common complication) during open or endoscopic carpal tunnel release.

S.K. Trehan • A. Daluiski (✉)
Department of Hand and Upper Extremity Surgery, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, USA
e-mail: DaluiskiA@hss.edu

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Variable Branching of the Median Nerve in the Carpal Tunnel

Lanz comprehensively classified anatomic variations of the median nerve in the carpal tunnel based on intraoperative observations from 246 carpal tunnel releases performed during a 4-year period (Fig. 1.1) [7, 8]. Median nerve anomalies were subdivided into four groups depending on the location and type of anomaly: (I) variation in the course of the thenar motor branch, (II) accessory branch(es) at the distal carpal tunnel, (III) high division of the median nerve, and (IV) accessory branch(es) proximal to the carpal tunnel [8]. Groups I and III will be discussed in-depth later in this chapter.

Lanz reported that 7% had accessory branches of the median nerve at the distal portion of the carpal tunnel (i.e., group II) in a series of 246 hands [8]. In a study of ten cadaveric specimens, Falconer and Spinner reported that two had multiple thenar motor branches of the median nerve, and three had Riche-Cannieu anastomosis [9].

Lanz reported that 1.6% had accessory branches of the median nerve proximal to the carpal tunnel in a series of 246 hands [8].

Thenar Motor Branch

The normal origin of the thenar motor branch is distal to the flexor retinaculum (i.e., "extraligamentous") and from the volar/central or volar/

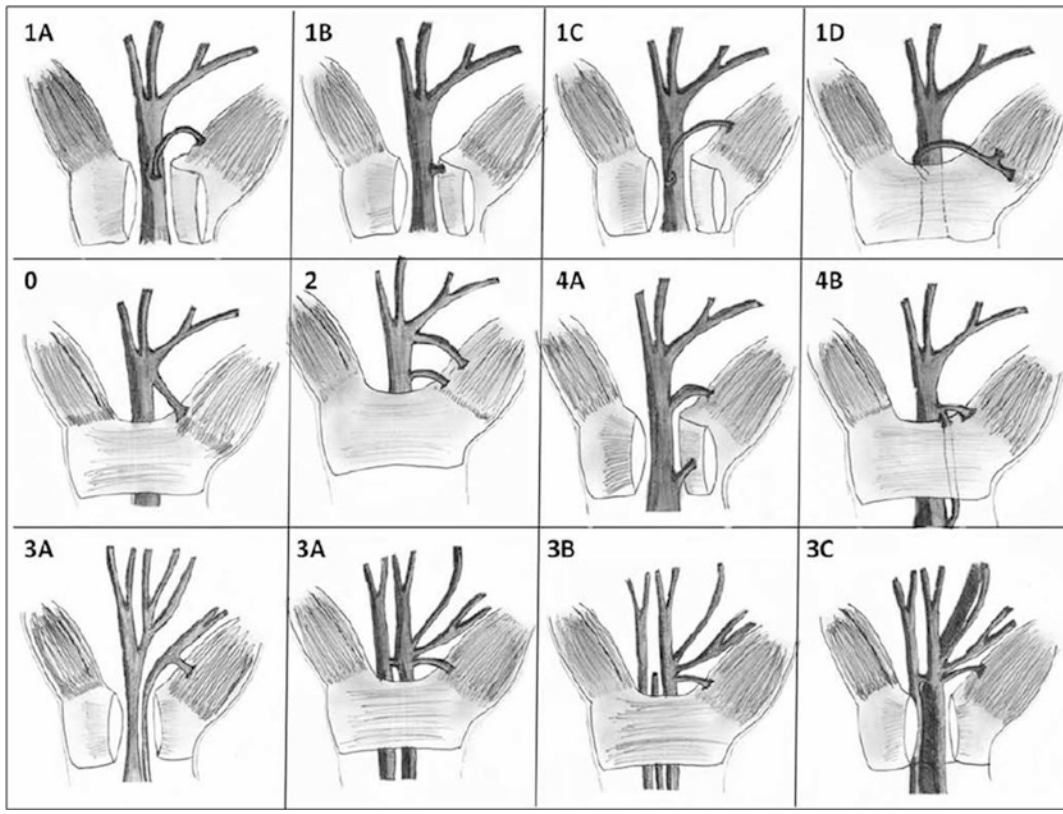

Fig. 1.1 Illustrations of median nerve anomalies in the carpal tunnel. Group 1 refers to thenar motor branch anomalies: (*A*) subligamentous, (*B*) transligamentous, (*C*) ulnar takeoff, or (*D*) supraligamentous. Group 0 refers to extraligamentous thenar motor branch. Group 2 refers to a distal accessory thenar branch. Group 3 refers to anomalies associated with high division of the median nerve: (*A*) without a persistent median artery or accessory muscle, (*B*) with a persistent median artery, or (*C*) with an accessory muscle. Group 4 refers to a proximal accessory thenar branch: (*A*) running directly into the thenar muscles or (*B*) joining another branch prior to reaching the thenar muscles. Figure and illustrations reproduced with permission from Demircay et al. [7]

radial aspect of the median nerve [10]. Variations in the origin and course of the thenar motor branch relative to the transverse carpal ligament were first described by Poisel [11]. In this original description, two anomalies were described: "subligamentous" (Fig. 1.1, 1A) in which the thenar motor branch originates beneath the transverse carpal ligament and "transligamentous" (Fig. 1.1, 1B) in which the thenar motor branch passes through the transverse carpal ligament. In his series of 100 specimens, Poisel reported that 46% were extraligamentous, 31% subligamentous, and 23% transligamentous [11].

This distribution of extraligamentous, subligamentous, and transligamentous branching patterns reported has been corroborated by other authors in both clinical and cadaveric series. Hurwitz published a series of 80 carpal tunnel releases in which the thenar motor branch was extraligamentous in 55%, subligamentous in 29%, and transligamentous in 16% [4]. In addition, 9% had an anomaly in which motor branch originated from the anterior aspect of the median nerve, coursed in an ulnar direction distally before coursing toward the thenar muscles superficial to the flexor retinaculum [4]. This anomaly was first described by Mannerfelt and Hybbinette and is associated with transversely oriented muscle fibers overlying the distal flexor retinaculum (most likely flexor pollicis brevis or abductor pollicis brevis) [4]. This "supraligamentous" course was included by Lanz in his classification (Fig. 1.1, 1D). In a cadaveric study of 60 specimens, Alizadeh et al. reported 47% of thenar motor branches were extraligamentous, 28% subligamentous, and 12% transligamentous [5]. Interestingly, the thenar branch originated from the ulnar aspect of the median nerve in 12% of specimens [5]. Lanz also included this anatomic variant in his classification (Fig. 1.1, 1C).

However, there has been debate in the literature regarding the incidence of these abnormalities—particularly the transligamentous and ulnar origin variants. The incidence of transligamentous branching has varied widely in the literature. Falconer and Spinner reported that 60% of ten cadaveric specimens had a transligamentous branching pattern [9]. On the other hand, Kozin reported that only 7% of 101 cadaveric specimens had a transligamentous branching pattern and concluded that previous studies had overestimated the incidence of transligamentous branching as a result of the close proximity of obliquely oriented fascia distally with the transverse carpal ligament [10]. Of note, Kozin did not observe any thenar motor branches originating from the ulnar aspect of the median nerve, and only 4% had multiple motor branches [10]. Similarly, in Lindley and Kleinert's clinical series of 526 carpal tunnel releases, only one patient had a thenar motor branch with an ulnar origin. Despite conflicting data on the incidence of the transligamentous and ulnar origin variants, awareness of all possible thenar motor branch anomalies is critical to prevent iatrogenic injury during carpal tunnel release.

Common Digital Nerves

Terminal branches of the median nerve include common digital nerves to the second and third web spaces. Engineer et al. described three variations of the third common digital nerve based on dissection of 20 cadaveric specimens (Fig. 1.2) [12, 13]. Type I originates proximal to the distal edge of the transverse carpal ligament and found in 15% of specimens. Type II originates distal to transverse carpal ligament, but proximal to the superficial palmar arch, and was found in 70% of specimens. Type III originates distal to the transverse carpal ligament and at (or distal to) the superficial palmar arch and was found in 15% of specimens [12]. Knowledge of type I third common digital nerve anatomy is critical to prevent iatrogenic injury during carpal tunnel release [12].

Palmar Cutaneous Branch

The palmar cutaneous branch arises from the volar/radial aspect of the median nerve 4.6 cm proximal to the distal transverse volar wrist crease [14]. Lindley and Kleinert noted two palmar cutaneous branch anomalies in their series of 526 open carpal tunnel releases. In one patient, the nerve pierced the flexor retinaculum and traveled with the median nerve, and in the second, the nerve originated ulnarly [1].

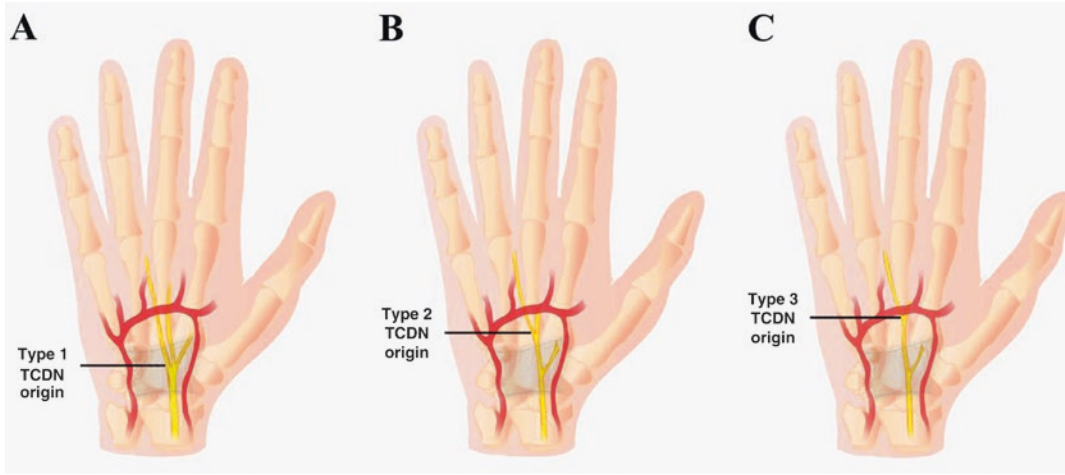

Fig. 1.2 Illustrations of variations in the origin of the third common digital nerve. (**a**) Type I originates from the median nerve within the carpal tunnel. (**b**) Type II originates distal to the transverse carpal ligament, but proximal to the superficial palmar arch. (**c**) Type III originates distal to the transverse carpal ligament and at/distal to the superficial palmar arch. Figure and illustrations reproduced with permission from Engineer et al. [12]

Median and Ulnar Nerve Anastomosis

The Martin-Gruber anastomosis consists of a branch of the median nerve crossing over to the ulnar nerve and has a variable incidence (10–23%) [15, 16]. Communicating branches between the ulnar and median sensory nerves distally have been described and are an important consideration during carpal tunnel release.

High Division of the Median Nerve

High division of the median nerve has been associated with separation by a persistent median artery, muscle belly of the flexor digitorum superficialis to the long or index finger, accessory palmaris longus tendon, and accessory lumbrical muscle [1, 2, 7, 8]. A subset of these anomalies was described by Lanz and compiled into Demircay et al.'s classification scheme (Fig. 1.1, 3). Lanz reported that 2.8% of 246 hands had a high division of the median nerve [8]. Lindley and Kleinert reported that 1% of median nerves exposed during 526 open carpal tunnel releases had a high division of the median nerve, which was frequently associated with a persistent median artery [1]. Amadio reported that 3.3% of median nerves had a high division [17].

Variable Course of the Median Nerve in the Carpal Tunnel

The course of the median nerve within the carpal tunnel is variable [7, 18]. The median nerve has either a straight or curved path within the carpal tunnel. If straight, the median nerve can either be in the middle of the flexor retinaculum (21.7%), deviated radially (43.3%), or deviated ulnarly (1.7%) [18]. If curved, the median nerve can either diverge in a radial (21.6%) or ulnar (11.7%) direction [18].

Summary

Hand surgeons need to be aware of the numerous anatomic variations that exist during carpal tunnel surgery. These variations can be responsible for inadvertent injury during routine surgical procedures.

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History of Carpal Tunnel Syndrome

2

Margaret E. Cooke and Scott F.M. Duncan

General Outline

- Before carpal tunnel syndrome was well understood, there was significant confusion as to pathophysiology that caused the classic sensory (paresthesias) and motor (thenar atrophy) symptoms. Three main ideas are developed to provide an explanation:
  - 1 = "post-traumatic" median nerve injury, usually seen in distal radius fractures with entrapment of the median nerve at the fracture site.
  - 2 = "acroparesthesia" attempted to explain only the sensory aspect of the syndrome with a lesion at the brachial plexus caused by compression of the plexus by cervical ribs.
  - 3 = "thenar neuritis" attempted to explain only the motor findings of thenar atrophy with a lesion at the motor branch of the median nerve at the border of the carpal tunnel.
- Finally, median nerve injury at the site of the carpal tunnel was determined to be the culprit, and surgical techniques emerged to increase the volume of the canal to relieve pressure on the nerve.

Carpal tunnel syndrome is a now relatively well-understood clinical phenomenon in which neuropathic symptoms are secondary to median nerve compression within the carpal tunnel. However it was not until the mid-1900s that the pathophysiology was sufficiently understood to provide a strong foundation for clinical care. Prior to this understanding, the symptoms of carpal tunnel syndrome were attributed to several different etiologies resulting in several different diagnoses. Three mechanisms were proposed to explain the symptomatology and physical findings: (1) entrapment of the median nerve at the site of an injury, such as the post-traumatic median neuropathy described in distal radius fractures; (2) compression of the lower trunk of the brachial plexus which was invoked to explain the sensory aspect of the syndrome, i.e., acroparesthesia; and (3) a lesion of the motor branch of the median nerve (e.g., thenar neuritis) as it passed beneath the anterior annular ligament of the wrist, which would explain the motor findings of thenar atrophy. It was only after understanding that the pathophysiology was related to compression of the median nerve at the level of the carpal tunnel that effective operative management emerged. The primary goal of operative treatment is to increase the volume of the carpal tunnel by releasing the transverse carpal ligament.

M.E. Cooke (✉)
Orhtopaedic Surgery, Boston Medical Center,
850 Harrison Avenue, Boston, MA 02118, USA
e-mail: Margaret.Cooke2@bmc.org

S.F.M. Duncan
Department of Orthopedic Surgery, Boston University/Boston Medical Center,
Boston, MA, USA

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Post-traumatic

One of the earliest reports of post-traumatic median neuropathy was described by Gensoul in 1836 [1]. He reported a case of direct injury to the median nerve by entrapment in an open distal radius fracture in an autopsy of a young girl who died of tetanus. Gensoul's description was followed by several others who described median nerve injury following distal radius fracture.

In 1854, Sir James Paget came very close to anticipating our current understanding of carpal tunnel pathophysiology in his *Lectures on Surgical Pathology* [2]. He described a case of median neuropathy that developed after a compression injury at the wrist. He noted that a "cord had been drawn very tight round this man's wrist seven years before the amputation of the arm. At this time it is probable the median and other nerves suffered injury." The second case that Paget described was a median neuropathy that developed after a distal radius fracture and resulted in ulcerations of his radial digits. He reports that these ulcers were "cured only by so binding the wrist that the parts on the palmar aspect being relaxed, the pressure on the nerve was removed. So long as this was done, the ulcers became and remained well; but as soon as the man was allowed to use his hand, the pressure on the nerves was renewed, and the ulceration of the parts supplied by them returned." It is clear through these descriptions that Paget recognized the pathologic effect of compression of the nerve at the wrist, as well as the therapeutic effect of relieving the pressure on the nerve.

In 1933, Abbott and Saunders published their classic cadaveric study that supported the notion that neuropathic symptoms may be due to increased pressure in the carpal tunnel [3, 4]. In this study, they injected dye into the forearm with the wrist held at different positions and described increased fluid resistance with acute flexion and ulnar deviation. The ability to manipulate the volume of the carpal canal and compression of the median nerve with varying wrist positions was an important discovery. This led to their recommendation to immobilize distal radius fractures with a neutral wrist position after fracture reduction, rather than the established Cotton-Loder position, which maintained the wrist in a flexed position.

This change in treatment was adopted and supported in the following years as more evidence mounted against immobilization with wrist flexion. In 1949, Meadoff recommended prevention of median neuritis after distal radius fracture with closed fracture reduction, neutral wrist immobilization, and surgical exploration of the median nerve with release of the transverse carpal ligament only after 4 months of failed conservative treatment [5].

Lynch and Lipscomb provided further support for this approach in their retrospective review of 600 patients with distal radius fractures followed for 10 years at the Mayo Clinic. In this cohort they found a 3.3% rate of associated carpal tunnel syndrome [6]. The majority of patients that developed carpal tunnel syndrome did so within 3 months of the inciting trauma. Two patients that were initially immobilized in full wrist flexion and ulnar deviation (Cotton-Loder position) immediately developed carpal tunnel syndrome requiring remanipulation of the wrist to a neutral position. Based upon their retrospective review and their surgical experience, these authors recommended conservative management with observation and neutral wrist positioning to treat median nerve symptoms, with surgical decompression reserved for severely symptomatic patients. As an alternative to incising the transverse carpal ligament, they noted the benefit of nonoperative treatment with steroid injections to decrease swelling. In their work, they were undoubtedly influenced by their Mayo colleagues P. S. Hench and E. C. Kendall who were awarded the Nobel Prize in Physiology or Medicine in 1950 for discovering the anti-inflammatory effects of corticosteroids [7].

Subsequent anatomical and physiological studies provided more evidence to support the surgical observations that wrist position was important in carpal tunnel pressures. An anatomical report in 1959 by Tanzier described compression of the median nerve with wrist and digit flexion as the long flexor tendons were displaced anteriorly [8]. In 1984 Gelberman quantitatively confirmed the effect of wrist position on carpal tunnel pressure [9]. Gelberman reported on the carpal tunnel pressures

of 22 patients with distal radius fractures. He found that the pressure increased 2.6-fold from neutral to 40 of wrist flexion and doubled with 20 of wrist extension. He concluded that with Colles' fractures the surgeon should avoid immobilization in significant flexion and that patients with acute carpal tunnel syndrome require operative decompression.

In 1987 Paley and McMurtry described nine case reports of distal radius fractures with volar displacement, eight of which developed acute or subacute median neuropathy [10]. They found the volar fragment 1 cm proximal to the transverse carpal ligament and displaced 1 cm volarly causing compression of the median nerve as it becomes more superficial to run through the carpal tunnel. They recommended treatment with reduction or removal of the volar fragment in addition to carpal tunnel release.

Acroparesthesia and Thenar Neuritis

Early reports described the sensory and motor findings of median nerve compression as separate entities: acroparesthesias and thenar neuritis. In the late 1800s, "acroparesthesia" became an accepted diagnosis to describe sensory alterations of the hand in the absence of motor dysfunction [11]. However, it would not be until the mid-1900s that acroparesthesia would be attributed to median nerve dysfunction and become synonymous with carpal tunnel syndrome.

In 1862 Raynaud attributed acroparesthesia to vasomotor dysfunction, although his description of the symptoms could be consistent with carpal tunnel syndrome: "a depressing sense of numbness and tingling… the tactile sense may be so much impaired that it is difficult for the fingers to retain small objects" [12]. In his initial thesis, Raynaud did not differentiate between vasospasm (what we call today Raynaud's disease) and fixed arterial occlusions (i.e., causing Raynaud's phenomenon). Each of these (vasospasm or fixed arterial occlusions) can reduce nutritive flow sufficiently that neurological function can be impaired. In either case, the impaired sensation in the fingers should also be associated with coolness, pallor, and/or cyanosis. Generally the acroparesthesia due to vasospasm is episodic (i.e., precipitated by stress or cold), although there are patients with persistent color changes (e.g., acrocyanosis) and numbness of the fingers in more severe cases of Raynaud's disease.

In Raynaud's era there were descriptions by others, including Gamberini, Romberg, Martin, Putnam, Schultz, and Handfield-Jones, of cases with a constellation of symptoms that we would recognize as idiopathic carpal tunnel syndrome today. In his 1855 case series of six female patients with nocturnal hand paresthesias, Handfield-Jones incorrectly postulated that the culprit was "brachial neuralgia" [11]. Similarly, "cervical rib syndrome," compression of the brachial plexus by a cervical rib, was popularized by Farquhar Buzzard, Physician Extraordinary to His Majesty the King, as a syndrome secondary to C7 nerve root compression leading to both thenar atrophy and sensory changes of the digits. This concept persisted and led to the recommendations of Farquhar Buzzard in 1913 that these patients should be treated with rib resection to relieve pressure on the brachial plexus [11, 13].

While "acroparesthesia" was used to describe the sensory symptoms of median nerve symptoms, James Ramsay Hunt coined the term "median thenar neuritis" in 1909 to denote the neuromuscular manifestations, e.g., thenar weakness and atrophy. He posited that this condition was caused by isolated compression of the motor branch of the median nerve at the border of the transverse carpal ligament [14, 15]. Hunt was followed by several others who described wasting of the thenar muscles. One of which was Harris who in 1926 attributed the cause of compression to work-related activities, like pressing a tool's handle into the palm [14]. In 1944, Barker and Hines would be the first to describe occupational arterial occlusive disease of the hand, associated with pallor, pain, paresthesia, and occasionally ulcerations of the fingers, an entity that can mimic carpal tunnel syndrome [16].

Although Marie and Foix described median nerve compression as the etiology for both sensory and motor dysfunction in 1913, it was not widely accepted until decades later. In 1938, Moersch described a case of spontaneous median

nerve compression, though he suggested that there were two lesions, one at the motor nerve branch and a second at the carpal tunnel [15]. In 1941 Woltman was the first to describe spontaneous median nerve compression by crowding of soft tissue structures in the carpal tunnel [15]. Zabriskie deduced that the sensory and motor findings were likely part of the same pathology, implicating median nerve compression at the transverse carpal ligament [15]. This directed the goal of treatment to relieving carpal tunnel pressure by releasing the transverse carpal ligament. This approach was anticipated in 1913 by Marie and Foix who were among the first to suggest surgical release of the transverse carpal ligament for resolution of symptoms. They were followed shortly by Cannon and Love who published a report of nine patients that had resolution of median neuropathy after surgical resection of the transverse carpal ligament [11, 17].

Despite this work, brachial plexus compression, usually from a cervical rib, was still the most common diagnosis for carpal tunnel syndrome. Finally, in 1947, Brain and Wilkinson published the first paper describing the pathophysiology of spontaneous median nerve compression in the carpal tunnel. They further clarified that the sensory changes and associated thenar atrophy "can be caused only by a median nerve lesion and not a lesion involving the brachial plexus" [15]. Moreover, they proposed treatment with early operative release of the transverse carpal ligament. While Brian is often acknowledged for this landmark paper, Phalen popularized our current understanding of the pathophysiology of carpal tunnel syndrome in several clinical descriptions in the early 1950s [18]. The term "carpal tunnel syndrome" was first used in print by Kremer in 1953.

Conclusion

Astute observations of early physicians anticipated our current understanding, which was based upon anatomical and physiological studies of the carpal tunnel, and careful surgical series that linked anatomy and physiology to the symptom complex. Once the pathophysiology of carpal tunnel syndrome had been elucidated, improved diagnostic aids and therapeutic approaches were developed. Currently, electromyography and nerve conduction studies may be used to confirm the diagnosis and quantify the severity of the pathology. Metabolic causes of carpal tunnel syndrome (e.g., hypothyroidism) should be considered, and other conditions that can mimic carpal tunnel syndrome including occupational arterial occlusive disease and Raynaud's disease should be excluded.

With an understanding of the pathobiology, surgical treatment has improved. Herbert Galloway performed the first carpal tunnel release in 1924. Open carpal tunnel ligament release was first described as a 4–5 cm curved longitudinal inter-thenar incision with release of the transverse carpal ligament under direct vision. Several modifications have since been made, including the length, location, and shape of the incision. Endoscopic carpal tunnel release was popularized in 1987 by Okutsu. Modifications to endoscopic techniques include single-portal (Agee) versus two-portal (Chow) surgical techniques. Jimenez published a description of six different endoscopic techniques for the carpal tunnel release. More recently, a Cochrane database study revealed no significant evidence favoring endoscopic release over open release [19]. With respect to conservative treatment strategies, in addition to night splints, other adjunctive strategies include steroid injections and anti-inflammatories.

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Pathophysiology of Carpal Tunnel Syndrome

3

Scott F.M. Duncan, Oam Bhate, and Hatim Mustaly

Abbreviations

BMI	Body mass index
CTS	Carpal tunnel syndrome
IGF-1	Insulin-like growth factor 1
IL-6	Interleukin 6
mRNA	Messenger ribonucleic acid
NCS	Nerve conduction studies
PGE2	Prostaglandin E2
TMNST	Tethered median nerve stress test
VEGF	Vascular endothelial growth factor
VGSC	Voltage-gated sodium channel

Introduction

Carpal tunnel syndrome, the most prevalent chronic peripheral nerve compression syndrome, is a suite of symptoms caused by localized median nerve compression at the wrist. The incidence of carpal tunnel syndrome is 99 per 100,000 individuals, and it is most common in patients over 40 years of age [1, 2]. Between 65% and 75% of cases are female patients [3]. Compression of the median nerve as it passes under the transverse carpal ligament in the carpal tunnel leads to mechanical compression and local ischemia, causing the median nerve to be impaired in the carpal canal [4, 5]. Carpal tunnel syndrome can manifest clinically with subjective signs such as paresthesia, proprioceptive alterations, and paresis, as well as objective signs, such as alterations in sensitivity and motor function, positive Tinel and Phallen tests, and atrophy of the thenar eminence [6]. The diagnosis of carpal tunnel syndrome is based on the classical symptoms of pain, numbness, tingling, and/or burning in the median nerve distribution in the hand, as well as abnormal median nerve function tested by Nerve Conduction Studies (NCS) [7]. Reported MRI findings in patients with carpal tunnel syndrome include swelling and flattening of the median nerve in the carpal tunnel, increased signal intensity on T2-weighted images as a result of edema, and palmar bowing of the flexor retinaculum [8, 9]. Its pathophysiology has not been fully elucidated, but the most probable causes are those associated with mechanical injury in the carpal tunnel, including ischemia, mechanical trauma, ectopic impulse generation, demyelination, tendonitis, and increased carpal tunnel pressure [5]. The majority of the current knowledge of the pathophysiology of compression-related neuropathies is derived from animal studies; however, a few

S.F.M. Duncan (✉)
Department of Orthopedic Surgery, Boston University/Boston Medical Center, Boston, MA, USA
e-mail: duncan.academic@gmail.com

O. Bhate • H. Mustaly
Boston University School of Medicine, Boston, MA, USA
e-mail: obhate@bu.edu; hatimv@bu.edu

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pressure-related studies of the carpal tunnel in humans have been performed [10–12]. Interpreting the data from these studies is challenging since it requires an understanding of the relationship between acute and chronic nerve injury [5].

Early on, the pathology resulting from chronic nerve compression is caused by breakdown of the blood-nerve barrier. This is followed by endoneurial and subperineurial edema. After that, the connective tissue layers that comprise the perineurium and epineurium thicken, and fibrosis occur. Organized fibrosis in the subperineurial space may result in the formation of Renault bodies; this could be related to repetitive movement and traction of the nerve. Subsequently, localized segmental nerve fiber demyelination occurs, especially of large nerve fibers. In advanced stages of progressive compression, severe diffuse demyelination and injury occur to both myelinated and unmyelinated fibers, eventually leading to Wallerian degeneration of the nerve fibers. Nerve fascicles located nearer to the site of compression undergo changes earlier than more distantly located nerve fascicles. These pathological changes depend on the amount and extent of the compressive forces [13]. Rydevik et al. [14] utilized a rabbit tibial nerve to examine the effect of graded compression on intraneural blood flow. It was found that an external pressure of 20 mmHg resulted in a reduction of venule blood flow, 30 mmHg caused axonal transport to be inhibited, and 80 mmHg caused intraneural blood flow to cease entirely. The impacts of prolonged nerve compression on nerve function have also been examined. The effects of different pressures (10, 30, and 80 mmHg) over various durations (4 h to 28 days) were studied in a rat model. It was found that subperineurial edema, inflammation, and the formation of fibrin deposits occur within hours and that fibrous tissue proliferation occurs within days; by 28 days, fibrosis was reported. Damage to axons was found at higher pressures of 80 mmHg [15]. Nerves with larger amounts of connective tissue and fewer fascicles might be better protected from compressive injury and might undergo the neural changes caused by compressive injury slower than nerves with less connective tissue [16].

Upton and McComas [17] proposed the "double crush" hypothesis. The authors proposed that proximally located nerve compression might result in increased susceptibility of distal sites to compression, as they found that there is a high incidence of carpal and cubital tunnel syndromes with associated cervical root lesions. Summation of compression along the nerve can cause changes in axoplasmic flow, leading to subsequent pathology [13].

Certain systemic diseases including diabetes, thyroid disease, alcoholism, and various arthritic states can cause peripheral neuropathies and increased susceptibility to nerve compression [13].

Vibration can also cause peripheral neuropathy [13]; several studies have shown an association between vibratory exposure and peripheral neuropathy [18–21]. The histological changes associated with vibration exposure are similar to those seen in compression neuropathy; intraneural edema, demyelination, and eventually axonal loss occur [21]. A strong association has been discovered between exposure to vibration and development of compression at the carpal tunnel [22].

Acute carpal tunnel syndrome is usually a result of trauma; it is the result of an acute elevation of the pressure in the carpal tunnel. This causes the epineural blood flow to be compromised, resulting in pain and dysesthesias in the median nerve distribution [4].

Anatomy

The carpal tunnel is a narrow U-shaped structure in the wrists. The bottom and the sides of the carpal tunnel are formed by the carpal bones. The roof of the canal is formed by a strong fibrous connective tissue band known as the flexor retinaculum (transverse carpal ligament) which attaches to the tubercle of the scaphoid, the ridge of the trapezium, and the ulnar aspect of the hook of the hamate and the pisiform. Nine flexor tendons that control the bending of fingers pass through the carpal tunnel. The median nerve, which controls the sensation of the thumb, index fingers, long fingers of the palmar side, and the muscles of the base of the thumb, passes through the carpal tunnel (Fig. 3.1). Other supporting structures called the extensor retinaculum exist on the dorsal wrist and a volar carpal retinaculum which exists on the volar side [5].

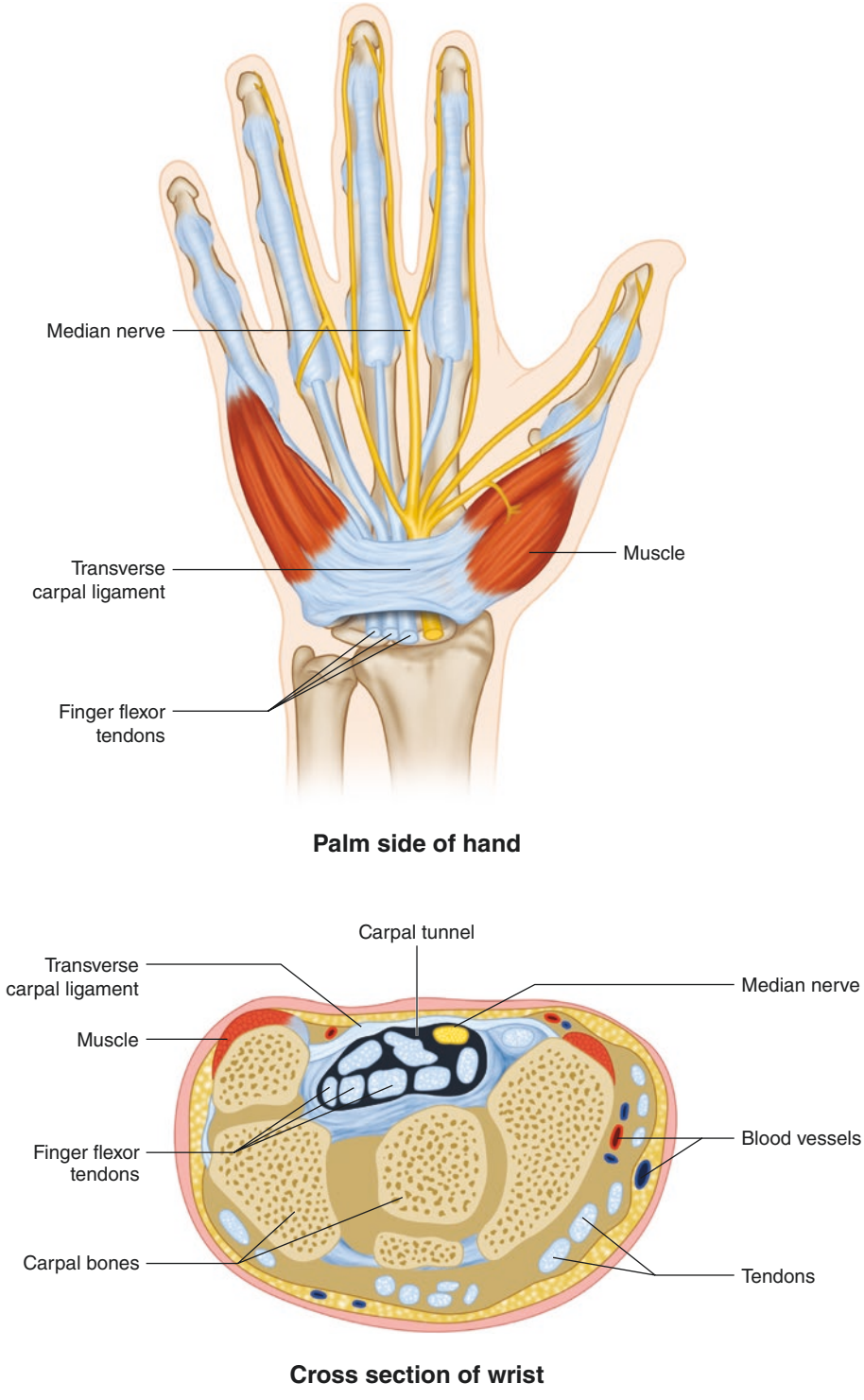

Fig. 3.1 Anatomy and cross section of carpal tunnel showcasing the underlying structures

Increased Pressure

Normal pressure in the Carpal tunnel ranges from 2 to 10 mmHg [23]. Changes in the wrist position or application of external forces can lead to increased pressure resulting in nerve entrapment and injury. It is not completely clear how the carpal tunnel pressure rises over time and as a result of wrist position. Within the carpal tunnel, pressure can be exerted on the median nerve both as a result of the hydrostatic pressure of the carpal tunnel interstitial fluid and as a result of direct contact between the median nerve and adjacent tissues [5]. The hydrostatic pressure may become elevated over time due to a combination of synovial tissue hypertrophy and the space constraint of the carpal tunnel [12]. Cadaver studies have shown that the most significant hypertrophy of the synovial tissue occurs at the entrance and exit of the carpal canal, where the tendons slide over the flexor retinaculum, using it as a pivot [24]. As wrist position changes, the hydrostatic pressure in the carpal tunnel is altered significantly; wrist extension causes a tenfold rise in the pressure, while wrist flexion results in an eightfold rise in the pressure [11, 12].

Extension of the wrist causes the compression of the extensor retinaculum on the dorsal side and an increase in spacing of the volar carpal ligament on the volar side. This increase in spacing causes the volar carpal ligament to squeeze against the volar surface of the carpal bones causing an increase in the pressure in the carpal tunnel. In wrist flexion, the flexor retinaculum presses the flexor tendons and the bursa against the head of the radius. This results in an increase in fluid pressure. In addition to the fluid pressure, the movement of flexor tendons causes friction affecting the median nerve [5].

The musculature surrounding the carpal tunnel is also known to play a role in increasing the pressure and causing entrapment of the median nerve. The lumbrical muscles, which are four small intrinsic muscles, are involved in intricate movements of the fingers. The lumbricals originate proximally from the flexor digitorum profundus and attach distally to the extensor expansions. Several reports have shown that the proximal attachments of the lumbrical muscles can be varied. Thus, if the lumbrical muscles originate closer to the transverse carpal ligament, their hypertrophy due to repetitive movement of the fingers can result in increased pressure in the carpal tunnel [25].

The palmaris longus is a weak wrist flexor muscle that is not present in a large minority of the human population. It has been hypothesized that the presence of a palmaris longus tendon may be an independent risk factor for the development of carpal tunnel syndrome [26]. Jafari et al. [27] found a statistically significant association between the development of carpal tunnel syndrome and the presence of a palmaris longus tendon. The shape and volume of the carpal tunnel might be affected by the presence of the palmaris longus, most notably when the wrist is extended under load [28]. It has been shown by a biomechanical study that the carpal canal fluid pressure is elevated by palmaris longus loading more than by any other tendon that passes through the carpal tunnel, provided that the palmaris longus is loaded beyond 20° of extension. When extended, the palmaris longus vector pulls the transverse carpal ligament in the direction of the median nerve (Fig. 3.2). The insertion of the palmaris longus into the palmar fascia that overlies the carpal tunnel likely exerts a pressure effect on the carpal tunnel, resulting in a predisposition to carpal tunnel syndrome [29].

Nerve Injury

Compression of the median nerve, due to mechanical forces, results in its demyelination ([30]; Fig. 3.3). In order for a focal demyelination to occur, pressure more than the systolic is required [23]. The demyelination not only occurs at the particular spot but also spreads to entire internodal segment. This results in a block of nerve transmission called neuropraxia.

Persistent compression can lead to a decrease in blood flow to the surrounding endoneurial capillary system and changes in the blood-nerve

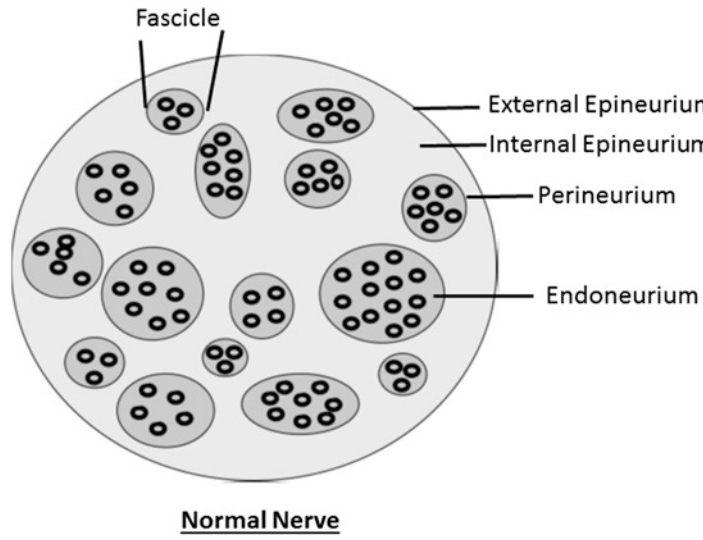

Fig. 3.2 Diagrammatic representation of the cross section of a peripheral nerve showing the connective tissue component

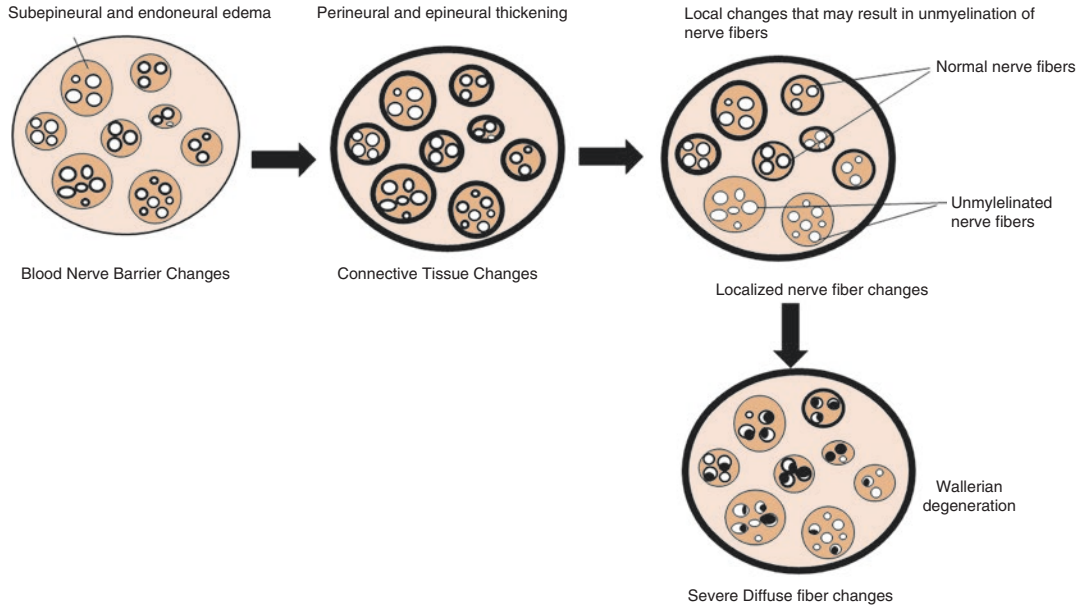

Fig. 3.3 Diagrammatic illustration of the internal changes in a nerve due to chronic nerve compression

barrier and endoneurial edema ([30]; Fig. 3.3). Decreased blood flow causes local ischemia and metabolite changes, whereas breach in the blood-nerve barrier can cause infiltration of inflammatory cells and proteins that can result in endoneurial edema. These factors can ultimately cause neuritis and result in axonal degeneration [23].

Nerve Tethering

The median nerve moves up to 9.6 mm during wrist flexion and slightly less during extension [31]. Nerve movement is crucial for normal physical activity; if nerve gliding is impaired, pain or

discomfort may result [13]. Nerve gliding prevents nerves from sustaining injury due to excessive stretch during joint movement and is dependent upon the extensibility of the layers of connective tissue that surround the nerve fibers, namely, the endoneurium, mesoneurium, perineurium, and epineurium [32]. When the median nerve is chronically compressed, fibrosis occurs, resulting in the inhibition of nerve gliding. This causes injury to the mesoneurium and subsequent formation of scar tissue. Mesoneural scarring results in the median nerve adhering to surrounding tissue and leading to traction of the median nerve during wrist motion as the median nerve attempts to glide from this immobilized position [33]. The tethered median nerve stress test (TMNST) is based on this and may be useful for the diagnosis of chronic low-grade carpal tunnel syndrome [34].

Involvement of Small Fibers

Arendt-Neisen et al. [35] attempted to measure the involvement of thin afferent nerves (which transmit pain signals) in carpal tunnel syndrome patients. They showed that the threshold of pain was increased in the third digit (innervated by the median nerve) as compared to the threshold of pain in the fifth digit (innervated by the ulnar nerve) in patients with carpal tunnel syndrome but not in controls, suggesting that small fibers are injured in carpal tunnel syndrome [5].

Small unmyelinated C fibers are also shown to be responsible for the various symptoms of the carpal tunnel syndrome. The transmission of pain signals through the unmyelinated C fibers is modulated via voltage-gated sodium channels (VGSC). Damaged C fibers cause an abnormal expression of VGSC that result in exaggerated ectopic responses to stimuli. These spontaneous firings result in a sensation of pain [36].

Breakdown in the Blood-Nerve Barrier

In the CNS, there is a highly selective semipermeable barrier formed by capillary endothelial cells connected to each other by tight junctions. It effectively separates the blood in the capillaries of the CNS from the CNS interstitial fluid. It allows certain substances, such as water, gases, and hydrophobic molecules to enter the interstitial fluid, along with other compounds essential for neuron survival such as glucose and amino acids. However, it prevents most other substances (including most pharmacological therapeutic agents) from entering the interstitial fluid of the CNS, thus providing a protective function preventing potentially toxic substances from entering and damaging the vital CNS.

Similarly, there is a "blood-nerve barrier," formed by the inner cells of the perineurium and the tight junctions of the endothelial cells of the endoneurial microvessels that branch off the radial and ulnar arteries proximal to the flexor retinaculum, regulating the intraneural environment and providing immunologic protection for the median nerve as it passes through the carpal tunnel. When nerve injury occurs, the blood-nerve barrier can break down at the level of the microvessels, resulting in an elevation of the intrafascicular pressure. Since there is no lymphatic circulation in the endoneurial space, edema can result subsequently, interfering with the microcirculation in the nerve fascicles [37]. Leaking capillaries in the endoneurium eventually allow proteins and fluid to enter the area and accumulate. This may cause a "mini compartment syndrome" of sorts as the pressure increases in the endoneurial space; eventually local ischemic damage to the nerve may occur [13]. The risk of blood-nerve barrier injury is especially high in patients with pre-existing vascular conditions or prolonged exposure to static loading [23].

Ischemic Injury

Gelberman et al. [10] demonstrated that the symptoms of carpal tunnel syndrome improve quickly following surgical carpal tunnel release, thereby implicating ischemic injury as an important component in carpal tunnel syndrome. Ischemic injury combined with an increase in mechanical contact pressure over time effects changes in the nerve fiber myelin sheath and causes axonal injury, which may be detected using neurophysiologic

testing like standard nerve conduction studies (NCS) [5]. However, in the absence of focal contact pressure, ischemia injures the axons but does not injure the myelin [14, 38]. In the early stages of focal ischemia, physiological impairment of nerves occurs in the absence of histological changes [38]. In the early stages of compression, venous outflow is obstructed. Therefore, the nerve becomes hyperemic and edematous; this might have particular importance in carpal tunnel syndrome pathogenesis. Sunderland [39] hypothesized that external pressure leads to a decrease in venous return. This would lead to the pressure rising in the area of entrapment as blood accumulates, ultimately leading to a blockage of flow in the vasa nervorum and leading to ischemia. Ischemic damage in compression neuropathies begins with elevated intrafunicular pressure, followed by capillary injury resulting in leakage and therefore edema, and finally results in blockage of arterial flow [5]. Lundborg et al. [40] showed that externally compressing the carpal canal causes the pressure inside the carpal canal to be elevated. When external pressure was applied to the carpal canal, subjects reported paresthesia-like symptoms followed by neurophysiologic changes; these symptoms and neurophysiologic abnormalities (attributed to conduction block) disappeared as soon as the external pressure was removed. However, if a blood pressure cuff on the upper arm was inflated to or above arterial pressure, the symptoms and neurophysiologic changes remained even after release of the compressive force on the carpal tunnel. Therefore, Lundborg et al. showed that ischemia, as opposed to mechanical deformation, was the primary cause of nerve fiber functional deterioration under pressure [5, 40].

Inflammation/Synovial Tissue Pathology

When carpal tunnel syndrome was first described, tenosynovitis was considered to be an important cause [5]. Repetitive motion of the hand may result in inflammation or hypertrophy of the synovial lining of the tendons that run through the carpal tunnel with the median nerve [12, 24]. This may contribute to median nerve compression [3, 41]. Hirata, H et al. showed that levels of interleukin-6 (IL-6), prostaglandin E-2 (PGE_2), and vascular endothelial growth factor (VEGF) were increased in CTS patients (2004). IL-6, PGE2, and VEGF are known to stimulate fibrogenesis (Meager 1986). Therefore, upregulation of these factors causes an increase in fibroblast density, type III collagen, and vascular proliferation [42]. These changes cause the total tissue volume in the carpal canal to increase thereby causing an increase in the baseline and mechanical pressures in the carpal tunnel [5].

Age

Altinok and Karakas [43] found a very strong correlation between age and bowing of the flexor retinaculum, the connective tissue sheath covering the carpal tunnel. Since Sarria et al. [44] suggested that bowing of the flexor retinaculum could be used as a diagnostic criterion for carpal tunnel syndrome, it is possible that age-related changes in the flexor retinaculum may be involved in the etiology of carpal tunnel syndrome. The mechanism behind age-related changes in the flexor retinaculum is unclear. They might be explained by an increase in the volume of the carpal tunnel in older people, although the mechanism of this is also unclear [45]. The presence of the carpal bones on the dorsal side of the carpal tunnel might prevent the contents of the carpal tunnel from extending dorsally, causing the flexor retinaculum to be pushed out by the enlargement of the tunnel contents. Another possibility is age-related laxity of the flexor retinaculum, which, if true, may itself cause an increase in the tunnel's volume [43]. It is possible that age-related collagen changes in the flexor retinaculum might cause the elasticity thereof to be decreased as individuals age. As a result, flexor retinaculum in older patients would be less likely to accommodate volume changes without increasing the pressure. This would therefore mean that any increase in the volume of the carpal tunnel contents in older patients would be more likely to cause the pressure in the carpal tunnel to increase than in younger patients, thereby making older patients more susceptible to carpal tunnel syndrome.

Gender

Women have a two- to threefold higher risk of developing carpal tunnel syndrome than men [46]; their risk is especially elevated around menopause. Therefore, it is suspected that female hormones may play a role in the high incidence of carpal tunnel syndrome in women [47]. This is further supported by the fact that the development of carpal tunnel syndrome has been reported to be linked to a large number of pregnancies [48], early menopause [49], bilateral oophorectomy [50], use of oral contraceptives [51], aromatase inhibitors [52], and hormone replacement therapy [51]. Additionally, it has been reported that estrogen receptor alpha is present in the transverse carpal ligament and in the flexor tenosynovium [53], and it has been demonstrated that the upregulation of estrogen receptors in tenosynovial tissue is associated with carpal tunnel syndrome in postmenopausal women [54]. It is known that estrogen regulates collagen synthesis and fibroblast proliferation [55]. When the collagen composition of tenosynovial tissue is altered, tissue compliance changes. This elevates the risk of shear injury of the tenosynovial tissue by the flexor tendons during finger motion [56]. It has been reported that estrogen receptors alpha and beta in the fibroblasts and synovial lining cells of the tenosynovium have higher immunoreactivities in patients with carpal tunnel syndrome than in controls. This could explain the relationship between female hormones and carpal tunnel syndrome pathogenesis. On the other hand, no correlation was seen between symptom severity and estrogen receptor expression in tenosynovial tissue [54].

A strong association exists between carpal tunnel syndrome and female gender; this has been proposed to be due to their smaller wrist and hand size [57]. Chiotis et al. [58] found that patients with carpal tunnel syndrome had larger carpal tunnel cross-sectional areas than those without carpal tunnel syndrome. They showed that a more circular carpal canal was linked to the development of carpal tunnel syndrome and suggested that a more circular carpal canal may somehow change the effect of elevated carpal canal pressure on the median nerve. It was found that in carpal tunnel syndrome patients, the contents of the tunnel took up a greater percentage of the tunnel's cross-sectional area than in those who do not have carpal tunnel syndrome, implying that carpal tunnel syndrome patients have "more" contents in the carpal tunnel than patients without carpal tunnel syndrome; this would fit with a higher pressure [59]. Sassi and Giddins [60] found that the relative cross-sectional area of the carpal tunnel in women is significantly smaller than in men. This means that while women have smaller carpal tunnels than men just because they have smaller hands, their carpal tunnels are actually disproportionately smaller than men's even taking into account their smaller hands [60]. This suggests that carpal canal size may have importance in the development of carpal tunnel syndrome.

Genetic Component of Carpal Tunnel

Multiple studies have shown that genetic factors play a major role in the development and risk of carpal tunnel syndrome [61–63]. It has been hypothesized that pathology of the flexor tendons and the subsynovial connective tissue play a role in the development of carpal tunnel syndrome [64, 65]. This is supported by the fact that sequence variants in the gene that codes for the alpha-1 chain of type V collagen, a part of the collagen fibril, the basic structural unit of tendons, have been demonstrated to affect risk of developing carpal tunnel syndrome [66]. Sequence variants in other collagen genes have also been shown to increase the risk of developing carpal tunnel syndrome [67]. A certain allele has been shown to be associated both with carpal tunnel syndrome [67] and with increased degradation of mRNA's encoding the alpha-1 chain of type XI collagen [68]. This suggests that decreased alpha-1 chain production, and therefore decreased type XI collagen synthesis, may be involved in the development of carpal tunnel syndrome [69]. Since types V and XI collagen both regulate the assembly and diameter of collagen fibrils, variation in the genes that encode them might change the mechanical properties of tendons and other extracellular structures in the

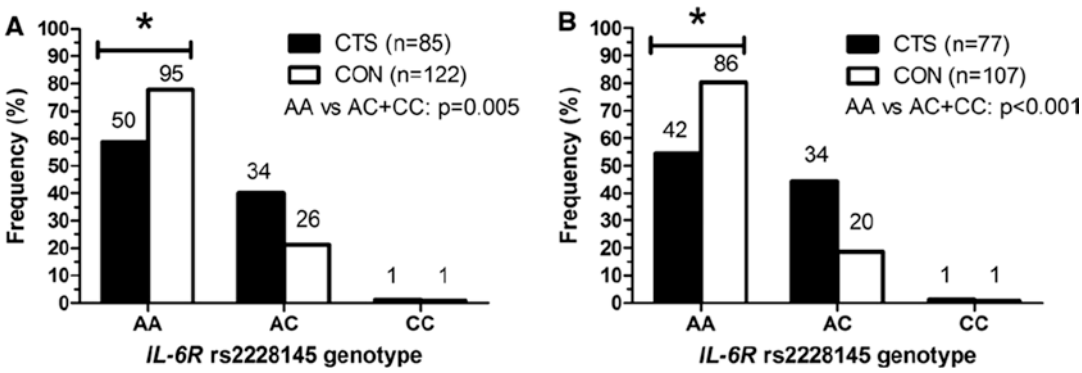

Fig. 3.4 Genotype frequency distributions of IL-6R rs2228145. "A" shows the results for all particiants; "B" shows the results for female participants only. *IL-6R* interleukin-6 receptor, *CTS* carpal tunnel syndrome group, *CON* control group, *Asterisk* significant difference

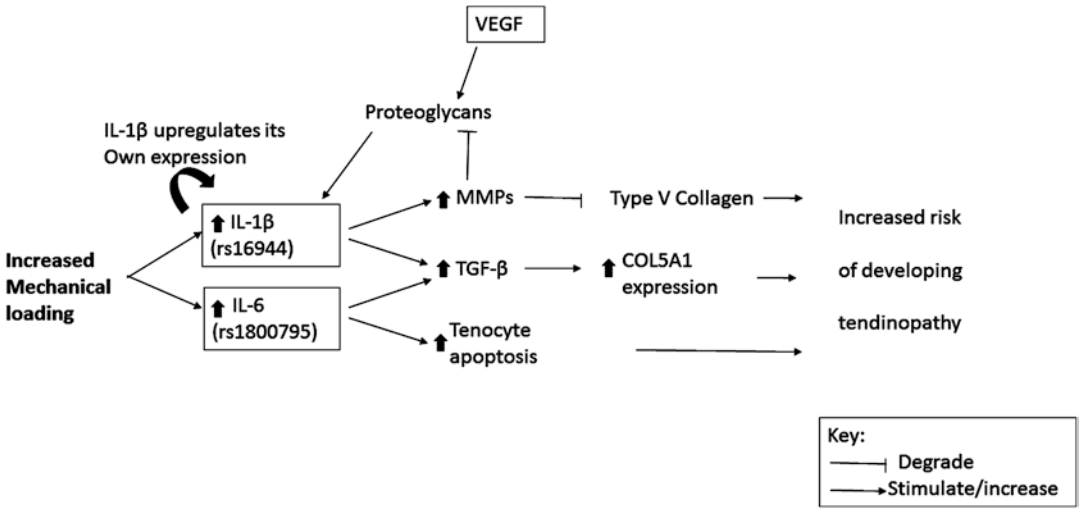

Fig. 3.5 Proposed pathway through which increased mechanical loading can modulate the risk of tendinopathy. *IL-6* interleukin-6, *IL-β* interleukin-1B, *MMP* matrix metalloproteinase, *VEGF* vascular endothelial growth factor (Figure taken from [61])

carpal tunnel, which may be implicated in the development of carpal tunnel syndrome. Another allele variant was found to be significantly associated with increased risk of carpal tunnel syndrome in females [67].

Additionally, a certain genotype of an interleukin-6 receptor gene was found to be independently associated with reduced risk of carpal tunnel syndrome, while other genotypes of the same gene were found to be associated with elevated risk of developing carpal tunnel syndrome. Certain variants of interleukin-1-beta and interleukin-6 genes were found to interact with the aforementioned interleukin-6 receptor gene to modulate the risk of developing carpal tunnel syndrome. This therefore suggests that the risk of developing carpal tunnel syndrome is associated partly by gene-gene interactions in cytokine signaling cascade. A certain allele of a regulatory interleukin-6 DNA sequence variant was found to be associated with elevated risk of developing carpal tunnel syndrome ([61]; Fig. 3.4). This allele is associated with decreased interleukin-6 expression, leading to low plasma interleukin-6 levels, and is hypothesized to lead to decreased tenocyte apoptosis ([70]; Fig. 3.5).

Familial Carpal Tunnel Syndrome

Numerous studies have indicated that carpal tunnel syndrome tends to run within families [71–77]. This trend is associated with a variety of defects, ranging from systemic biochemical anomalies to heritable structural aberrations of the carpal tunnel itself [78]. Biochemical alterations associated with familial carpal tunnel syndrome include various point mutations that yield transthyretin variants, resulting in familial amyloidosis polyneuropathy [76, 77]. Systemic disorders associated with the development of carpal tunnel syndrome include inheritable myopathies [71] and familial hypercholesterolemia [74]. One often reported structural aberration associated with familial carpal tunnel syndrome is a thickening of the transverse carpal ligament [72]; this includes one report of a median nerve aplasia distal but not proximal to a thickened transverse carpal ligament in a child with three immediate family members having the same abnormality [75]. Congenitally small carpal tunnel, distal prolongation of the superficial flexor muscle bellies, anomalous muscles, and anomalous paths of the medial artery and median nerve branches are some structural alterations associated with familial carpal tunnel syndrome [73]. There is quite a bit of disagreement over whether or not carpal tunnel syndrome is inheritable [78]. Tanzer [79] described carpal tunnel as a "familial trait" in 18% of surgical patients. Phalen [3] concluded that "there is probably some familial predisposition to carpal tunnel syndrome." Danta [72] reported that children with carpal tunnel syndrome often had a family member with the same symptoms as the child (Table 3.1). While Stevens et al. [48] failed to find a familial trend in carpal tunnel syndrome, Radecki [80] demonstrated an increased incidence of family occurrence in carpal tunnel syndrome patients. Alford et al. [78] found a high incidence of familial carpal tunnel syndrome in patients with bilateral carpal tunnel syndrome, which may suggest either a systemic biochemical anomaly or a heritable anatomical variation in the size of the carpal tunnel or the size of its contents. However, they were unable to rule out environmental factors as a cause of familial carpal tunnel syndrome [78].

Table 3.1 Factors that contribute to carpal tunnel syndrome

Age
Gender
Genetics
Body mass index
Medical conditions
Diabetes
Thyroid dysfunction
Acromegaly
Rheumatoid arthritis

Obesity

Obesity, as measured by increased BMI (body mass index), has been associated with increased risk and increased severity of carpal tunnel syndrome ([81]; Table 3.2). Kouyoumdjian et al. [85] found that higher BMI increases the risk of developing carpal tunnel syndrome, but is not correlated with the severity thereof. Werner et al. [83] showed that patients with BMI greater than 29 had a risk of carpal tunnel syndrome that was 2.5 times higher than the risk for slender individuals (BMI < 20). Dieck and Kelsey [82] identified recent weight gain as a possible risk factor for carpal tunnel syndrome; this supports the idea that fluid retention in the soft tissues of the carpal tunnel somehow contributes to the development of carpal tunnel syndrome. It has been suggested that individual characteristics such as BMI, age, wrist dimensions, and hand dominance are more important in determining one's risk of developing carpal tunnel syndrome than work-

Table 3.2 Comparison of BMI in CTS and controls in four articles

	BMI/CTS	*n*	BMI/controls	*n*
Dieck and Kelsey [82]	27.0	40	25.0	1043
Werner and Albers [83]	28.90 ± 6.80	261	26.20 ± 6.00	688
Stallings et al. [84]	30.15 ± 7.49	300	25.96 ± 5.04	300
Kouyoumdjian et al. [85]	28.38 ± 4.69	141	25.43 ± 4.80	343

BMI body mass index, *CTS* carpal tunnel syndrome, *n* number

related factors. In fact, it was found that BMI can be used to accurately predict which industrial workers would develop median nerve slowing [86]. Radecki [87] demonstrated that prolongation of median latencies was associated with increased BMI regardless of whether or not the symptoms were considered work related. The exact pathophysiology behind this result is still not well understood. It has been suggested that the cause-effect relationship between increased BMI and the development of carpal tunnel syndrome could be due to an increase in the amount of fatty tissue present inside the carpal canal or due to elevated fluid pressure in the carpal canal in obese individuals [83]. Radecki [87] stated that individuals with increased BMI have increased translocated blood volume from the legs after lying down. This extra volume must go somewhere other than the thorax; if it goes into the arms, an elevated blood volume in the arms while lying down would cause the veins of the flexor synovial tissue and cause tissue pressure in the carpal tunnel to become elevated. Such synovial engorgement explains both the noninflammatory edema and elevated mean tissue pressures above critical pressure in the carpal tunnels of patients who have carpal tunnel surgery. Sustained increase in the carpal tunnel hydrostatic pressure can result in impaired blood circulation resulting in ischemia, local demyelination, and axonal loss. In addition, the sustained pressure can result in fibrosis and thickening of the subsynovial connective tissue and canal [88]. Furthermore, obesity is one of the components of metabolic syndromes that can result in peripheral neuropathy. Mechanisms by which obesity and metabolic syndrome can cause nerve injury include fatty deposits in the nerves, oxidative stress, mitochondrial dysfunction, and glycation of extracellular proteins. Neuropathy causes the median nerve to be more vulnerable to compression within the carpal tunnel [89].

Diabetes and Carpal Tunnel Syndrome

Carpal tunnel syndrome has been shown to occur in 6–30% of patients with diabetes. Increased duration of diabetes has also been shown to be associated with an increase in the prevalence of carpal tunnel syndrome [90]. The incidence of carpal tunnel syndrome is also higher in patients with type 1 diabetes as compared to those with type 2 diabetes [90]. In fact, Singh et al. [90] found that the lifetime risk of developing carpal tunnel syndrome in patients with type 1 diabetes is 85% (95% CI: 72–97%) after 54 years of type 1 diabetes.

Several mechanisms have been proposed to explain carpal tunnel syndrome in patients with diabetes. One mechanism suggests that type 1 diabetes results in increased nonenzymatic glycosylation of collagen fibers. Glycosylation causes a decrease in the compliance of the collagen fibers. These stiffened fibers accumulate in the flexor synovium causing it to thicken, which could cause carpal tunnel syndrome [91]. Other causes of higher incidence of carpal tunnel syndrome in diabetes patients include increased expression of certain cytokines, demyelination of Schwann cells, and increase in connective tissue and extracellular fluid within the carpal tunnel. In addition, diabetes has been associated with impaired vitamin B6 and vitamin C metabolism. Keniston et al. [92] showed that an increased vitamin C to vitamin B6 ratio can result in symptoms associated with carpal tunnel syndrome. Multiple studies have shown that the development of carpal tunnel syndrome is associated with microvascular complications of diabetes including peripheral neuropathy, retinopathy, and nephropathy [93, 94]. It has been hypothesized that when underlying diabetic polyneuropathy is present, the median nerve could be more susceptible to the effects of elevated pressure in the carpal tunnel, because of elevated risk of endoneurial ischemia [90].

Dellon and Mackinnon [95] showed that diabetic nerves are more susceptible to compression in the streptozocin model. It seems that glucose enters the nerve directly since the blood-nerve barrier permits glucose to cross freely; this results in endoneurial edema. The glucose subsequently gets metabolized to hydrophilic polyols, which cause additional fluid to move into the endoneurial space. The ensuing edema causes endoneurial hydrostatic pressure to increase;

eventually myelin changes occur. It seems that anything that changes axoplasmic physiology can make the nerve more susceptible to compression neuropathy [13].

Thyroid Dysfunction

Patients with hypothyroidism have also been shown to have a higher prevalence of carpal tunnel syndrome [96]. The exact mechanism by which hypothyroidism affects neuropathy is still unclear. One proposed mechanism is the accumulation of mucopolysaccharides in the soft tissues surrounding the peripheral nerves. This accumulation may result in axonal degeneration and ultimately cause nerve dysfunction [97]. Another proposed mechanism is that hypothyroidism may cause swelling of the synovial membrane around the tendons in the carpal tunnel. This results in increased pressure in the carpal tunnel, causing impingement of the median nerve and symptoms of carpal tunnel syndrome [98].

The duration of the hypothyroid state can have an impact on the treatment of patients with carpal tunnel syndrome. Kasem et al. [99] showed that carpal tunnel syndrome could be reversed in hypothyroid patients by using hormone replacement therapy for 3 months. Hence, Kasem et al. propose that hormonal replacement therapy should be considered prior to any surgical intervention for carpal tunnel syndrome in hypothyroid patients. However, the reversal of carpal tunnel syndrome was seen only in newly diagnosed hypothyroid patients. Long-duration hypothyroidism may cause irreversible carpal tunnel syndrome, and a surgical intervention may still be the best course of treatment in those cases [98].

Acromegaly

Up to 64% of patients with acromegaly have been reported to have symptomatic carpal tunnel syndrome [100], and over 80% of patients with acromegaly have subclinical abnormalities on nerve conduction studies [101]. In most cases, significant improvement is seen after circulating growth hormone levels are lowered [100, 102–105]. However, the underlying pathophysiology is uncertain [106, 107]. Studies of median neuropathy in acromegaly have proposed various pathogenic mechanisms, including an increase in the amount of connective tissue in the carpal tunnel [107], demyelination of Schwann cells [108], bony or synovial overgrowth of the carpal bones [102], or an increase in the amount of extracellular fluid in the tunnel [106]. The exact role of growth hormone and IGF-1 in the development of carpal tunnel syndrome is still not known [109].

Jenkins et al. [109] found that the clinical symptoms of median neuropathy in acromegaly are associated with an increase in the size of the median nerve in the carpal tunnel; this is consistent with edema of the median nerve. This is also supported by the occurrence of increased signal intensity on T2-weighted images and rapid reduction of nerve size and resolution of symptoms that occurs after levels of circulating growth hormone are decreased. However, nerve conduction is chronically impaired, implying that this edema must result in damage to the myelin sheathes [110]. It was found that there is no change in bowing of the flexor retinaculum in acromegaly patients, suggesting that the total volume of the contents of the carpal tunnel did not increase [109]. This is in contrast with typical MRI findings in patients with carpal tunnel syndrome not associated with acromegaly [8]. Jenkins et al. [109] failed to find a correlation between levels of growth hormone or IGF-1 and radiologic or electrophysiologic measurements either before or after treatment. They also found that levels of growth hormone and IGF-1 were equally elevated in patients with acromegaly, regardless of whether or not they displayed symptoms of carpal tunnel syndrome. However, the reported reduction in nerve swelling after levels of growth hormone and IGF-1 were lowered implies that they are somehow involved in the pathogenesis of acromegaly-associated carpal tunnel syndrome [100, 102–105]. Jenkins et al. [109] concluded that the predominant mechanism of pathology in acromegaly-associated carpal tunnel syndrome is edema of the perineural sheaths rather than increased volume of the contents of the carpal tunnel. They also concluded that the rapid resolution of edema after circulating growth hormone

and IGF-1 levels are lowered and associated resolution of neuropathic symptoms indicates that aggressive treatment of the underlying pituitary hypersecretion rather than local carpal tunnel decompression is needed in acromegalic patients exhibiting symptoms of carpal tunnel syndrome.

Rheumatoid Arthritis

Rheumatoid arthritis, a systemic inflammatory disease primarily affecting synovial joints, can cause anatomical changes in the carpal tunnel, which can result in the development of carpal tunnel syndrome [111]. It is known that rheumatoid arthritis causes tenosynovitis around the transverse carpal ligament and flexor tendons; this results in elevation of the pressure within the carpal tunnel, leading to the development of carpal tunnel syndrome [112]. Rheumatoid arthritis is considered a risk factor for CTS; it has been reported that patients with rheumatoid arthritis are 2.23–2.9 times as likely to develop carpal tunnel syndrome as those without rheumatoid arthritis [51, 96]. Although prolonged duration of rheumatoid arthritis can lead to histopathological changes in the tendons of the wrists resulting in abnormal synovial proliferation and damage to the tendons [113], no statistically significant correlation was found between carpal tunnel syndrome occurrence and rheumatoid arthritis duration [114].

Conclusion

Carpal tunnel syndrome is a constellation of symptoms that are associated with the compression of the median nerve. Several causes have been described that ultimately result in increased pressure in the carpal tunnel causing the symptoms of numbness, tingling, or weakness of the hands. Mechanical factors such as repetitive stress or trauma to the wrist result in damage to the median nerve and inflammation of the surrounding tissues. Carpal tunnel syndrome has also been strongly associated with medical and physical conditions such as diabetes, hypothyroidism, acromegaly, and rheumatoid arthritis. People with certain genetic makeup, certain environmental exposures, and hormonal changes have also been shown to have a higher prevalence of carpal tunnel syndrome. Accumulation of damage over the years and changes within the tunnel and the surrounding tissues have also been shown to play a role in the development of the symptoms. Even though several of these risk factors have been identified, the pathophysiology of carpal tunnel syndrome is still not fully understood. It is likely that several of these described factors may play a role simultaneously in the development of the symptoms. More research is needed to determine the precise cause and the process that leads up to the symptoms of carpal tunnel syndrome.

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Clinical Presentations and Diagnosis

4

Edward Diao

Carpal Tunnel Syndrome: A Definition

For a general definition of carpal tunnel syndrome, the American Association for Orthopaedic Surgeons clinical practice guidelines on the diagnosis of carpal tunnel syndrome (2007) are as good as any.

"Carpal Tunnel Syndrome is a symptomatic compression neuropathy of the median nerve at the level of the wrist, characterized physiologically by evidence of increased pressure within the carpal tunnel and decreased function of the nerve at that level. Carpal Tunnel Syndrome can be caused by many different diseases, conditions and events. It is characterized by patients as producing numbness, tingling, hand and arm pain and muscle dysfunction. The disorder is not restricted by age, gender, ethnicity, or occupation and is associated with or caused by systemic disease and local mechanical and disease factors." [1].

E. Diao (✉)
Orthopaedic Surgery and NeuroSurgery, University of California, San Francisco, CA 94143, USA

California Pacific Medical Center,
450 Sutter Street, Suite 910, San Francisco, CA 94108, USA
e-mail: ediao@sf-sc.com

Burden of Disease and Impact of CTS in the USA

"During 1998, an estimated three of every 10,000 workers lost time from work because of carpal tunnel syndrome. Half of these workers missed more than 10 days of work. The average lifetime cost of carpal tunnel syndrome, including medical bills and lost time from work, is estimated to be about $30,000 for each injured worker [2]." 2005 statistics indicate nearly half the workers who lost time from work because of carpal tunnel syndrome missed over 31 days of work [3]. The US Bureau of Labor Statistics [4] indicates there were 16,440 cases of carpal tunnel syndrome involving lost work days in 2005. Carpal tunnel syndrome has the highest median number of days away from work [3], and the major industry division with highest number of events and exposures is manufacturing [5].

Etiology

The consensus opinion of the AAOS Clinical Practice Guideline Workgroup states that patients with carpal tunnel syndrome experience numbness and tingling in the sensory distribution of the median nerve. They may also have hand pain. If the syndrome is untreated over time, pain may be felt proximally in the forearm. Some

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combination of pressure × time is thought to result in progression of this condition. The duration and intensity of the paresthesias may increase. Sensory loss and median motor paralysis with atrophy of the thenar muscles may occur. It is believed that the earlier the diagnosis is made, the less likely is the occurrence of irreversible damage to the nerve. The accuracy of differential diagnosis from radiculopathy and metabolic, genetic, and other forms of neuropathy is achieved through careful history taking, physical examination, and laboratory tests, as well as clinical experience with all of these conditions [6].

Typical and Atypical Presentations

Patients with carpal tunnel syndrome usually present with clinical symptoms. These may include pain, weakness, and numbness. The typical anatomic distribution of these symptoms is the median nerve distribution, mainly the thumb, index, middle finger, and the radial one half of the ring finger.

A "typical" patient will complain of pain with repetitive or heavy use of the hand, thumb symptoms of weakness, and radiating numbness in the median nerve distribution. The patient may have nocturnal waking and describe a typical maneuver of having to sit up or "shake the hands" to try to relieve such symptoms. Patients may have tried anti-inflammatories or a wrist immobilizer splint to try to decrease symptoms, and these may or may not have been effective.

It is important that the clinician does not fall into the trap of assuming that every case of hand numbness or tingling is carpal tunnel syndrome. Clearly, at least in the USA, carpal tunnel syndrome is a clinical entity that is relatively well known. However, most patients don't know the specifics of what this clinical entity is and certainly are not able to differentiate this more popularly described condition and differentiate it with many other conditions that may "mimic" classic carpal tunnel syndrome. Thus, the burden of making or confirming the diagnosis falls on the clinician.

Confounding the diagnosis of carpal tunnel syndrome is the fact that there are instances of "double crush" where a nerve compression in one part of the peripheral nervous system potentiates a lower irritation or pressure threshold for compression syndrome in another part of the peripheral nervous system. Most classically proximal nerve compression at the cervical spine, thoracic outlet, or about the elbow or forearm can mimic carpal tunnel syndrome and/or be a cause of "double crush." A partial list of diagnoses is listed in Table 4.1.

Table 4.1 Differential diagnosis for CTS

Cervicalgia	Cervical spine compression
Herniated cervical disk	Cervical root compression
Herniated cervical disk	Brachial plexopathy
Thoracic outlet syndrome	Humeral level nerve compression
Parsonage turner syndrome	Cubital tunnel syndrome
Elbow tendonitis (medial or lateral)	Pronator syndrome
Radial tunnel syndrome	Tendonitis of the flexor compartments (FCR, FCU)
Flexor tenosynovitis or the wrist or hand	Trigger finger
Extensor tendonitis in any of the six dorsal compartments	Dupuytren's contracture
De Quervain's tendonitis	Basal joint of thumb arthritis

Atypical innervation may result in an atypical pattern of nerve compression, particularly with the Martin-Gruber anastomosis. Rarely, patients may present with atrophy and yet deny prior symptoms of pain or numbness. Thus, the presentation of carpal tunnel syndrome in patients may vary significantly from case to case.

Risk Factors

Several key comorbidities and/or human factors are associated with an increased incidence of carpal tunnel syndrome. These include pregnancy, advancing age, female gender, specific occupations, hand-related repetitive motions, strong family history, and specific medical disorders such as hypothyroidism, diabetes, autoimmune diseases, rheumatological diseases, arthritis,

obesity, renal disease, trauma, anatomic predisposition in the wrist and hand due to shape and size, infectious diseases, and substance abuse. In many cases, there is no identifiable comorbidity or causal relationship. These are "idiopathic CTS cases" [1].

History

It is essential to ask the right questions in obtaining the history for a patient who is suspected of carpal tunnel syndrome. This is particularly important since the patient may have their own ideas of what the etiology of the problem is, which might be correct or incorrect. The index of suspicion must reside with the clinician in terms of asking the right questions.

The way I like to approach this is to ask the typical questions in obtaining information in any investigation, modified for carpal tunnel syndrome. Very simply these are who, how, what, when, and where.

Who/How?

It means asking these questions: How did it start? Was there a single traumatic episode? Was there repetitive use over time, with a slow gradual onset?

What?

What are the symptoms? Is it pain, is it numbness, is it tingling, or is it weakness? What are the activities that are primarily impaired? What are the activities that are provocative that reproducibly and reliably "bring out" the symptoms?

When?

When do the symptoms occur? Is it stable throughout the day? Are there provocative activities that bring it out or tend to bring it out? Are symptoms worse at night? Is nocturnal waking a feature? If so, does this happen nightly? This symptom has a lot to do with the intensity of the condition and may be very useful in guiding the decision to embark on treatment, including surgery.

Where?

Where do the symptoms occur? What is the distribution of symptoms? Is it all five fingers? Is it a "classic" median nerve distribution of the thumb, index, middle, and the radial portion of the ring finger? Is the pinky finger spared? Furthermore, is it just the hand, or does it involve more proximal upper extremity or the entire arm? If it's the entire arm, a strong suspicion of a "double crush" involving proximal nerve compression should be more thoroughly evaluated and considered.

Pattern

What is the pattern up until now? What might the pattern be going forward? Often patients would like the clinician to "predict the future," in terms of progression of their symptoms based on their current situation. In order to get a complete history, you have to know what the pattern up until the present has been.

In terms of the future pattern or "natural history" of this or any other disorder, there are always three choices: it gets better, it gets worse, or it stays the same. Yes, this is absurdly simplistic, but it is important to try to elicit the past pattern and get more detail on the progression of symptom etiology that has brought the patient to the physician's office.

In terms of the present, and the future, there are two key things to try to consider. One is the duration of symptoms, and the second is the severity of the symptoms. The duration can be ascertained to some degree with the patient's cooperation and if the patient is a reasonable historian. On the other hand, severity cannot be easily determined by history or physical exam, but this can be inferred by the careful conducting of the history and support of physical exam.

Electrodiagnostic testing may give some indication of this severity, but not the likelihood of progression or rate. Confirmation of CTS can be obtained in the diagnostic testing which will be discussed in the sections to follow.

Physical Exam

Inspection of the involved upper extremity should start with the neck and shoulder girdle exam. The contralateral side should always be inspected in unilateral cases. The neck should be tested for range of motion in terms of rotation, flexion and extension, and lateral bend. Nerve compressive signs should be observed, and compression testing performed. Any tenderness should be noted, either locally or especially if there is any radiating pain.

In terms of the shoulder girdle, palpation of the trapezius, the paracervical area, the supraclavicular area, the area around the clavicle, and the infraclavicular area of the upper chest should be carefully and sequentially palpated to elicit tenderness or irritation symptoms. The axilla should be palpated, and any radiating pain should be noted. The shoulder girdle should be tested for range of motion, instability, and impingement. Any pain should be noted.

Provocative tests for the thoracic outlet syndrome (TOS) such as Wright's maneuver, Adson's maneuver, and overhead fisting should be performed. Thoracic outlet syndrome is a very commonly diagnosed condition in my clinical practice. Because of the lack of good diagnostic tests for this condition, I find that the condition of TOS is often overlooked. TOS is the cause for many patients to have arm and hand symptoms that can mimic or exist in conjunction with carpal tunnel syndrome.

The elbow exam is extremely important in these patients. There are many conditions about the elbow that cause pain and disability that can mimic carpal tunnel syndrome. Direct palpation of the elbow with particular attention to the biceps insertion anteriorly, the medial epicondyle, the lateral epicondyle, and posteriorly the olecranon should be performed. Tenderness about the elbow with epicondylitis is another common clinical scenario seen in my practice.

Nerve compression about the elbow and forearm that does not involve the median nerve can cause significant symptoms. The cubital tunnel is located between the medial epicondyle and the olecranon tip, on the posteromedial side of the elbow. It is a common site of compression and in fact is the no. 2 upper extremity compressive diagnosis. A positive Tinel's sign, or sensitivity to palpation, or nerve subluxation with elbow flexion and extension, or increase in symptoms with elbow flexion, is a maneuver that should be performed by the clinician. The medial epicondyle may be tender to palpation either on the bony prominence or slightly distally at the muscle belly of the flexor-pronator mass. As the ulnar nerve enters the forearm between the heads of the flexor carpi ulnaris, provocative or resistive testing of the flexor pronator muscles including the flexor carpi ulnaris is recommended.

On the lateral side, lateral epicondylitis is a common condition that may or may not be related to sports activities or repetitive use. The tenderness may be on the lateral epicondylar ridge itself or more distally in the supination/extension muscle group.

On the lateral side, the radial nerve courses around the head and neck of the radius bone and between the heads of the supinator muscle. Compression of the radial nerve should always be evaluated. Radial tunnel syndrome is another condition that should be carefully assessed by the clinician. Tenderness several centimeters distal to the lateral upper condyle to deep palpation and/or a positive Tinel's test is an indicator of this condition. Provocative testing of wrist extension against resistance can be positive with radial tunnel syndrome. More fulminant radial nerve compression can result in motor weakness in the radial nerve-supplied muscles. These two entities, lateral epicondylitis and radial tunnel syndrome, can exist together.

In terms of the forearm, the volar forearm should not be neglected. Tenderness of the flexor pronator muscles either coming off the medial upper condyle on the medial side of the elbow or in the midline of the volar aspect of the forearm in supination

and the proximal one third can be associated with pronator syndrome. This is a compressive neuropathy of the median nerve proximal to the wrist. This can exist alone or in conjunction with traditional carpal tunnel syndrome at the wrist.

At the wrist itself, all flexor tendons and all extensor tendons should be inspected and palpated in their compartments for tenderness or crepitus or swelling. Any of these structures can have a tenosynovitis associated with them. Of course the most common is the first dorsal compartment, or de Quervain's tendinitis, but flexor carpi ulnaris and flexor carpi radialis tendinitis are common. Extensor carpi ulnaris, flexor digitorum communis, and extensor carpi radialis brevis and longus tendinitis are all additional clinical entities that can cause pain and require treatment including surgery.

In the hand, inspection should be performed for any sign of thenar atrophy. Basal joint arthritis or other radial-sided bone and joint deformities can "mimic" thenar atrophy. Having the patient touch the thumb to fifth fingertip allows evaluation of both the thenar and the hypothenar muscle bulk and strength; this also tests aspects of ulnar nerve motor function. Intrinsic muscle testing by crossing the fingers should be carried out to further test ulnar nerve motor function.

The palm should be palpated for trigger finger or tendinitis or A1 pulley fullness. Digital flexion and extension should be performed actively and then passively to further check for flexor tenosynovitis/trigger finger.

Sensory examination using two-point discrimination, Semmes-Weinstein monofilament, vibrometry, texture discrimination, etc. are important for defining the anatomical distribution of any sensory changes that may be present. According to the American Academy of Orthopaedic Surgeons, sufficient evidence does not exist from the literature to recommend one test over another or to suggest the overall utility of a test in diagnosing carpal tunnel syndrome. Manual muscle testing of the upper extremity including evaluation for obvious muscle atrophy is important especially for the thenar muscle area. I recommend grip and pinch strength measurements bilaterally for all of my patient evaluations. The presence of thenar atrophy has a high predictive value in carpal tunnel syndrome, but its appearance can be rare [7].

Provocative Tests

There are several provocative tests that should be considered to aid in the evaluation and diagnosis of carpal tunnel syndrome. The Tinel's sign (Fig. 4.1) involves percussion over the median nerve along its pathway from the forearm to the wrist in the proximal to distal direction.

Where Tinel's sign is positive, paresthesias are elicited in the median nerve distribution. The Tinel's sign, however, is diagnostically valid in a percentage between 58% and 67% of the cases of patients whose electromyographic tests are positive; in 20% of the cases, instead, Tinel's sign may be positive in the absence of compression disease [5]. It is important to do Tinel's testing from the axilla to the wrist on both sides to avoid a "false-positive" test at the carpal tunnel.

Another important test is Phalen's test (Fig. 4.2). This is done by holding the wrist in maximal flexion for up to 60 s: if a sensation of numbness as well as paresthesia on the first three fingers occurs within that time, it is considered diagnostic.

Phalen believed that this was due to compression of the nerve between the proximal edge of the transverse ligament and the adjacent flexor tendons. This has been validated by several modern studies. It has been demonstrated that

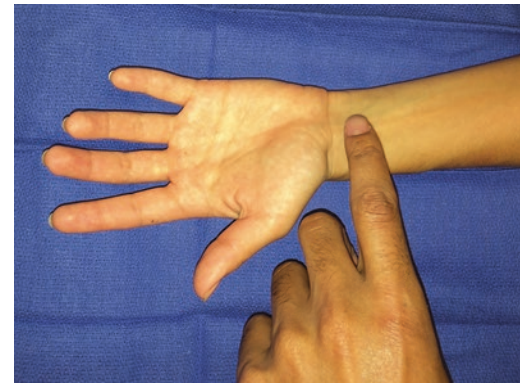

Fig. 4.1 Tinel's sign involves percussion over the median nerve

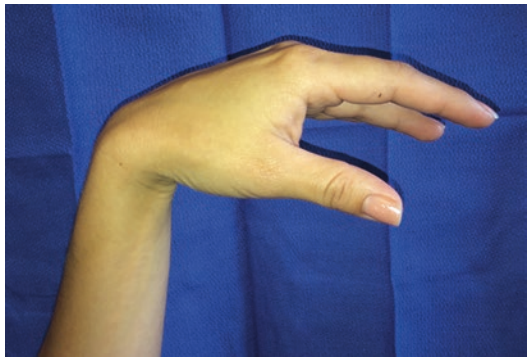

Fig. 4.2 Phalen's test is done by holding the wrist in maximal flexion for up to 60 s. Numbness and paresthesia on the first three fingers is considered diagnostic

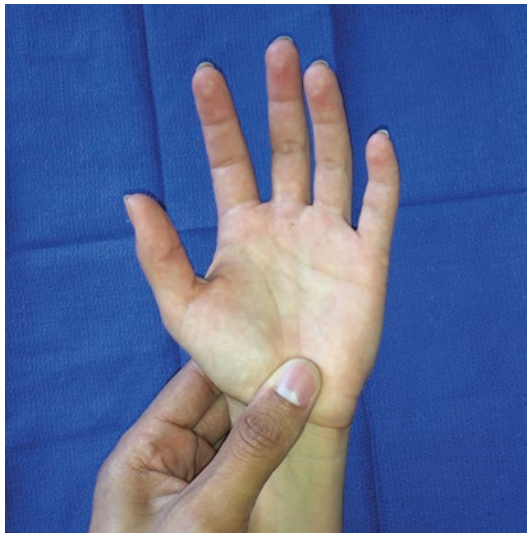

Fig. 4.3 The carpal compression test will elicit paresthesia in the territory of the median nerve distribution when the physician applies pressure for up to 30 s

Phalen's test is positive in 66–88% of the patients with CTS, even if it can be positive in almost 20% of normal patients. A positive response obtained by combining Phalen's and Tinel's test is diagnostically important insofar as it identifies close to 90% of positive patients with CTS [8, 9].

A third important test is the compression test (Fig. 4.3) of the median nerve, described by Durkan [10]. This test involves evaluating the onset of paresthesia in the territory of median nerve distribution when the physician applies pressure with his thumb at the level of the carpal tunnel for up to 30 s.

Durkan reports that this test is positive in 87% of patients with CTS. Williams [11] reports that this test is positive in 100% of patients.

Sensibility Testing

The most widely used test is Von Frey's pressure test with Semmes-Weinstein monofilaments. This test involves perpendicular application on the fingertips of monofilaments with different thicknesses; the amount of pressure applied is just enough to obtain flexion of the filament: the test is positive when the patient correctly identifies the stimulated finger. During a study carried out on a series of patients with CTS, Von Frey's test proved to be significant in 52% of the cases, while Weber's two-point discrimination test was significant only in 30% of the cases.

Another threshold test is the vibration test described by Szabo et al. [12]. Just as the ability to discriminate between two points deteriorates with age, so does the perception of vibrations in the threshold value with aging has not been defined. Sensitivity evaluation tests must prove to be altered only in the territory of distribution of the median nerve. Therefore, if extension of hypoanesthesia to the palm is present, the involvement of the sensitive palmar branch (originating proximally to the transverse ligament) should be suspected, and further differential diagnostic evaluations should be undertaken.

Atrophy

Examination of the muscles of the hand to screen for thenar atrophy or weakness is recommended. Thenar prominences are thenar muscles innervated by the motor branch of the median nerve which arises from the nerve where it emerges from the carpal canal; however, there is ulnar innervation of a portion of the flexor pollicis brevis. Concomitant or confounding basal joint of thumb arthritis must be considered.

To test that of the thumb's abductor pollicis brevis muscle (Fig. 4.4), the patient is asked to place the first finger perpendicular to the palm

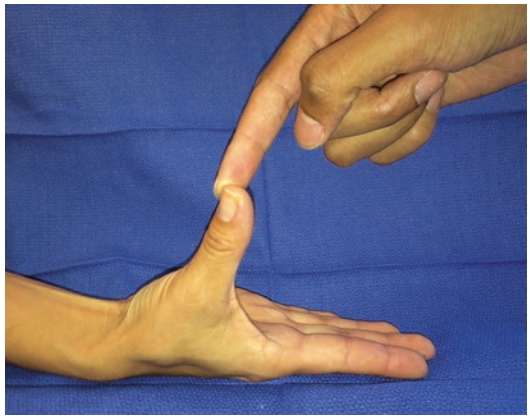

Fig. 4.4 Testing the abductor pollicis brevis muscle requires placing the patient's first finger perpendicular to the palm; pressure is exercised directly in the adducted direction

and to resist pressure exercised, directly in adducted direction, on the distal phalanx.

Position and force are compared to the other hand. With a weak short abductor, the first digital ray can be abducted with the APL, which is innervated from the radial nerve, and can be brought toward the palm with the long flexor which is innervated by the median nerve proximally to the carpal tunnel. The position of the thumb will facilitate flexion of the IP joint. However, the patient will not be able to position the thumb at a full 90° from the palm's surface if there is a median nerve motor deficit.

The opposition function (Fig. 4.5) can be tested by having the patient touch the tip of the thumb to the tip of the fifth finger.

The patient is asked to resist, while the examiner is trying to separate the two digits. All the thenar muscles are tested, and the opponens pollicis muscle is the primary contributor to this motion and function.

Lastly, hypotrophy or atrophy of the thenar muscle may be a result of chronic nerve compression. In rare cases, this finding may be the most prominent characteristic of carpal tunnel syndrome.

Sensitivity and Specificity of Tests

No one test has been identified as a "gold standard" for identifying carpal tunnel syndrome. In several studies, Phalen's sign ranged in sensitivity from 0.46 to 0.80 and in specificity from 0.51 to 0.91 [13–16]. Tinel's sign ranged in sensitivity from 0.28 to 0.73 and in specificity from 0.44 to 0.95 in several studies [7, 14–16]. The median nerve compression test ranged in sensitivity from 0.04 to 0.79 and in specificity from 0.25 to 0.96 in several studies [14, 16, 17]. Combining the results of more than one provocative test increases the sensitivities and specificities of the testing. For example, in one study, combined results of Phalen's and median nerve compression tests yielded a sensitivity of 0.92 and a specificity of 0.92 [16]. Reverse Phalen's, tethered median nerve stress test and the tourniquet test have been evaluated only a few times, leaving insufficient evidence to draw any conclusions as to their accuracy in the diagnosis of carpal tunnel syndrome [7, 14, 15]. The clinical tests for carpal tunnel syndrome by themselves do not reliably diagnose carpal tunnel syndrome. Similarly, electrodiagnostic studies by themselves also do not reliably diagnose carpal tunnel syndrome. However, when the symptoms, clinical tests, and electrodiagnostic tests are combined, statistical significance ($p < 0.05$) is obtained when compared

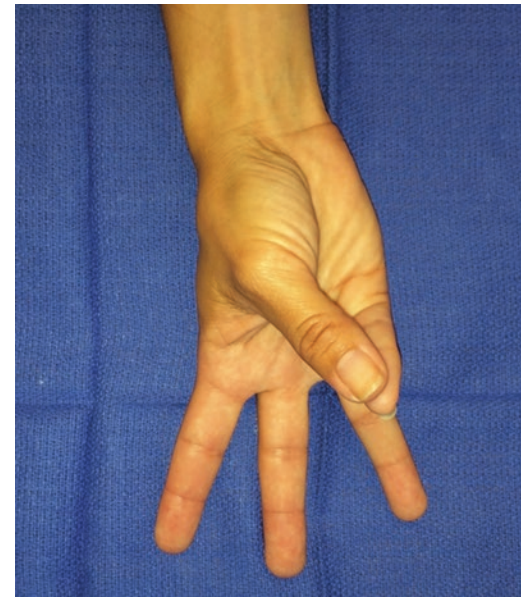

Fig. 4.5 The thenar and opponens pollicis muscle can be tested by having the patient touch the tip of the thumb to the tip of the fifth finger and resist as the physician tries to separate the two digits

to postsurgical outcomes. Some of these studies have looked at:

- Motor and sensory tests + distal motor latency of the median nerve, antidromic sensory nerve conduction velocity, EMG examination of abductor pollicis brevis [1, 18]
- Range of motion, grip strength, pinch strength, monofilament sensory evaluation, Phalen's, Tinel's + sensory latency over 3.5 ms [1, 4]
- Phalen's or Tinel's + motor latencies > 4.0 ms, sensory latencies > 3.7 ms, amplitudes < 20 μV, or a conduction velocity < 50 m/s with evidence of fibrillation [1, 13]
- Sensory tests + prolonged median sensory conduction velocity, distal motor latency to abductor pollicis brevis [1, 5]

I routinely use Phalen's, Tinel's, and carpal tunnel compression (Durkan) tests in the office. I note any thenar atrophy and do basic sensibility testing to light touch and two-point discrimination.

Summary The clinician should be knowledgeable about the range of presentations, typical and atypical, for carpal tunnel syndrome and also the various other upper extremity conditions from which carpal tunnel syndrome should be distinguished. Skillful history taking should be coupled with a broad general neck to fingertip exam with appropriate specialized tests.

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Differential Diagnosis of Carpal Tunnel Syndrome

5

Cameron W. Schick and F. Thomas D. Kaplan

Introduction

Carpal tunnel syndrome is the most commonly diagnosed compressive neuropathy of the upper extremity [1]. It is the third most common procedure performed by orthopedic surgeons, just behind knee and shoulder arthroscopy [2]. Patients with carpal tunnel syndrome may present to physicians from across all facets of medicine from primary care to specialized surgery. Despite its high prevalence and characteristic features, the diagnosis can at times be challenging. Not all patients present with typical symptoms, and multiple conditions can lead to carpal tunnel syndrome. There are multiple criteria for diagnosis, and patients often do not exhibit all signs and provocative maneuvers. Finally, surgeons should be keen to remember that not all hoof beats come from horses: there are many conditions which may mimic carpal tunnel syndrome.

The primary cause of carpal tunnel syndrome is median nerve compression from within the carpal canal [3]. This is verified by an increase in the internal pressure within the carpal tunnel. Any condition that decreases the available space or increases the volume of the contents within the fixed capacity of the carpal canal can induce carpal tunnel syndrome. Although the majority of CTS is idiopathic, systemic conditions such as DM, hypothyroidism, or RA may predispose one to developing CTS. Hormonal changes as seen in pregnancy, collagen conditions, and acromegaly may also increase risk of CTS. Those with a disproportionately smaller canal due to abnormal development, a congenital condition, or secondary to trauma from a fracture will see higher pressures and may be at increased risk of developing carpal tunnel syndrome.

Carpal tunnel syndrome typically presents with symptoms of nocturnal paresthesias in the median nerve distribution and activity-related symptoms that often occur with prolonged grip [4]. Symptoms often occur when driving or holding a cellular phone, and patients are frequently woken from sleep with painful, numb hands. To resolve the paresthesias, patients note the need to lower and shake their hands.

The diagnosis of carpal tunnel becomes less clear as the subjectivity of complaints increases. Patients may complain of pain that radiates up the forearm or all the way to the shoulder. Symptoms may involve the entire hand, suggesting more than isolated median nerve involvement. Patients often have difficulty describing their symptoms and may not understand the difference between numbness, tingling, pain, and weakness. These symptoms are common with carpal tunnel syndrome, but can be present with many other conditions.

C.W. Schick • F.T.D. Kaplan (✉)
Indiana Hand to Shoulder Center,
8501 Harcourt Rd., Indianapolis, IN 46260, USA
e-mail: tkaplan@ihtsc.com

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In situations where the complaints are typical for carpal tunnel syndrome, and the classic provocative tests are positive, the diagnosis is straightforward, and the physician can be confident in his or her decision. When other complaints or clinical issues confound the presentation, the picture is murkier. The current American Academy of Orthopaedic Surgeons guidelines for the diagnosis of carpal tunnel syndrome recommend obtaining an accurate history and performing a physical examination evaluating personal characteristics: sensation, motor function, and provocative/discriminatory tests [5]. Additionally, electrodiagnostic testing is recommended when thenar atrophy and/or constant numbness is present, to differentiate among other potential etiologies, especially when surgical treatment is being considered. MRI, CT, and pressure-specified sensorimotor devices are not recommended for use in routine carpal tunnel syndrome.

When evaluating a patient with suspected median nerve neuropathy, physicians should consider the etiology of their patients' symptoms prior to determining treatment. There are two main categories to consider: those conditions causing CTS and those conditions that may appear to be CTS, but are due to a different pathology. Although most commonly carpal tunnel syndrome is idiopathic, there are many conditions which can result in compressive neuropathy of the median nerve in the carpal tunnel, which are discussed elsewhere in this book. Table 5.1 lists categories of conditions that may mask as CTS.

Conditions Masking as Carpal Tunnel Syndrome

The focus of this chapter will be those conditions that may fool the patient or the practitioner into thinking carpal tunnel syndrome is the primary problem. The differential diagnosis is broad, and it is helpful to divide potential etiologies into neurologic and non-neurologic conditions. Organizing in this manner may help optimize efficiency in diagnosis and avoid unnecessary testing/costs.

Table 5.1 Conditions that present with a clinical picture similar to carpal tunnel syndrome

Neurologic conditions	Non-neurologic conditions
• Neoplastic – Intracranial neoplasm – Pancoast tumor – Peripheral nerve tumor • Neurologic – Multiple sclerosis – Amyotrophic lateral sclerosis – Brachial plexopathy – Thoracic outlet syndrome – Parsonage-Turner syndrome – Pronator syndrome – Polyneuropathy • Cervical – Cervical spondylosis and myelopathy – Cervical radiculopathy (C5, C6) – Syrinx • Inflammatory – Churg-Strauss syndrome – Polyarteritis nodosa • Traumatic – Median nerve laceration – Median nerve contusion – Median nerve ischemia	• Neoplastic – Melorheostosis – Myxofibrosarcoma of the forearm – Lipoma • Vascular – Hand-arm vibration syndrome – Hypothenar hammer syndrome – Raynaud's phenomenon – Vascular shunt • Degenerative – FCR/FCU tenosynovitis or calcific tendonitis – Osteoarthritis – Overuse syndrome – Fibromyalgia • Inflammatory – Polymyalgia rheumatica – Gout – Pseudogout – Lupus – Rheumatoid arthritis • Infectious – Herpes zoster – Mycobacterial – Gonococcal

Neurologic Conditions

There are multiple neurologic conditions that present with symptoms similar to carpal tunnel. These can be divided into benign and malignant neurogenic tumors, primary neuropathic conditions, inflammatory, cervical, and traumatic etiologies.

Tumors

Many types of tumors may present with symptoms that appear to be CTS. The most proximal site of compression was described by Dunkow et al. in 2004, when they reported on a glioblastoma causing symptoms of numbness and tingling in the median nerve distribution [6]. The patient presented with numbness in the left index, middle, and ring fingers and a positive Tinel's over the median nerve at the wrist, but a negative Phalen's test. Electrodiagnostic studies suggested cervical pathology; however, a cervical spine magnetic resonance (MR) scan excluded a cervical etiology. Symptoms progressed to involve the small finger, and the patient had decompression of median and ulnar nerves at the wrist with no improvement. Following development of wrist extensor weakness, MR of the brain showed a 5 cm parietal lobe tumor. This case highlights the importance of asking about central symptoms such as headaches, personality changes, nausea/vomiting, seizures, or memory loss.

Cervical spine neoplasms have also been implicated in creating carpal tunnel complaints. Tumors of the foramen magnum can present with hand numbness, weakness, and clumsiness before other neurologic findings are obvious. In a series of 57 patients, Yasuoka et al. found three patients were initially misdiagnosed with carpal tunnel syndrome [7]. These patients will often have other findings not typical of carpal tunnel syndrome including gait disturbances, hyperreflexia, neck pain, and a Babinski sign [8].

Tumors in the upper apices of the lungs, such as a Pancoast tumor, may encroach on the brachial plexus as the tumor becomes larger [9]. As the tumor escapes the confines of the thoracic cavity, it invades the superior thoracic inlet and can compress the medial cord of the brachial plexus [10]. Sensory and motor deficits typically also involve the ulnar nerve distribution. Additionally, Horner's syndrome is present in up to 50% of patients, and many will also have constitutional symptoms such as fatigue, fever, or weight loss. Interestingly, pulmonary symptoms are uncommon early in the disease process.

Peripheral nerve tumors such as a schwannoma can develop within the median nerve or its branches and cause carpal tunnel symptoms [11–13]. Although these are usually asymptomatic at first, as they enlarge, neurologic symptoms may develop. Schwannomas are most often benign, slow-growing, encapsulated lesions that are amenable to surgical excision. Unlike neurofibromas, schwannomas can be separated from the nerve avoiding injury to surrounding axons. In addition to symptoms of numbness/tingling, a palpable mass may be present as it enlarges. Padua et al. described five patients found to have schwannomas with presenting symptoms of carpal tunnel syndrome, three of whom had prior surgical treatment with persistent symptoms. They found ultrasound to be particularly helpful in these cases which tended to have some "incongruous aspects" [13]. Additionally, when a peripheral nerve tumor is suspected, MRI should be obtained to evaluate the characteristics of the mass prior to consideration of surgical excision or biopsy, as malignancy may be present.

Neuropathies

Neuropathy is a broad category with many conditions that cause median nerve symptoms. Patients often have trouble deciphering which digits have sensory abnormalities and may misinterpret radial or ulnar neuropathy as carpal tunnel syndrome. Pronator syndrome is a compressive neuropathy involving the median nerve occurring at the elbow. Patients have numbness in the median nerve distribution as with carpal tunnel syndrome with the addition of numbness in the territory of the palmar cutaneous branch of the median nerve. Complaints of pain and numbness are more common during

activity with absence of nocturnal symptoms. Provocative tests include tenderness along the course of the median nerve across the elbow, pain with resisted pronation with the elbow in extension, and pain with resisted middle finger proximal interphalangeal joint flexion. Pronator syndrome is rare in comparison to CTS, but may coexist and should be considered in all patients presenting with carpal tunnel complaints [14].

Peripheral neuropathies have many potential causes including diabetes, nutritional deficiencies, human immunodeficiency virus, uremia, and vascular. Many cases are symmetric with symptoms commonly affecting the distal aspect of the longest nerve fibers, explaining typical onset of foot symptoms prior to those in the hand. Polyneuropathy may present with asymmetric symptoms though, especially in diabetics [15]. In these cases, it can be more difficult to differentiate from a compressive etiology. Diagnosis of peripheral neuropathy is based on a combination of neuropathic symptoms, signs, and electrodiagnostic studies, with signs being better than symptoms in making the diagnosis [16]. Signs of sensory loss occur in non-dermatomal, non-single nerve distribution patterns. Motor findings are atrophy and weakness of intrinsic muscles, with secondary joint deformity. Tendon reflexes are often diminished or absent. The electrodiagnostic study most helpful for confirming the diagnosis of a peripheral neuropathy is the nerve conduction study (NCS). Findings of an abnormality of any attribute of nerve conduction in two separate nerves, one of which must be the sural nerve, are the minimum criterion to support the diagnosis. If sural sensory and peroneal motor NCSs are normal, there is no evidence of a peripheral neuropathy [16]. If either is abnormal, NCS of at least the ulnar sensory, medial sensory, and ulnar motor nerves in both arms is performed. The addition of radial nerve studies is helpful particularly in those patients with suspected carpal or cubital tunnel syndrome, since compressive neuropathy may coexist with peripheral neuropathy.

Multiple sclerosis is an uncommon cause of failed carpal tunnel decompression [17]. Presenting symptoms are commonly central, such as unilateral visual disturbance, hemifacial spasm, and vertigo [18]. Lhermitte's symptom, an electric-shock-like sensation that can run down the back, or into the arms and/or legs triggered by neck motion, is strongly linked to multiple sclerosis [19]. Other peripheral symptoms may occur, which may simulate carpal tunnel syndrome; however, patients do not have typical nocturnal or provocative daytime symptoms.

Lesions of the brachial plexus may also create symptoms that may be confused with carpal tunnel syndrome. The median nerve originates from the lateral and medial cords of the brachial plexus with contributions from C6 to T1. Traumatic causes of brachial plexopathy are typically high-energy and result from motorcycle or other motor vehicle accidents where the arm is subjected to a traction or crush injury. Patients with anterior shoulder dislocation may also have compressive injury to the plexus. "Burners" or "stingers" are traction injuries occurring when the head and neck are forcefully pushed sideways and down, affecting one arm. They occur during a fall to the head, as may occur during wrestling or most commonly during a football tackle. These traumatic causes are usually easily differentiated from CTS due to the history of injury, though in multi-trauma patients, injury to the shoulder and hand/wrist may coexist, and acute CTS should be excluded by clinical exam and/or pressure monitoring of the carpal tunnel.

Neuralgic amyotrophy, or Parsonage-Turner syndrome, is a rare, likely autoimmune, disorder which causes pain and sensory and motor changes in peripheral nerves. Pain is the presenting symptom in 90% of cases, followed by weakness within 24 h in one third of patients, within 2 weeks in 70% of patients, and within 1 month in 85% [20]. Most commonly, the shoulder girdle muscles are involved, including the infraspinatus, supraspinatus, deltoid, biceps, and triceps, though weakness may be limited to the muscles supplied by a single nerve. Paresthesias and hypoesthesia are present in the majority of patients, again most frequently about the shoulder. Pure sensory neuralgic amyotrophy can occur, and when it does, it typically affects the median, medial antebrachial, and lateral antebrachial cutaneous nerves, potentially

mimicking carpal tunnel syndrome. The abrupt onset of the symptoms, significant pain, and weakness in muscles other than the thenars help distinguish patients with Parsonage-Turner syndrome from those with carpal tunnel.

Cervical Disorders

Neck pain is a common condition, with 1 year prevalence rates of 4.8–79.5% (mean 25.8%) [21]. Underlying spondylosis, spondylolisthesis, and disc herniation may lead to nerve compression and symptoms of a peripheral compressive neuropathy. Cervical radiculopathy involves one or more nerve roots, creating pain, numbness, and weakness in a dermatomal distribution. Sixth cervical root compression, seen in 25% of patients, causes numbness in the thumb and index fingers, whereas seventh cervical root involvement (60% of patients) causes numbness in the middle finger [22]. Patients with C6 involvement most closely mimic carpal tunnel syndrome, but these patients do not typically exhibit abductor pollicis brevis atrophy as is seen in advanced carpal tunnel. Nocturnal symptoms are less frequent as well. In a study by Chow et al., 84% of patients with isolated carpal tunnel syndrome had nocturnal symptoms compared to only 10% in the group with isolated cervical spondylosis [23]. Additional findings in patients with C6 radiculopathy include weakness (elbow flexion, wrist extension, and forearm supination), diminished reflexes (brachioradialis and biceps), and cervical pain, loss of motion, and a positive Spurling's test (reproduction of symptoms by positioning the neck in extension, rotating toward the side of symptoms, and applying axial load).

Cervical myelopathy occurs secondary to spinal cord compression. It may result from disc herniation, spondylolisthesis, or a space-occupying lesion. The clinical picture in patients with myelopathy tends to be quite variable and requires a high index of suspicion. Crandall and Batzdorf described five broad categories of cervical myelopathy including "brachialgia and cord syndrome" which may present with symptoms of carpal tunnel syndrome [24]. Symptoms may be non-dermatomal and often bilateral. Patients complain of diffuse numbness and the insidious onset of clumsiness, hand weakness, and worsened handwriting. As the condition advances, intrinsic atrophy progresses and may become severe. This constellation of findings was described as "myelopathy hand" by Ono et al. in 1987 [25]. They described two signs specific to the disorder. The "finger escape sign" is positive when after asking the patient to extend and adduct their fingers, the small finger drifts into abduction in less than 30 s. The "grip and release" test indicates myelopathy when the patient is unable to repeatedly open and close their fists at least 20 times in 10 s [22]. Myelopathic patients have weakness and spasticity, with exaggerated wrist flexion during finger extension and wrist extension during finger flexion.

Ziadeh and Richardson described the case of a patient with cervical syrinx who presented with symptoms of carpal tunnel syndrome [26]. The patient presented with a several year history of left thumb, index, and middle finger numbness. Symptoms were worse at night and with keyboard use. A night splint failed to control symptoms, as did physical therapy, ergonomic evaluation, and prescription anti-inflammatory medication. The patient denied weakness, clumsiness, or gait disturbance, but close physical evaluation demonstrated hyperreflexia and a positive Spurling's maneuver, highlighting the importance of a complete examination in all patients with presumptive diagnosis of carpal tunnel syndrome. A cervical spine MR demonstrated a syrinx from C1–C2 to T10–T11 with an Arnold-Chiari type I malformation.

Inflammatory Conditions of the Nervous System

Inflammatory disease can not only be a cause of carpal tunnel syndrome but can also mimic carpal tunnel by creating neuropathy proximally. Disorders such as polyarteritis nodosa, lupus, and rheumatoid arthritis can develop vasculitis affecting the peripheral nerves and lead to upper extremity dysesthesia. A case highlighting this

etiology was presented by Sethi et al. in a patient with Churg-Strauss syndrome [27]. Churg-Strauss syndrome is an autoimmune condition causing asthma and inflammation of small- and medium-sized vessels leading to mononeuritis multiplex or polyneuropathy. In their case, the patient presented with right thumb, index, and middle finger numbness. Neurologic symptoms progressed with involvement of the contralateral hand and visual disturbance leading to consideration of alternative diagnoses.

Polymyalgia rheumatica can also cause symptoms of carpal tunnel syndrome. In a series of 177 patients, Salvarani et al. found 14% with carpal tunnel complaints [28]. Patients with polymyalgia rheumatica often have multiple distal musculoskeletal findings including edema, tenosynovitis, and joint pain which can help differentiate the disease from idiopathic carpal tunnel syndrome. Patients are usually over the age of 50 and have an elevated erythrocyte sedimentation rate and C-reactive protein. Response to oral corticosteroids is dramatic, while nonsteroidal anti-inflammatories are ineffective.

Traumatic Neurologic Injuries

Traumatic injuries to the median nerve must always be considered when evaluating a patient with symptoms of carpal tunnel syndrome. Sharp lacerations from a piece of glass or a knife may be obvious. Less obvious situations may present with dysesthesias and a remote history of injury. Browett et al. reported on two patients who suffered injuries to their volar wrists from a piece of glass with no immediate neurologic symptoms [29]. One patient developed paresthesia in the median nerve distribution 3 days later, while symptoms took 3 months to occur in the other when while extending her wrist, the patient had the sudden onset of pain and numbness in her thumb. Findings at exploration in the latter patient confirmed partial laceration of the median nerve with a glass fragment embedded in the radial side.

Blunt trauma occurring anywhere in the extremity or neck can injure nerve fibers which terminate in the median nerve or the median nerve itself. As these are typically associated with a significant trauma, the location of the injury is often known. However, acute carpal tunnel can coexist in patients with concomitant injury to the hand or wrist or develop from reperfusion injury. A detailed neurologic examination is critical in trauma patients to determine whether nerve damage is present as a result of the injury. In obtunded patients in which an examination isn't possible, close compartment monitoring is necessary, and prophylactic fasciotomies and carpal tunnel decompression are warranted in patients with prolonged arm ischemia due to vascular injury.

Non-neurologic Disorders

Another set of conditions that can present symptoms of carpal tunnel syndrome are those of non-neurologic origin. Often, they impair nerve function by increasing pressure on the median nerve, while some directly affect blood flow to the nerve.

Vascular Conditions

Symptoms of carpal tunnel syndrome may occur with a number of vascular conditions. Raynaud's disease, hypothenar hammer syndrome, and hand-arm vibration syndrome can all cause symptoms of numbness and tingling in the median nerve distribution [9, 30, 31]. In Raynaud's disease, patients complain of blanching or cyanosis in the fingers triggered by cold or other stressors. Numbness can coexist with the vascular changes and may be the primary complaint. Patients with carpal tunnel syndrome may also complain of coldness in the fingers which is thought to be caused by increased sympathetic activity during periods of increased median nerve compression. Treatment should be focused based on which factors most frequently trigger the symptoms, concentrating on Raynaud's for those with symptoms only occurring with cold exposure. Patients may also suffer from both conditions. In a group of 30

patients with carpal tunnel syndrome, Chung et al. [32] found 60% had concurrent Raynaud's disease based on objective impairment of arterial pulse following cold immersion.

Hand-arm vibration syndrome is characterized by neural and/or vascular symptoms in patients with a history of vibration exposure. Neural symptoms are due to damage to the nerves resulting in paresthesias, pain, sensory loss, and muscle wasting. Finger blanching and pain result from digital vessel spasm and progressive occlusion. Some patients will progress to trophic changes in the fingertips as is seen in other causes of vascular ischemia. Diagnosis is based on the presence of symptoms with a history of significant vibration exposure and should be considered in patients with a 5-year vibration exposure over 5000 h [31]. The importance of distinguishing between the two conditions was highlighted by Pelmear et al. who found that surgical treatment may make the hand-arm vibration syndrome patient worse due to further reduction in grip strength [33].

Proximal vascular conditions can compromise circulation to the median nerve resulting in symptoms of carpal tunnel syndrome. Arm and forearm fistulas placed for vascular access can create a steal phenomenon reducing blood flow distally [34, 35]. In a series of 271 patients undergoing carpal tunnel release, Seifert et al. found 24 patients developed carpal tunnel syndrome following placement of an arteriovenous shunt in the forearm [35]. All were successfully treated with carpal tunnel release. In more severe cases of steal syndrome, reduction of flow through the shunt is achieved by placement of a band, though ligation of the fistula may be necessary to prevent trophic changes and tissue loss [36].

Arthritis

Symptoms of arthritis can sometimes mimic carpal tunnel syndrome especially in patients who have difficulty localizing and describing their symptoms. Patients may complain of pain and aching in the entire hand, wrist pain, and increased symptoms with use with either condition. It is usually easy to differentiate arthritic symptoms from true carpal tunnel syndrome due to the lack of paresthesias, presence of joint deformity, and differing temporal relationship of symptoms. Many patients have coexisting symptoms of both conditions, however, and arthritic degeneration of the scaphotrapeziotrapezoidal joints, radiocarpal joint, and pancarpal joints can lead to mass effect leading to carpal tunnel syndrome. The size of the carpal tunnel can be reduced by osteophyte formation, synovial proliferation, and joint collapse [37].

Tenosynovitis

Multiple forms of tenosynovitis can present in the hand and wrist. Most are clearly differentiated from carpal tunnel syndrome based on location, history, and physical examination. Localized forms of tenosynovitis are easiest to diagnose and fortunately most frequently seen. Typical findings are swelling and tenderness along the tendon sheath, pain with resistance, and warmth. Those occurring near the carpal tunnel include inflammation of the flexor carpi radialis, flexor carpi ulnaris, and first dorsal compartment tendons (extensor pollicis brevis and abductor pollicis longus). Calcific tendonitis causes severe pain, erythema, and swelling about the wrist and when occurring in a tendon within the carpal tunnel can precipitate acute carpal tunnel syndrome [38].

More diffuse tenosynovitis can be harder to differentiate from carpal tunnel syndrome. Patients may complain of numbness, burning pain in the hand and wrist, and weakness. Symptoms are most common with increasing activity, with nighttime numbness and awakening less frequent. Patients often associate occurrence of symptoms with job-related activity such as typing and writing. Several syndromes with subjective diagnostic criteria, including repetitive strain injury, overuse syndrome, fibromyalgia, and dystonia, have been described which may mimic carpal tunnel syndrome [39–41]. Management of these patients without objective evidence of carpal tunnel syndrome (positive electrodiagnostic studies, provocative testing for carpal tunnel, and loss of sensation in the median

nerve distribution) involves ergonomic evaluation, hand therapy, activity modification, and steroid injection into the carpal tunnel. If a patient does not respond to conservative care and has positive provocative findings of carpal tunnel syndrome, a diagnostic steroid injection into the carpal tunnel should be considered. Carpal tunnel syndrome can exist in patients with normal electrodiagnostic studies [42], and carpal tunnel release can be helpful in these patients, particularly if they have shown a positive response to steroid injection.

Infectious

Several infectious causes may create symptoms of carpal tunnel syndrome either due to direct injury to the nerve or mass effect on the nerve. Mycobacterial infections are among the more common causes of infection-related carpal tunnel symptoms, although gonococcal tenosynovitis has been described as well [43]. In a series of 12 patients with *Mycobacterium tuberculosis*-related carpal tunnel, Hassanpour and Gousheh found half the patients had positive Tinel's sign or Phalen's sign, but all had significant swelling of the volar wrist [44]. Intraoperatively, the median nerve was found encased in thickened synovial tissue with associated rice bodies. Treatment, in addition to complete release of the transverse carpal ligament, should include radical tenosynovectomy and postoperative antibiotic therapy. Similar intraoperative findings have been described in cases of *Mycobacterium avium* complex infection as well [45]. Surgeons should have a high index of suspicion for possible mycobacterial infection in the presence of significant swelling and rice bodies and should send cultures specific for mycobacterial organisms which require special media (Lowenstein-Jensen or Middlebrook) incubated for 6–8 weeks at both 37 °C and 31 °C as some species require lower temperatures for isolation.

Another mycobacterial infection which can mimic carpal tunnel syndrome is *Mycobacterium leprae*. Koss et al. described a case of a young college student who had immigrated from Cambodia with persistent symptoms following carpal tunnel release [46]. In addition to persistent numbness and thenar weakness, the patient also had anesthetic cutaneous lesions isolated to the median nerve territory. Exploration of the median nerve revealed a "large, woody, indurated nerve with fatty infiltration."

Herpes zoster can also mimic carpal tunnel syndrome. Bekler et al. reported on a woman with severe pain in the median nerve distribution and weakness of the thenar muscles referred for surgical decompression [47]. The patient was noted to have dermal bulbous lesions in the first web and thenar region and was treated with observation and analgesics, with complete resolution of symptoms.

Inflammatory

Acute and chronic carpal tunnel syndrome can result from multiple inflammatory causes. Gout and pseudogout can lead to either an acute tenosynovitis with resultant swelling and increased pressure in the carpal tunnel or chronic compression of the median nerve from a space-occupying lesion. In acute cases, initial management includes elevation, edema control, colchicine, and oral or injectable steroids. Very close monitoring is required, and surgical decompression justified if symptoms fail to improve within 24–28 h. Operative treatment in acute cases can be complicated by wound dehiscence and drainage [48]. In chronic cases, in addition to tenosynovial proliferation, uric acid and calcium pyrophosphate crystal deposits can form tophi and tumoral calcific masses, respectively [49–51]. These are best treated with both release of the transverse carpal ligament and excision of the mass.

Rheumatoid arthritis, polymyalgia rheumatica, and systemic lupus erythematosus patients also commonly develop carpal tunnel syndrome. Medical management of rheumatoid arthritis often successfully relieves symptoms as the acute inflammation diminishes, and surgical decompression is reserved for patients with persistent

symptoms. For patients with polymyalgia rheumatica, oral corticosteroids typically result in prompt improvement in symptoms [28].

Neoplastic

Non-neurologic tumors should also be considered in the differential diagnosis of carpal tunnel syndrome. Multiple benign and malignant tumors can arise in the carpal tunnel creating a space-occupying lesion increasing pressure on the median nerve. Ganglia, lipomas, synovial chondromatosis, giant-cell tumor of tendon sheath, and vascular tumors are some of the benign tumors reported [52–55]. Malignant tumors must also be considered, with synovial cell sarcoma, squamous cell carcinoma, epithelioid sarcoma, and myxofibrosarcoma described [56–59].

Neoplasms outside of the carpal tunnel can also mimic carpal tunnel syndrome. De Vos et al. reported a case of melorheostosis, a rare progressive disorder in which there is thickening of cortical bone, in a patient referred for carpal tunnel syndrome. Instead, the patient was found to have melorheostosis of the distal humerus causing proximal median nerve dysfunction and was treated with neurolysis and resection of the sclerotic bone [60]. Myxofibrosarcoma of the forearm has also been found to cause median nerve symptoms [56].

Summary

Many conditions, both neurologic and non-neurologic, exist that cause or mask as carpal tunnel syndrome. Particularly in patients who present with symptoms outside the typical spectrum of carpal tunnel complaints, clinicians must keep their minds open to alternate etiologies. Even in patients with typical symptoms, several conditions exist that mimic carpal tunnel syndrome. Having an understanding of these conditions should aid surgeons in making a more expedient diagnosis and referral to the proper specialist and avoid unnecessary surgical intervention.

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CTS Associated or Caused by Other Medical Conditions

6

Christina M. Ward

Hand surgeons should be familiar with a variety of medical conditions associated with carpal tunnel syndrome (CTS). In some instances, the presence of an underlying medical disease may influence treatment or prognosis. For example, the progression of CTS symptoms in a patient with rheumatoid arthritis can signal increased flexor tenosynovitis and the need for more aggressive rheumatologic treatment. This chapter presents a spectrum of medical illnesses associated with CTS and their effects on treatment and prognosis.

Diabetes Mellitus

Diabetes mellitus affects the largest number of patients with CTS. The prevalence of CTS in diabetic patients is 15–25% [1], and up to 80% of type 1 DM patients will develop CTS over their lifetime [2]. According to a recent meta-analysis, type 1 or type 2 DM is associated with a twofold increased risk of CTS [3].

DM patients are also more likely to develop other neuropathies such as sensorimotor polyneuropathy. Nerve conduction studies can differentiate between patients with diabetic polyneuropathy and compression from carpal tunnel syndrome, and many patients will have both. Perkins et al. reported that CTS is present in 2% of the general population, 14% of DM patients without diabetic polyneuropathy, and 30% of DM patients with polyneuropathy [4].

Corticosteroid injection may relieve CTS symptoms in DM patients, but practitioners should warn patients that the corticosteroid can elevate their blood glucose for several days. Kim et al. found that 80% of DM patients had elevated blood glucose levels for up to 5 days following an injection of 10 mg of triamcinolone [5]. Corticosteroid injections may be less effective in DM patients, as DM patients were more likely than non-DM patients to undergo carpal tunnel release (CTR) for recurrent symptoms after corticosteroid injection [6].

Diabetic patients can expect similar results after CTR as nondiabetic patients, although their recovery may be slightly slower. Thomsen et al. found no difference in sensation, strength, patient satisfaction, or patient-reported outcomes between DM and non-DM groups 5 years after CTS surgery [7, 8]. One year after surgery, DM patients were more likely to complain of cold intolerance, but this difference resolved by the 5-year follow-up [7, 8]. Likewise, Cagle et al. found that diabetic patients improved more slowly but had similar functional results to non-DM patients 6 weeks after surgery [9].

C.M. Ward (✉)
Department of Orthopaedics, University of Minnesota, Regions Hospital, 640 Jackson Street, Saint Paul, MN 55101, USA
e-mail: Christina.M.Ward@Healthpartners.com

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There is no evidence to support routine use of prophylactic antibiotics in DM patients undergoing CTR. Harness reported very low infection rates after CTR in both diabetic (0.55%) and non-diabetic patients (0.33%) and no difference between those treated with prophylactic antibiotics and those without [10].

Hypothyroidism

Estimates of the association between CTS and hypothyroidism vary. Oktayoglu reported 32.5% of patients being treated for hypothyroidism met criteria for CTS based on electrophysiological studies [11]. Eslamian et al. also identified CTS based on electrophysiological studies in 32.5% of 40 patients with untreated hypothyroidism [12]. In contrast, Shiri's meta-analysis found a modest association between hypothyroidism and suggested that the association may be exaggerated by publication bias [13].

Although patients with hypothyroidism may have CTS, screening all patients with CTS for hypothyroidism is low yield. De Rijk et al. identified two new cases of hypothyroidism out of 516 patients with CTS and no known history of hypothyroidism [14]. Similarly, Vashishtha et al. diagnosed two new cases of hypothyroidism among 100 patients indicated for carpal tunnel release [15].

Treatment with thyroid replacement can improve nerve function on electrophysiologic testing [16, 17]. Kececi found statistically significant changes in median motor distal latency and amplitude and median sensorial nerve conduction velocity after 3 months of thyroid replacement treatment [16]. Unfortunately, in most hypothyroid patients, CTS symptoms persist even after appropriate treatment with thyroid replacement [17].

No studies directly address the role of bracing, steroid injection, or carpal tunnel release in hypothyroid CTS patients.

Acromegaly

Acromegaly results from excessive secretion of growth hormone, commonly due to a pituitary adenoma. The majority of acromegaly patients will demonstrate electrophysiologic changes in the median nerve at the wrist, although they may or may not report CTS symptoms [11]. MRI studies of acromegaly patients with CTS demonstrate enlargement of the median nerve [18].

Although a high percentage of acromegaly patients will have CTS, acromegaly is sufficiently rare that screening CTS patients for elevated growth hormone is not indicated. Zoicas et al. screened 196 patients indicated for CTR and found no patient with acromegaly [19].

Treatment of the underlying cause of acromegaly can decrease CTS symptoms [18, 20]. Sasagawa et al. noted improvement in nerve conduction velocities and patient-reported symptoms one year after adenoma resection in seven of eight patients with acromegaly and CTS [18]. In a group of four acromegaly patients with persistent CTS after treatment for elevated growth hormone, Iwasaki reported successful symptom relief with carpal tunnel release [21].

Obesity

Increased BMI and obesity have been linked to carpal tunnel syndrome. In a recent meta-analysis of 58 studies, obese patients had a twofold increased risk of CTR. That same study estimated that each one unit increase in BMI correlated with a 7.4% increase in CTS and increased the risk of CTR by 7.4% [22].

However, obese patients are also more likely to have other comorbidities that can contribute to CTS risk. Specifically, those obese patients that meet criteria for metabolic syndrome (Table 6.1) tend to have more severe CTS than those who have diabetes or obesity alone [23]. Mondelli et al. also identified truncal obesity measured by

Table 6.1 Criteria for metabolic syndrome

Central obesity (waist circumference > 102 cm in males and >88 cm in females)
Hypertriglyceridemia (triglycerides ≥ 150 mg/dL)
Low serum HDL-C (<40 mg/dL in males and <50 mg/dL in females)
Hypertension (blood pressure ≥ 130/85 mm Hg or taking antihypertensive medication)
Fasting plasma glucose ≥ 100 mg/dL

waist circumference/hip circumference as a risk factor for CTS [24].

Few studies examine the effect of weight loss on CTS symptoms. Kurt et al. found no improvement in median nerve conduction despite 3 months of weight loss in obese patients [25]. Castro Ado et al. identified no difference in CTS prevalence between patients awaiting bariatric surgery and those who had undergone bariatric surgery [26].

Rheumatoid Arthritis

Rheumatoid arthritis (RA) may be associated with an increased incidence of CTS, although study results vary. Karadag identified ultrasound evidence of CTS in 17 of 100 women with RA compared to 4% of age-matched controls [27]. In a larger study of 1070 RA patients, the CTS incidence was 4.2 per 1000 person-years which is very similar to the rate in the general population [28].

Practitioners should not assume upper extremity numbness in RA patients is due to CTS as nerve dysfunction can result from several different mechanisms associated with RA. Cervical spine instability or degeneration can lead to nerve dysfunction. In addition, damage to the nerve vascular supply can cause neuropathy not associated with compression. Some patients may experience a "double crush" if there are multiple points of nerve compression or damage [29].

Few studies describe outcomes after CTS treatment in RA patients. Muramatsu et al. reported mostly good and excellent results after CTR in 15 patients [29], and they suggested doing flexor tenosynovectomy only in those with florid tenosynovitis. Belcher et al. reported good results following endoscopic CTR with no tenosynovectomy in "selected" RA patients (seropositive but clinically well controlled) [30].

Gout

Gout is not a common cause of CTS, but gout patients can experience deposition of monosodium urate crystals in the soft tissues in and around the carpal tunnel. Wrist MR in patients with tophaceous gout identified tophi in the floor of the carpal tunnel, flexor tendons, wrist joint, and extensor tendons [31]. Gouty tophi and liquefied tophi have been implicated in several cases of acute carpal tunnel syndrome [32]. Although it may be indicated to relieve pressure on the nerve, carpal tunnel release in the setting of tophaceous gout can lead to poor wound healing and persistent drainage [31, 32].

Pregnancy

Between one third and one half of women will report CTS symptoms during pregnancy, and approximately 17% will have electrophysiologic evidence of CTS [33, 34]. Typically, symptoms worsen during the course of the pregnancy and are most severe in the third trimester [25]. After 30 weeks, most pregnant women experience an increase in extravascular fluids (fluid retention) which likely contributes to median nerve compression [25]. A recent review found that 50% of patients still report symptoms 1 year after delivery and 30% will still have symptoms 3 years postpartum [35].

Nighttime bracing, steroid injection, and carpal tunnel release surgery are all treatment options for pregnant patients. In one study of 20 pregnant women with CTS, injection with dexamethasone and lidocaine both decreased symptoms and improved their electrophysiologic exam. No study has directly examined the safety of carpal tunnel steroid injection during pregnancy, but no complications have been reported from this treatment [34].

If possible, surgery should be avoided during pregnancy because symptoms will often resolve after delivery. However, if necessary, carpal tunnel release can be performed under local anesthetic with a tourniquet. Assmus and Hashemi found 98% of 133 pregnant patients reported good or excellent results after CTR [36].

Infectious Conditions

A variety of atypical infectious organisms can lead to CTS, including mycobacteria and fungi. In most of these cases, patients experience a

slowly developing swelling over the volar wrist and median nerve dysfunction. Advanced imaging such as MRI will reveal thickening of the flexor tenosynovium, but cannot differentiate between infectious and other causes of tenosynovitis such as rheumatoid arthritis. Significant asymmetric swelling over the flexor tendons or a history of immune compromise should prompt consideration of atypical infection, and biopsy of inflammatory tenosynovial tissue should be obtained for fungal and AFB cultures.

Tuberculosis in the hand most commonly presents as slowly progressive flexor tenosynovitis [37]. The tenosynovitis appears as swelling proximal and distal to the transverse carpal ligament and sometimes communicates with the radial or ulnar bursa. Rice bodies may be seen upon opening the carpal tunnel. Treatment consists of operative decompression and debridement along with antituberculosis antibiotics [38]. Delay in diagnosis and treatment can lead to flexor tendon rupture. Most patients will not have systemic or pulmonary manifestations of their tuberculosis infection [37].

Fungal infection with *Histoplasma capsulatum* or *Sporothrix schenckii* can also cause flexor tenosynovitis and associated CTS [39, 40]. *Histoplasma capsulatum* can be found in cat and bat feces and is endemic to portions of North, Central, and South America. The majority of patients with reported cases of CTS due to histoplasmosis occurred in immunocompetent patients [41]. *Sporothrix schenckii* typically causes a lymphocutaneous infection following inoculation of the hand or arm from a plant puncture, but can cause a proliferative tenosynovitis in the carpal tunnel [42].

Amyloidosis

Certain forms of amyloidosis can cause CTS. Thirty-eight percent of patients with Finnish gelsolin amyloidosis (also known as Meretoja syndrome) reported CTS symptoms [39]. This autosomal dominant syndrome consists of eye problems (corneal lattice dystrophy), lax facial skin (cutis laxa), and paresis of facial nerves. One quarter of patients in the Finnish gelsolin amyloidosis registry underwent carpal tunnel release surgery.

Some researchers suggest that amyloid deposition may contribute to so-called idiopathic CTS. Uchiyama et al. reported some degree of wild-type transthyretin amyloid was present in the tenosynovium of 34% of patients undergoing CTR for presumed idiopathic CTS, which was higher than age-matched controls. This type of amyloid deposition is known to be age related. The presence of amyloid did not impact functional outcome after CTR in the patients with amyloid deposition [40, 43].

Mucopolysaccharide Storage Diseases

Mucopolysaccharide storage diseases (MPSD) can cause both trigger digits and carpal tunnel syndrome in children. Deficiency in 1 of 11 enzymes necessary for breakdown of glycosaminoglycans (GAGs) results in systemic deposition of GAGs (Table 6.2). In the hand, this manifests as skeletal dysplasia as well as thickening of the flexor retinaculum, tenosynovium, and epineurium [44]. Although hematopoietic stem cell transplantation and enzyme replacement therapy mitigate many MSPD manifestations, these therapies do not seem to prevent or cure CTS [45].

MPSD patients rarely present with typical CTS complaints of numbness and paresthesias, but may exhibit behaviors such as clumsiness, gnawing of hands, withdrawal of hands from others, and nighttime waking [44].

MPSD should be considered in any child presenting with CTS. If initial urine testing reveals excessive urinary excretion of glycosaminoglycans, the patient should be referred to a geneticist for a complete evaluation. In a patient with a known diagnosis of MPSD, Holt et al. recommend screening for CTS beginning at age 3 [44]. Using the adjacent ulnar nerve as a control, nerve conduction values can confirm the diagnosis of CTS. Treatment for CTS should include carpal tunnel release through an extended carpal tunnel incision combined with flexor tenosynovectomy

Table 6.2 Enzyme deficiencies in mucopolysaccharide storage diseases

Type	Common name	Deficient enzyme	Accumulated products
MPS I H MPS I H/S MPS I S	Hurler Hurler-Scheie Scheie	Alpha-L-iduronidase	Heparan sulfate Dermatan sulfate
MPS II	Hunter	Iduronate-2-sulfatase	Heparin sulfate Dermatan sulfate
MPS III A MPS III B MPS IIIC MPS IIID MPS IIIE	Sanfilippo	Sulfamidase Alpha-*N*-acetylglucosaminidase Acetyl-CoA-glucosaminide-acetyltransferase *N*-acetylglucoosamine-6-sulfatase *N*-glucosamine 3-*O*-sulfatase	Heparin sulfate
MPS IV A-B	Morquio	*N*-acetylgalactosamine-6-sulfatase Beta-galactosidase	Keratin/chondroitin sulfate
MPS VI	Maroteaux-Lamy	Arylsulfatase B	Dermatan sulfate
MPS VII	Sly	Beta-glucuronidase	Heparan sulfate Dermatan sulfate Chondroitin 4,6-sulfate
MPS IX	Natowicz	Hyaluronidase	Hyaluronic acid

and potentially excision of FDS tendons in severe cases. Nerve conduction changes may persist after surgical treatment.

Hemodialysis

Patients on hemodialysis for end-stage renal disease are at risk for developing carpal tunnel syndrome, although the exact incidence is not known. Increased extracellular fluid volume secondary to uremia, amyloid deposition in the soft tissues including the epineurium, and fluid shifts during hemodialysis contribute to CTS in HD patients [46]. CTS may occur in the arm with or without an arteriovenous fistula [46]. Although many patients require HD as the result of DM complications, CTS occurs regardless of the cause of their renal disease, and the likelihood of developing CTS correlates with the duration of hemodialysis [47].

Most hemodialysis patients who undergo CTR will experience a decrease in symptoms. Kang et al. reported a higher incidence of wound healing problems and recurrent CTS in hemodialysis patients compared to age-matched patients with idiopathic CTS. In that study, 30 of 36 hemodialysis patients reported fewer CTS symptoms 2 years after CTR [47].

Conclusion

Although most patients will have idiopathic CTS, surgeons should recognize associated medical conditions and their impact on treatment and prognosis.

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7 Interpretation of Electromyography and Nerve Conduction Studies

Katherine A. Impastato and Jeffrey B. Friedrich

The Utility of Understanding EMG and NCS

A good history and physical exam can strongly suggest a specific diagnosis, but electrodiagnostic studies are the only tool by which we can obtain an objective physiologic measure of neurologic and muscular function. One must also consider the potential of identifying concomitant or alternative neurological disorders as the cause of the patient's symptoms, which occurs as much as 42% of the time [1]. Electrodiagnostic studies consist of a combination of nerve conduction studies and electromyography (further referred to as EMG/NCS) that are typically performed simultaneously. NCS are used to evaluate motor and sensory nerves, while EMGs provide information about the muscle innervated by the nerve. Together, EMG/NCS provide a dynamic, real-time snapshot of the function of the pertinent portions of the peripheral nervous system and associated muscular system, respectively. They are most beneficial when used as an extension of the physical exam to provide insight into the contribution of the nerves and muscles to abnormalities seen on exam. Unlike radiologic studies that provide a static image of the presence or absence of an anatomical explanation for an abnormal exam, EMG/NCS provides information about the function of specific anatomic components. EMG/NCS are used in conjunction with a directed neurologic exam to diagnose and localize pathology. Once the pathology is localized, the differential diagnosis is narrowed to guide subsequent evaluation and medical or surgical intervention. For example, in a patient with thumb, index, and middle finger numbness and hand weakness, there may be a median neuropathy at an entrapment site within the carpal tunnel, a brachial plexus lesion, or a cervical radiculopathy. EMG/NCS are done to help localize the site of pathology, thereby guiding further treatment. They are also useful to determine severity and prognosis. For example, a neuropraxia has a good prognosis where axonotmesis has a poor prognosis. They are also valuable to documentation in workers' compensation cases and patients with potential for secondary gain.

K.A. Impastato
University of Washington, Seattle, WA, USA

J.B. Friedrich (✉)
Plastic and Reconstructive Surgery and Orthopedic Surgery, University of Washington, Seattle, WA, USA
e-mail: jfriedri@uw.edu

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Physiology of Neurons and Muscle Cells: Why Electrodiagnostic Testing Works

Axons are composed of a semipermeable membrane with potassium channels, sodium channels, chloride channels, and sodium-potassium ATP-dependent pumps. At rest, there is a 60–90 mV membrane potential present established by the differences in concentration of these ions inside and outside of the cell, with the intracellular region being relatively electronegative in comparison with the extracellular region. This equilibrium/resting membrane potential is formed when there is balance between electrical and concentration forces between these ions, chiefly due to potassium channels that are always open. When a stimulus of any sort causes the membrane to reach its threshold potential (usually 15–20 mV less negative than resting membrane potential), the voltage-gated sodium channels open, allowing influx of sodium and the generation of a self-propagating action potential. This "all-or-none" phenomenon is critical to the basis of electrodiagnostic studies. In an intact motor unit, an anterior horn cell body or its axon that is stimulated above its threshold potential will propagate a full action potential including synchronous depolarization of the muscle fibers it innervates. Therefore, abnormalities can be localized during an EMG/NCS by testing at different levels along a nerve distribution. Myelinated neurons propagate via saltatory conduction during which the action potential "jumps" along the nodes of Ranvier, skipping the myelinated portions of the nerve. This drastically increases the velocity of the action potential by decreasing the time spent repolarizing, as there are no potassium channels in the nodes.

It is important to consider several factors that affect action potential propagation other than pathology alone. The temperature of the extremity being analyzed, gender, age, extremity length, and digit circumference are all important factors to consider. The only factor amenable to change is temperature. The relationship between surface temperature and NCV has been measured in the median motor and sensory nerves, and there is a 1.5 m/s decrease in velocity per degree of Celsius decrease [2]. There is debate as to whether passive warming, active warming, or a calculation is best to account for differences in body temperature. It is important to know what method a particular laboratory uses and if this is standardized among all patients so that comparisons can be made.

EMG and NCS Technical Considerations

Typically NCS are done prior to the EMG portion, as EMGs are painful and not always tolerated by patients. The American Association of Electrodiagnostic Medicine (AAEM) began a critical literature review of 165 articles to define the practice standards and practice guidelines for electrodiagnostic studies of carpal tunnel syndrome. Based on a comparison of pooled sensitivities and specificities of electrodiagnostic techniques to diagnose carpal tunnel, they published recommendations for diagnosis of CTS to minimize the number of tests needed to make the diagnosis and eliminate use of techniques with poor sensitivity and specificity. The EMG techniques evaluated included median sensory and mixed nerve conduction: wrist and palm segment compared to forearm or digit segment, comparison of median and ulnar sensory conduction between wrist and ring finger, median sensory and mixed nerve conduction between wrist and palm, comparison of median and ulnar mixed nerve conduction between wrist and palm, median motor nerve conduction between wrist and palm, comparison of median and radial sensory conduction between wrist and thumb, median sensory nerve conduction between wrist and digit, median motor nerve distal latency, median motor nerve terminal latency index, comparison of median motor nerve distal latency (second lumbrical) to the ulnar motor nerve distal latency (second interossei), and sympathetic skin

response. Based on their review, they limited the practice standard to an evaluation of the median sensory NCS between the wrist and digit for a distance of 13–14 cm. If the initial result is abnormal, an adjacent sensory nerve of the symptomatic limb should be evaluated for comparison. If the initial test is normal, then the examiner has three options to complete the evaluations. It is considered standard of care to either perform a median sensory NCS or mixed NCS across the wrist and compare to the ulnar sensory NCS or mixed NCS across the wrist over the same distance, perform median sensory NCS and compare to ulnar or radial sensory NCS between wrist and ring finger in the same limb, or perform median sensory NCS or mixed NCS at wrist and palm segment distal to the carpal tunnel to compare to itself in the forearm (proximal to the carpal tunnel). The authors concluded that NCS alone have >85% sensitivity and >95% specificity to confirm the diagnosis of carpal tunnel syndrome. While NCS were not as sensitive or specific for CTS, it was concluded that it provides insight into the localization of pathology elsewhere allowing the examiner to evaluate less common areas of compression.

Nerve Conduction Studies

NCS are performed by selecting known stimulation recording sites. Electrodes are placed over the nerve in question or a muscle it innervates. The nerve is stimulated to produce an action potential that then self-propagates to the location of the electrode. Electrodes are able to detect the electrical gradients caused by the action potential as it propagates beneath it. The electrical gradients are converted into a waveform that is displayed with time on the x-axis and voltage on the y-axis. These waveforms, referred to as the evoked response, can then be evaluated. The velocity of propagation and morphology of different aspects of this waveform are used to correlate findings with possible disease processes. Different portions of the nerve are evaluated independently and then compared to localize pathology.

Sensory Nerve Conduction Studies

When evaluating a sensory nerve, the action potential can be obtained in the anatomical direction (orthodromic recordings) or in the opposite direction (antidromic), typically depending on ease of the study. For example, it is easier to record an action potential at the fingertip where the nerve is superficial than it is to record the nerve in the forearm. Therefore the electrode is usually placed over the finger, and the sensory nerve is stimulated more proximally, in an antidromic direction. As in all NCS, the nerve is stimulated, and electrodes are placed a known distance from the stimulation site over the distribution of the nerve. The electrodes detect the electrical gradient that is depicted as a waveform referred to as a SNAP (sensory nerve action potential). For sensory nerve studies, important aspects of the waveform are onset latency, peak latency, amplitude, area, and nerve conduction velocity. Abnormalities in a sensory nerve can be revealed by comparing multiple segments of the same nerve to detect any discrepancies in these aspects of the waveform or velocity.

Motor Nerve Conduction Studies

Evaluation of motor nerves by NCS is similar to the evaluation of sensory nerves with the exception that the action potential is recorded over a muscle supplied by the nerve being evaluated, rather than a distant aspect of the nerve itself. The onset latency, amplitude (which can be artificially reduced in patients with myopathy or neuromuscular junction disorders), and area are, again, directly recorded. However, to accurately examine the motor nerve conduction velocity, the examiner must account for the latency inherent in the neuromuscular junction and conduction between muscle fibers. This is performed by

using two different stimulation sites for each aspect of the nerve tested. The distance between the two sites is divided by the change in latency recorded at each site, effectively removing the time added for neuromuscular junction transmission and muscle fiber conduction.

Needle Electromyography

NCS alone is the primary tool needed for diagnosis of carpal tunnel syndrome; however, less common entrapments require needle EMG for localization. For example, an abnormal EMG of the pronator teres points to an upper arm lesion, while abnormalities in FDP and FPL point to AIN branch compression, and abnormalities in abductor pollicis brevis indicate possible compression of the recurrent branch of the median nerve. Thus, it is as important to record normal findings as it is to record abnormal findings.

EMGs can be significantly painful to some patients, so remaining focused and beginning with the highest yield aspects of the test are necessary to obtain meaningful information. Prior to beginning EMG testing, the examiner should know the differential diagnosis and understand which areas need to be evaluated by EMG to serve this purpose.

During the EMG portion of electrodiagnostic testing, a needle electrode is inserted through the skin and fascia into the muscle. EMG assesses the entire motor unit—the motor nerve's cell body in the anterior horn, its axon, and all of the motor fibers it innervates. In areas of fine motor control, a single motor neuron may innervate as few as ten muscle fibers (e.g., extraocular muscles), whereas other motor units consist of a single neuron innervating 2000 muscle fibers (such as spinal postural muscles). For each muscle, the insertional activity, spontaneous activity, motor unit potentials, and recruitment capacity are evaluated.

Insertional Activity

As the needle is inserted into the muscle, it causes a mechanical depolarization of the muscle fibers that are recorded by the needle electrode. Decreased insertional activity can indicate either incorrect placement of the needle or muscle depolarization abnormality. This is seen in atrophic muscles, muscles that have been replaced by fibrous tissue, or muscles otherwise incapable of depolarizing. Prolonged or increased insertional activity alone cannot be used to make a diagnosis. It does support the diagnoses of acute denervation or primary myopathy when seen in conjunction with spontaneous activity at rest, as discussed below.

Spontaneous Activity

At rest there should be electrical silence. When a nerve is cut, the muscle fibers it previously innervated become hypersensitive, discharging spontaneously. Fibrillations, positive sharp waves, complex repetitive discharges, and fasciculation potentials are abnormal findings associated with muscle damage secondary to this denervation or primary myopathy. *Fibrillations* are most commonly associated with denervation but are also seen in myopathies or early after upper motor neuron injury. The amplitude of the fibrillation may give insight to the onset of the abnormality. After denervation, the muscle fiber's resting membrane potential becomes less negative and thus closer to threshold potential, and it also begins to oscillate [3, 4]. The oscillating membrane eventually reaches the threshold potential depolarizing the muscle fiber, causing a recurring and recordable electrical potential. *Positive sharp waves* have essentially the same significance as fibrillations and are likely caused by single muscle fiber discharge [5]. *Complex repetitive charges* are also similar to fibrillations and positive sharp waves but instead represent groups of muscle fibers spontaneously depolarizing in synchrony. *Fasciculation potentials* are spontaneous contraction of a portion of a muscle that is visible from the surface. Unlike fibrillations, fasciculations involve the entire motor unit with the action potential originating within the anterior horn or ectopically anywhere along the axon.

Motor Unit Potentials

A motor unit is the anterior horn cell, its axon, and all of the muscle fibers innervated by that

axon. When a single muscle fiber depolarizes, it generates a measurable action potential with a characteristically triphasic waveform. When multiple muscle fibers within a single motor unit are stimulated to synchronously depolarize, the individual voltages are summated to produce a motor unit potential (MUAP), which is also characteristically triphasic. The morphologic aspects most important when examining the MUAP are its amplitude, duration, and number of phases. The number of muscle fibers innervated is reflected in the amplitude. The duration of the MUAP depends of the conduction velocity of the axon. The number of phases in the waveform is dependent on the synchrony of the muscle fiber making up the motor unit. If there is a delay in the depolarization of some of the muscle fibers within the motor unit, it will present as polyphasic potentials (more than four phases). For example, if a nerve is transected, all of the muscle fibers within its motor unit are denervated. Nearby axons will begin sprouting to reinnervate the nearby muscle fibers. The more muscle fibers these axons innervate, the greater their amplitude will be. Early in this process, the sprouts are not myelinated. Evaluation of the non-myelinated sprouts will show increased duration of the MUAP, consistent with slowing. The MUAP will also have a polyphasic potential, due to lack of synchrony of muscle fibers receiving stimulation from nerves with varying degrees of myelination. In myopathies where random muscle fibers degenerate, the MUAP would have diminished amplitude, shorter duration, and polyphasic nature secondary to the increased gaps to bypass.

Recruitment Capacity

The patient is asked to activate a muscle minimally then at increasing intensity up to maximal voluntary contraction capacity. The amplitude, duration, number of phases, and firing rate are all evaluated. As the intensity of the contractions increases, the number of motor units recruited should also increase. In a normal healthy person, there are no areas remaining at baseline. Thus, when all of the motor units are appropriately recruited, their potentials will overlap to maintain a maximally flexed muscle. It is more difficult to differentiate between patients with upper motor neuron loss, lower motor neuron loss, or with poor effort; they will all have reduced recruitment. In patients with poor effort, there will oftentimes be bursts of normal recruitment followed by diminished recruitment. In muscle fiber loss, when the patient is asked to perform a minimally activating test, there will be over-recruitment of muscles producing a high-frequency wave. Immediately following an acute injury to the nerve, there will be decreased recruitment of the motor units, but because Wallerian degeneration will take time to reach the level of the muscle, there will not be any fibrillations or positive sharp waves until several weeks later.

Interpretation of NCS and EMG

Interpretation of Nerve Conduction Studies

One should begin by evaluating the onset latency of motor NCS and the onset or peak latency of sensory NCS. Onset latency is measured as the time from stimulation to the beginning of the waveform. Peak latency is the time from stimulation to the peak of the waveform.

To accurately examine the motor nerve conduction velocity, the examiner must account for the latency inherent in the neuromuscular junction and in conduction between muscle fibers. This is done by using two different stimulation sites for each aspect of the nerve tested. The distance between the two sites is divided by the change in latency recorded at each site, effectively removing the time added for neuromuscular junction transmission and muscle fiber conduction. If one were to assess the onset latency of a sensory nerve, no additional calculation is required because the test is purely a test of the sensory nerve's speed of conduction.

For carpal tunnel syndrome, a distal sensory latency of greater than 3.2 ms or motor latency of greater than 4.3 ms is considered abnormal.

Depending on the machine being used, the examiner may prefer to use peak latency to evaluate sensory NCS. This is because the background

noise in sensory examinations is louder, making defining a clear onset of the waveform difficult.

Second, the amplitude of the waveform is evaluated. In general the amplitude provides an estimate of the quantity of functional motor units. Motor nerves are measured in mV and sensory nerves in amplitude. A low-amplitude waveform may indicate axon loss or a conduction block. In axon loss, stimulation of an axon segment both proximal and distal to the injured area will be diminished over time secondary to Wallerian degeneration. In these instances, it is difficult to use electrodiagnostic studies to localize pathology as an injury in the brachial plexus or in the forearm over time will have similar effects on the amplitude of the waveform over the entire length of the nerve. An amplitude loss of 50% is considered pathologic when comparing the amplitude at different locations along the nerve. For example, the amplitude at the elbow, forearm, and wrist is measured, and if there is a 50% reduction in the amplitude between the wrist and the elbow, it is an indication of pathology between those two locations.

Finally, conduction velocity is evaluated. Motor NCS can evaluate nerve segments where slowing in a particular area provides useful localizing information. A velocity of less than 52 meters per second is abnormal.

Needle Electromyography Interpretation

Needle EMG provides localizing information, an estimated length of time the lesion has been present, and if there is reinnervation.

Anatomy and innervation of the musculature are most important when localizing a lesion during EMG. When a lesion of a peripheral nerve is suspected, an evaluation of muscles innervated by the same peripheral nerve but different nerve roots should be done. Conversely, when a radiculopathy is suspected, evaluation of muscles innervated by different peripheral nerves with a common nerve root would provide the most meaningful information.

EMG can also provide insight into the length of time since the lesion arose. The amplitude of the fibrillation may give insight to the onset—immediately following injury, there will not be fibrillations because it will take time for Wallerian degeneration to reach the level of the muscles. After 3–6 weeks, EMG will detect large-amplitude fibrillations associated with recent muscle denervation, and as the muscle atrophies over time, it will produce smaller-amplitude fibrillations.

The electrical activity studied with EMG is the insertional activity, spontaneous activity, and motor unit potentials, and a diminished insertional activity is concerning for muscle fibrosis, whereas an increased insertional activity (more than 300–500 ms) is concerning for early denervation. In terms of spontaneous activity, a normal muscle is silent, whereas abnormal muscles will show fibrillations or positive sharp waves spontaneously. Motor unit potentials in normal muscles are characteristically bi- or triphasic. Demyelinating or axonal neuropathies will also have bi- or triphasic potentials, whereas damage to the more proximal, anterior horn cell or myopathies may have polyphasic potentials.

Example 1: Carpal Tunnel Syndrome
Summary of Findings:

1. Left median motor study to APB has markedly prolonged distal onset latency, normal compound muscle action potential (CMAP), and normal conduction velocity in the forearm.
2. Left ulnar motor to ADM has normal distal onset latency, CMAP, and normal conduction velocity in the forearm.
3. Left median sensory to the thumb and ring finger is absent.
4. Left radial sensory to the thumb and ulnar sensory to the ring finger have normal peak latency and sensory nerve action potential (SNAP).
5. Left transpalmer study with markedly prolonged median peak latency, normal ulnar peak latency, and SNAPs.
6. Left combined sensory index (CSI) study is abnormal at 2.5 ms (CSI is defined as median

Nerve Conduction Studies

Motor Summary Table

Site	Onset (ms)	Peak (ms)	O-P Amp (mV)	P-T Amp (mV)	Full Area (mV·ms)	Sitel	Site2	Delta-0 (ms)	Dist (cm)	Vel (m/s)
Left Median >40y/o Motor (Abd Poll Brev) 31.4°C										
Wrist	**6.1**	9.4	10.4	14.9	55.07	Elbow	Wrist	4.2	22.0	52
Elbow	10.3	13.4	8.9	12.1	49.92					
Left Ulnar ADM >40y/o Motor (ADM (8 cm)) 31.8°C										
Wrist	3.1	6.7	8.0	10.6	42.26	B Elbow	Wrist	3.3	20.5	62
B Elbow	6.4	10.2	7.9	10.4	40.41	A Elbow	B Elbow	1.3	9.5	73
A Elbow	7.7	11.7	7.3	9.8	39.57					

Comparison Summary Table

Site	Peak (ms)	P-T Amp (µV)	Sitel	Site2	Delta-P (ms)	Dist (cm)
Left Median/Radial Comparison (Thumb) 32.4°C						
Median	**Absent**		Median	Radial		10.0
Radial	2.9	13.6				
Left Median/Ulnar Comparison (Digit 4) 32.3°C						
Median Wr	**Absent**		Median Wr	Ulnar Wr		14.0
Ulnar Wr	3.3	12.0				
Left Palmar Comparison (Wrist (8 cm)) 30.1°C						
Median Palm	**4.5**	9.6	Median Palm	Ulnar Palm	2.5	8.0
Ulnar Palm	2.0	15.8				

Needle EMG Monopolar

Side	Muscle	Nerve	Root	Ins Act	PSWs	Fibs	Fib Amp	Fascic	Other	Min Amp uV	Max Amp uV	MUAP Dur	Phasicity	Recruit
Left	Trapezius	SpinalAcc	CN XI, C3-4	Nml	0	0		0	0	1200	3500	Nml	Nml	Full
Left	Supraspinatus	SupraScap	C5-6	Incr	3+	3+		0	0	600	2500	Incr	Incr	Reduced
Left	Infraspinatus	SupraScap	C5-6	Incr	2+	2+	100	0	0	600	3000	Incr	Sl Incr	Reduced
Left	Pect major – Sternal Head	Med Pectoral	C7-8	Nml	0	1+		0	0	600	2200	Incr	Incr	Mildly Reduced
Left	Serratus Anterior	LongThor	C5-7	Incr	1+	2+	100	0	0	1200	3500	Nml	Sl Inc	Mildly Reduced
Left	LatisDorsi	ThoracoDors	C6-8	Incr	1+	2+	100	0	0	1200	5000	Nml	Nml	Mildly Reduced
Left	Deltoid	Axillary	C5-6	Incr	4+	3+	300	0	0					None
Left	Biceps	Musculocut	C5-6	Incr	3+	3+	100	0	0					None
Left	Triceps Long	Radial	C6-7-8	Incr	4+	3+	150	0	0					None
Left	Triceps Lat	Radial	C6-7-8	Incr	4+	3+	125	0	0					None
Left	BrachioRadial	Radial	C5-6	Incr	3+	3+	100	0	0					None
Left	1st Dorsal Int	Ulnar	C8-T1	Incr	2+	3+	200	0	0					None
Left	ExtDigCom	Radial (Post Int)	C7-8	Incr	4+	3+	75	0	0					None
Left	Abd Poll Brev	Median	C8-T1	Incr	3+	3+	100	0	0					None

minus radial latency to thumb + median minus ulnar latency to ring + median minus ulnar latency across the palm. Normal CSI at the Carpal Tunnel is <1.0 ms).

Example 1—electrodiagnostic evidence of left motor and sensory demyelinating median mononeuropathy at the wrist

Example 2: Brachial Plexus Injury

Positive sharp waves (PSWs), fibrillation potentials (fibs), fibrillation amplitude (fib amp), fasciculation (fascic), motor unit action potential (MUAP)

Summary of Findings:
NCS:

1. There are absent left median and ulnar motor responses.
2. There are absent left median sensory responses to the thumb and index fingers.
3. There is absent left ulnar sensory response to the small finger.

EMG:

1. In this patient, studies over the volar forearm including pronator teres and proximal median nerve were not tested due to healing graft, and the cervical paraspinals were not tested due to a Miami-J collar.
2. The left spinal accessory nerve is normal.
3. The left long thoracic, medial pectoral, and thoracodorsal nerve demonstrate less spontaneous activity, mildly reduced recruitment, and evidence of reinnervation.
4. The left axillary, musculocutaneous, radial, median, and ulnar nerve demonstrate extensive denervation with no observable voluntary motor units.

Example 2—electrodiagnostic evidence of traumatic nerve injury to multiple peripheral nerves and the brachial plexus of the left upper extremity. Given the diffuse nature of findings, it is difficult to precisely localize the injury. However, the pattern is suggestive of less severe brachial

Nerve Conduction Studies

Motor Summary Table

Site	Onset (ms)	Peak (ms)	O-P Amp (mV)	P-T Amp (mV)	Full Area (mV·ms)	Site 1	Site 2	Delta-0 (ms)	Dist (cm)	Vel (m/s)
Left Median >40y/o Motor (Abd Poll Brev) 33.2°C										
Wrist	ABSENT									
Left Ulnar ADM >40y/o Motor (Abd Dig Minimi) 34.2°C										
Wrist	ABSENT									

Anti Sensory Summary Table

Site	Peak (ms)	O-P Amp (µV)	P-T Amp (µV)	Delta-0 (ms)	Dist (cm)	Vel (m/s)
Left Median Thumb (Wrist) 33.8°C						
Thumb	ABSENT					
Left Median Long (Wrist) 33.8°C						
Thumb	ABSENT					
Left Ulnar >40y/o Anti Sensory (5th Digit) 34.4°C						
Wrist	ABSENT					

plexus injury with concomitant, and more severe injury, to peripheral nerves.

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Imaging of the Carpal Tunnel and Median Nerve

8

Akira M. Murakami, Andrew Kompel, Alda Cossi, O. Kenechi Nwawka, and Ali Guermazi

Introduction

Carpal tunnel syndrome (CTS) is the most common entrapment neuropathy of the upper limb, with an estimated prevalence that is reportedly as high as 5% of the general population [1]. CTS is primarily a clinical diagnosis, made by an accurate patient history and physical exam. Electrodiagnostic tests (EDTs) may be performed to support the diagnosis, to differentiate among alternative diagnoses, or to further evaluate the presence of thenar atrophy and/or persistent numbness. Diagnostic imaging, such as conventional radiography, computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound, is not routinely utilized [2, 3]. Despite this, radiologic studies can provide valuable supplemental information to the clinical exam and EDTs that can impact patient care. Specifically, these modalities can identify clinically relevant variant anatomy or diagnose different causes of secondary CTS such as space-occupying lesions or conditions. In postoperative patients, imaging may be able to identify causes of refractory or recurrent symptoms such as perineural fibrosis or insufficient tunnel release.

Recent advances in the imaging techniques of MRI and ultrasound have allowed detailed imaging of the median nerve that can provide morphologic and metabolic information that was not previously available. In particular, ultrasound now has a similar sensitivity and specificity to EDT and thus is a potential noninvasive screening exam for CTS [4]. The developing use of ultrasound elastography may further advance this sensitivity. In addition, with an increasing number of wrist MRIs performed, an understanding of carpal tunnel anatomy and related CTS imaging findings is critical.

Anatomy

A detailed review of the wrist anatomy is beyond the scope of this chapter. However specific points of the anatomy that are relevant to imaging will be discussed. The deep concave border of the carpal tunnel is made up of the capitate, hamate, and triquetrum. As most imaging modalities effectively depict the tunnel in the axial plane, the walls of the tunnel are often

A.M. Murakami (✉) • A. Kompel • A. Cossi
A. Guermazi
Department of Radiology, Boston University School of Medicine, Boston Medical Center, 820 Harrison Ave, FGH Building, Boston, MA 02118, USA
e-mail: akira.murakami@bmc.org

O.K. Nwawka
Department of Radiology and Imaging, Hospital for Special Surgery, Weill Medical College of Cornell University, 535 East 70th Street, New York, NY 10021, USA

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more readily recognized, particularly by ultrasound and radiography. On the lateral wall, there is the scaphoid and trapezium. On the medial wall, there is the pisiform and hamate hook. The roof of the tunnel is covered by a thick, ligamentous band known as the flexor retinaculum. Laterally, the retinaculum attaches to the tubercles of the scaphoid and trapezium, and medially it attaches to the pisiform and hook of the hamate [5, 6].

Most of the tunnel is occupied by the flexor tendons of the hand, which include four flexor digitorum profundus and four flexor digitorum superficialis tendons. The flexor pollicis longus tendon is located along the radial aspect of the tunnel. A common synovial tendon sheath invests the flexor digitorum profundus and superficialis tendons. A separate synovial tendon sheath invests the flexor pollicis longus tendon sheath [5–7]. The sheath can often be seen outlining the tendons particularly on MRI, and it can become more conspicuous on other modalities when synovitis is present.

Within the distal forearm, the median nerve can be found between the muscle bellies of the flexor digitorum profundus and flexor digitorum superficialis. As the nerve approaches the carpal tunnel, it gives off a small superficial palmar cutaneous branch that courses superficial to the flexor retinaculum to supply sensation to the thenar eminence. The nerve courses laterally, to enter the carpal tunnel lying superficial to the flexor pollicis longus and index finger flexor digitorum superficialis tendons. After exiting the carpal tunnel, the median nerve sends a primary motor branch to the abductor pollicis brevis muscle and additional branches to the opponens pollicis, the superficial head of the flexor pollicis brevis, and the first and second lumbricalis. Sensory branches at this point supply the medial thumb, index, middle, and lateral ring fingers [5–7].

Variant anatomy within the carpal tunnel is frequently seen on imaging. The median nerve can be bifid at the carpal tunnel inlet; prevalence in the general population can be as high as 26%. A persistent median artery of the forearm is an embryologic remnant accessory artery arising from the ulnar artery in the proximal forearm. Within the carpal tunnel, the artery courses along the ulnar margin of the median nerve and can be seen in up to 20% of cadaveric dissections. When associated with a bifid median nerve, the artery can course between the nerve divisions, either enveloped in a common epineurium or as separate structure [6]. Anomalous muscles within the carpal tunnel, such as an accessory flexor digitorum superficialis muscle belly, have been reported as infrequent causes of carpal tunnel syndrome [8].

Radiography/Computed Tomography

The role of radiography and computed tomography (CT) is limited, as both modalities depict soft tissue structures with relatively poor contrast compared to MRI and ultrasound. However, in certain scenarios, these modalities may play a complementary role. For example, mineralization and calcifications present in mass lesions or amyloid deposits within the carpal tunnel may appear as relatively nonspecific foci of hypointense MRI signal or bright/echogenic shadowing foci on ultrasound. Such lesions can readily be detected and distinguished on radiography and CT. In the setting of trauma, both modalities can identify fracture patterns within the wrist that can potentially create mass effect on the carpal tunnel.

In radiography, the carpal tunnel view is optimal. The forearm is pronated and placed on the film cassette with the patient dorsiflexing the hand by the fingertip, with the opposite hand. The central X-ray beam is angled approximately 25–30° and directed at the volar surface of the carpal bones (Fig. 8.1), displaying the carpal tunnel in the axial plane. While soft tissue contrast is limited by the modality, mineralization within the tissue can be accurately visualized within the carpal tunnel space. Additionally, fractures of the hook of the hamate (Fig. 8.2), pisiform, and trapezium are more conspicuous compared to the typically performed three view radiographs (frontal, oblique, and lateral).

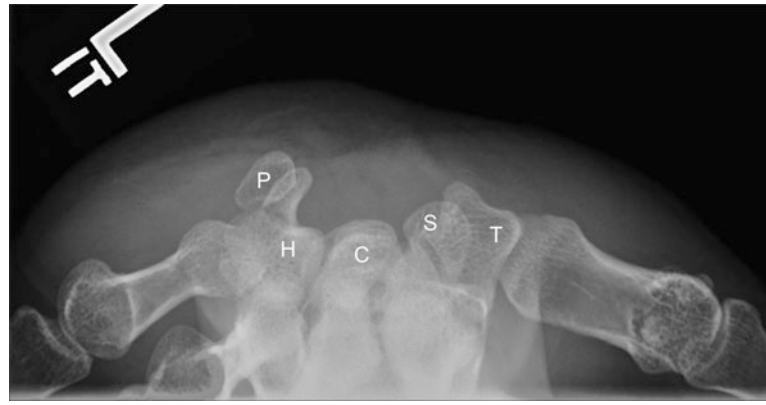

Fig. 8.1 Carpal tunnel view radiograph—normal anatomy; *P* pisiform, *H* hamate, *C* capitate, *S* scaphoid, *T* trapezium

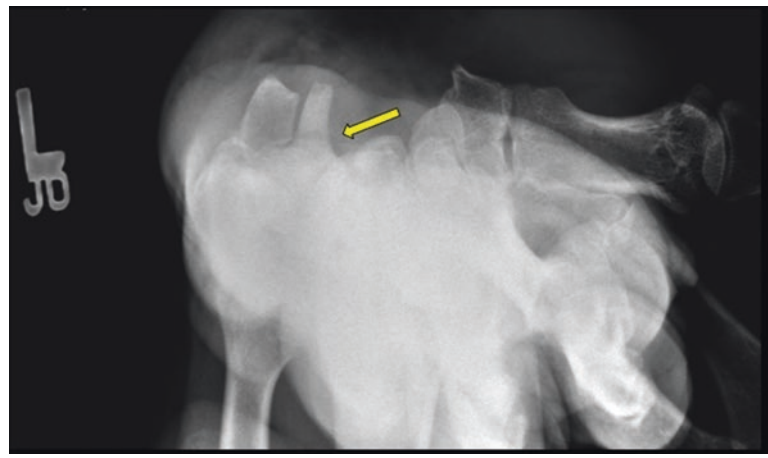

Fig. 8.2 Carpal tunnel view radiograph—fracture at the base of the hook of the hamate (*yellow arrow*)

Computed tomography (CT) has increased sensitivity for detecting soft tissue mineralization and fracture. The contours of mass lesions are more evident by cross-sectional imaging, but soft tissue contrast remains limited by the modality. The thin slice acquisition of multidetector array CT acquires isotropic data sets which allow multiplanar reformats to be created. These reformats increase the sensitivity for fracture (Fig. 8.3) and for space-occupying lesions within the carpal tunnel.

Magnetic Resonance Imaging

MRI depicts the carpal tunnel and potential pathology with high spatial resolution and soft tissue contrast. While imaging sequence protocols vary between institutions, the axial plane is frequently performed and highly diagnostic. Generally, a fluid-sensitive sequence such as a fast spin-echo proton density (PD) or T2-weighted sequence is utilized, depicting edema patterns as a bright or hyperintense signal. Because the nerve is small, edema signal can often be obscured by the surrounding fat; such sequences are thus often performed with fat suppression, making the signal more conspicuous. Commonly used methods of fat suppression are frequency-selective saturation of the fat resonance or a short tau recovery (STIR) [9]. Nonfat-saturated T1-weighted or fast spin-echo PD sequences are often included for anatomic detail of the tendons, median nerve, bone contour, and flexor retinaculum. While there is no particular standard matrix for carpal tunnel imaging, sequences on routine wrist evaluations can range from a matrix of 256 × 256 to as high as 512 × 256. Regardless of the matrix, the images

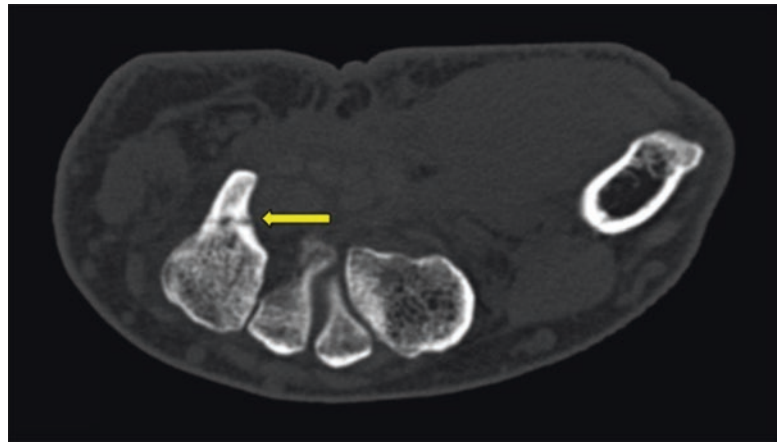

Fig. 8.3 Computed tomography axial image—fracture at the base of the hook of the hamate (*yellow arrow*)

must be able to display the overall morphology of the nerve and its cross-sectional area, both of which are of particular relevance in CTS imaging. The field of view is usually set at 8 cm, and slice thickness is acquired between 2 and 3 mm [7, 9] (Figs. 8.4, 8.5, 8.6, and 8.7).

The median nerve contours seen on MRI are defined by its outermost connective tissue sheath, called the epineurium. A surrounding rim of epineural fat may be visible, appearing as a high-signal rim on PD- or T1-weighted images and low signal on fat-suppressed imaging. High-resolution imaging may also depict the individual nerve fascicles, which should demonstrate intermediate signal slightly higher than that of the normal muscle. The loss of the normal internal fascicular architecture of the nerve coupled with high signal within the nerve is an abnormal finding, suggesting edema or neuritis. Segmental or diffuse enlargement of the nerve is also commonly seen with neuritis. When the median nerve demonstrates focal or fusiform thickening, one should assess for a possible neoplasm or posttraumatic neuroma [9, 10].

On fast spin-echo PD- and T2-weighted sequences, the normal muscle is intermediate-signal intensity. Acutely denervated, muscle tissue will demonstrate abnormal MRI signal that precedes actual muscle volume loss and atrophy. This abnormal signal or prolonged T2 relaxation time is hyperintense (bright) on PD- and T2-weighted sequences. This change is thought to be due to fluid movement from the intracellular space into the extracellular space as well as capsular engorgement and increased muscle blood volume [7, 11, 12]. The chronic findings of muscle atrophy and fat replacement are also well depicted on fast spin-echo PD- or even better on T1-weighted sequences, as fat is bright or hyperintense on these sequences.

On a conventional wrist MRI, there are four general categories of imaging findings in carpal tunnel syndrome: increased median nerve size, median nerve flattening, median nerve signal change, and flexor retinaculum bowing. Each of these criteria has varied sensitivities and specificities for CTS when evaluated individually. However, when combined as an overall impression, MRI has a sensitivity as high as 96% but a low specificity (33%) [13].

Median Nerve Enlargement

Patients with carpal tunnel syndrome can often have median nerve enlargement (Fig. 8.8). This is most objectively assessed by measuring the cross-sectional area of the nerve on an axial image. In the literature, three levels within the wrist have been most commonly used as landmarks for measurement: (1) distal radioulnar joint (DRUJ), (2) pisiform, and (3) hamate.

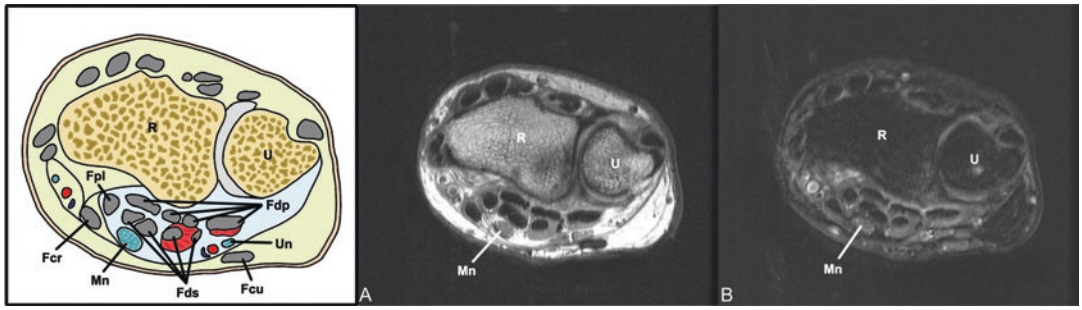

Fig. 8.4 Axial MRI proton density (**a**) and T2 fat saturation (**b**)—normal anatomy at the level of the DRUJ; *R* radius, *U* ulna, *Mn* median nerve, *Un* ulnar nerve, *Fdp* flexor digitorum profundus, *Fds* flexor digitorum superficialis, *Fpl* flexor pollicis longus, *Fcr* flexor carpi radialis, *Fcu* flexor carpi ulnaris

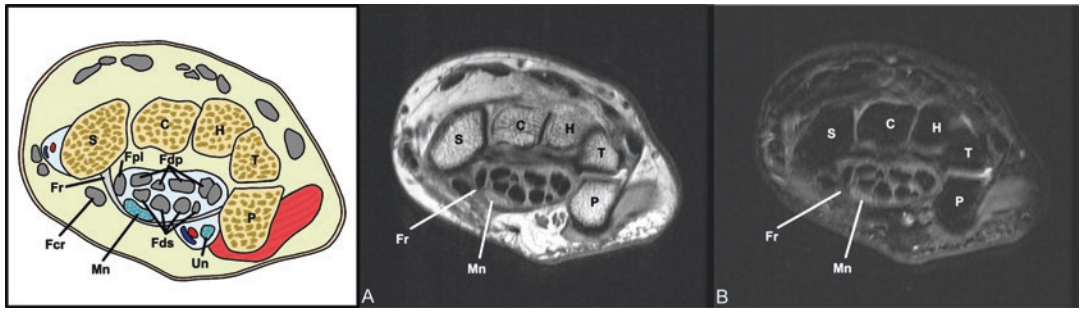

Fig. 8.5 Axial MRI proton density (**a**) and T2 fat saturation (**b**)—normal anatomy at the level of the pisiform; *S* scaphoid, *C* capitate, *H* hamate, *T* triquetrum, *P* pisiform, *Mn* median nerve, *Un* ulnar nerve, *Fdp* flexor digitorum profundus, *Fds* flexor digitorum superficialis, *Fpl* flexor pollicis longus, *Fcr* flexor carpi radialis, *Fcu* flexor carpi ulnaris, *Fr* flexor retinaculum

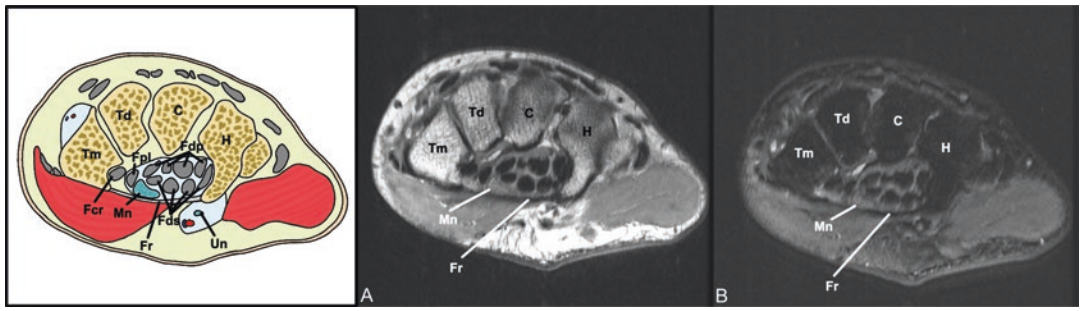

Fig. 8.6 Axial MRI proton density (**a**) and T2 fat saturation (**b**)—normal anatomy at the level of the hamate; *Tm* trapezium, *Td* trapezoid, *C* capitate, *H* hamate, *Mn* median nerve, *Un* ulnar nerve, *Fdp* flexor digitorum profundus, *Fds* flexor digitorum superficialis, *Fpl* flexor pollicis longus, *Fcr* flexor carpi radialis, *Fr* flexor retinaculum

Absolute cutoff values for the normal median cross-sectional area have varied between studies, some with less than desirable reproducibility [14]. A more useful and reproducible reference standard for CTS is the ratio of the surface area of the median nerve at the level of the pisiform relative to the median nerve surface area at the DRUJ. Quantitative analysis

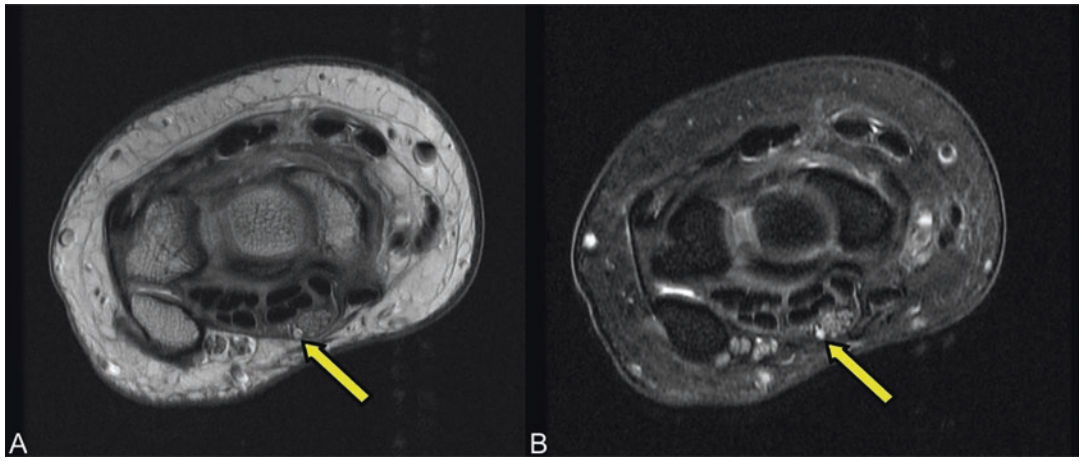

Fig. 8.7 Axial MRI proton density (**a**) and T2 fat saturation (**b**) at the level of the pisiform—median nerve enlargement and high signal with variant vascular anatomy; persistent median artery (*yellow arrow*)

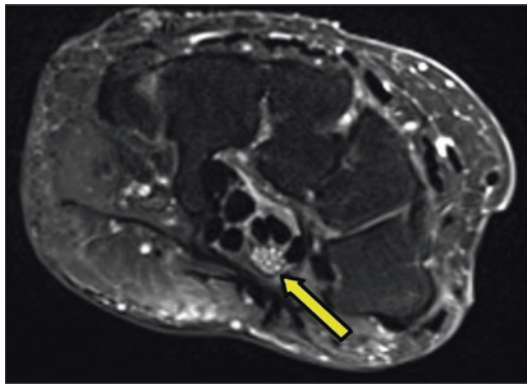

Fig. 8.8 Axial MRI T2 fat saturation—median nerve enlargement with high internal signal (*yellow arrow*) and bowing of the flexor retinaculum

has shown that in normal asymptomatic subjects, the mean pisiform/DRUJ ratio is 1.1. In patients with CTS, the mean pisiform/DRUJ ratio is as high as 2.4 [15]. While the mean cross-sectional area ratio can also be taken at the level of the hamate, the difference between normal and CTS is not as large. Careful measurements of the median nerve cross-sectional area can be time-consuming, and an effective method for determining median nerve enlargement is finding a nerve that is 2–3 times larger at the pisiform than at the DRUJ.

Median Nerve Flattening

The median nerve normally undergoes a small degree of flattening within the carpal tunnel; however, excessive nerve flattening can indicate CTS. As this observation can be subjective, a flattening ratio can be a more effective means of quantitatively determining the severity. The ratio is made by measuring the major and minor axes of the nerve at the level of the DRUJ as well as within the carpal tunnel. In patients with CTS, the mean flattening ratio at the DRUJ is 1.8 at the distal radius, but increases up to 3.8 at the level of the hamate [12, 15]. Thus, a median nerve that is 3–4 times wide as it is thick is associated with CTS (Fig. 8.9).

Flexor Retinaculum Bowing

Normally, the flexor retinaculum is flat or convex at the level of the hamate, where thickness is the greatest. In CTS, a bowed flexor retinaculum implies median nerve compression. The degree of bowing can be quantified by dividing the distance of palmar displacement of the retinaculum by the distance between the hook of the hamate and the tubercle of the trapezium. In normal patients, the ratio ranges from 0 to 0.15. In

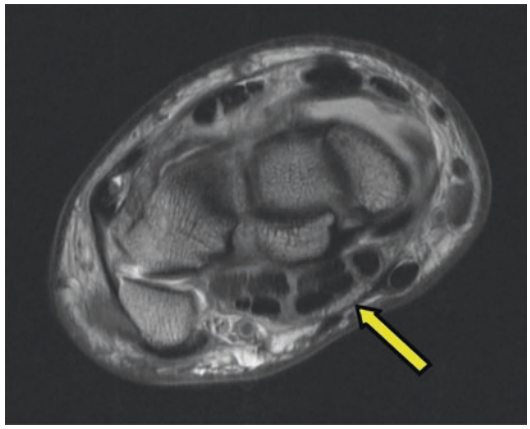

Fig. 8.9 Axial MRI PD—flattening of the median nerve (*yellow arrow*) at the level of the pisiform

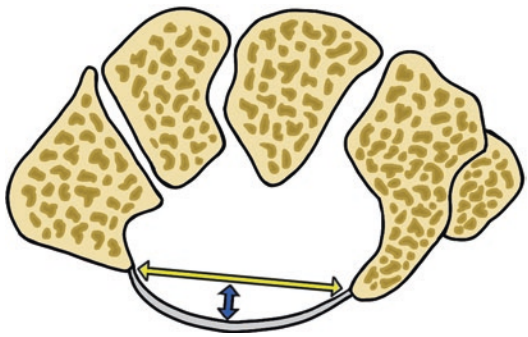

Fig. 8.10 Flexor retinacular bowing ratio—distance of palmar displacement (*blue arrow*) divided by the distance between the hamate hook and trapezium (*yellow arrow*)

patients with carpal tunnel syndrome, this ratio is between 0.14 and 0.26 [15] (Fig. 8.10).

Hyperintense Median Nerve Signal

Normally, the median nerve will have an internal signal similar to or slightly higher than that of muscle tissue on fast spin-echo PD- and T2-weighted sequences. The signal is generally uniform throughout the length of the nerve within the field of view. When the median nerve is bright or high signal on these sequences, the finding is highly sensitive for CTS (88%). This finding however should be treated with caution, as it is unfortunately low in specificity (39%) [13]. The hypothesized pathophysiology for abnormal signal of the nerve may be related to localized edema signal or fluid accumulation within the endoneural spaces [9]. On routine MRI sequencing of the wrist, this finding is made by visual inspection; no reliable quantitative measuring system is accepted. Despite the potential for subjectivity, studies have shown at least substantial inter-reader agreement (weighted kappa = 0.71) when judging median nerve signal abnormality [13] (Fig. 8.11).

Additional MRI Findings

Thenar muscle denervation effect on MRI is indicated by high signal on either PD- or T2-weighted fat-suppressed imaging. This finding is not particularly sensitive for CTS (10%) but is highly specific (96%) (Fig. 8.12) and considered a late-stage finding, correlating with clinically severe CTS and high-grade denervation by EDT [10].

When mechanical compression is the cause of CTS, there are many pathologic lesions that can be discovered by MRI. Flexor tenosynovitis due to infectious or inflammatory arthropathy (such as rheumatoid arthritis or gout) or nonspecific repetitive motion can be indicated by the high fluid signal and distension outlining the flexor tendons on either PD- or T2-weighted sequences (Fig. 8.13). Space-occupying lesions such as ganglion cysts or neoplastic lesions can also be implicated in nerve compression. If a neurogenic tumor or sarcomatous lesion is suspected, MRI protocols that are further optimized for soft tissue imaging may be needed for characterization. This includes the use of pre- and post-intravenous contrast T1-weighted fat-suppressed sequences which can further grade the lesion margins and its overall vascularity and enhancement [16] (Fig. 8.14).

Postsurgical MR Imaging

MRI can be helpful in evaluating the causes of recurrent CTS after surgical release. Similar to pretreatment imaging, the findings have varied sensitivities and specificities and should be combined with EDT findings. In addition to the routine axial wrist sequences, pre- and post-intravenous

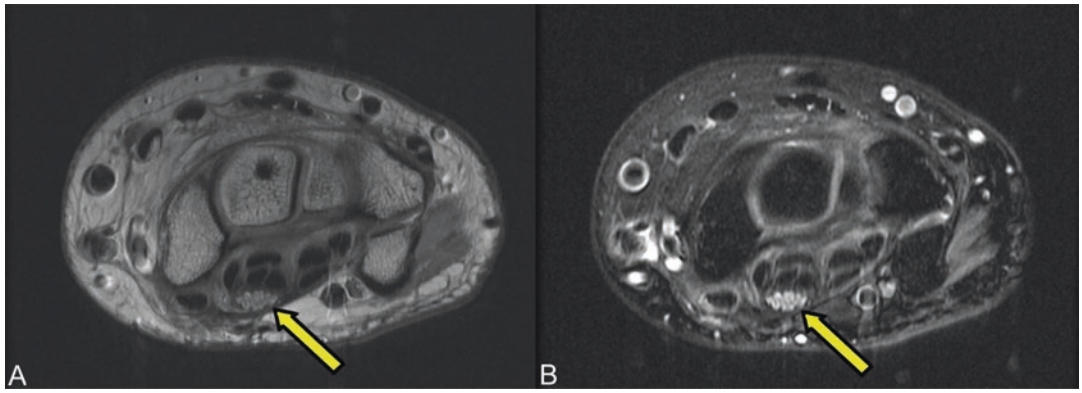

Fig. 8.11 Axial MRI proton density (**a**) and T2 fat saturation (**b**) at the level of the pisiform—median nerve enlargement and high-signal intensity (*yellow arrow*)

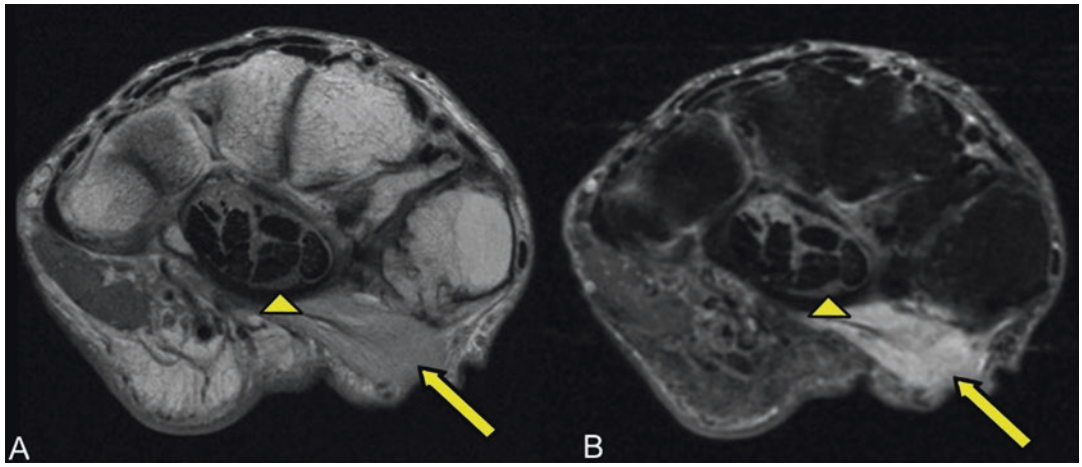

Fig. 8.12 Axial MRI proton density (**a**) and T2 fat saturation (**b**)—muscle atrophy and denervation high signal within the thenar muscles (opponens pollicis and abductor pollicis brevis, *yellow arrow*). The median nerve is flattened within the carpal tunnel (*arrowhead*)

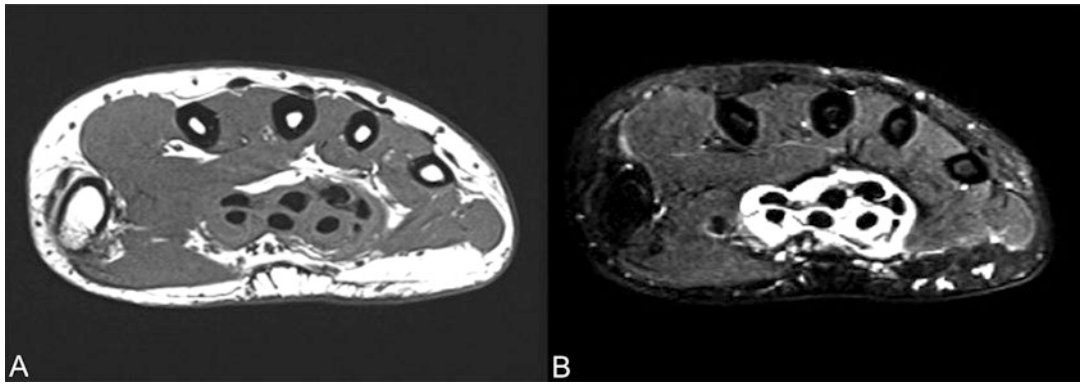

Fig. 8.13 Axial MRI T1 (**a**) and T2 fat saturation (**b**)—tenosynovitis of the flexor tendons in rheumatoid arthritis

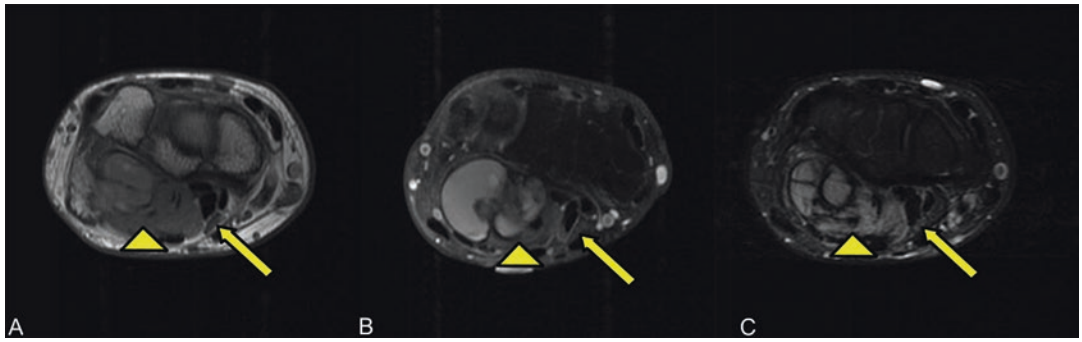

Fig. 8.14 Axial MRI T1 (**a**), T2 fat saturation (**b**), and T1 fat saturation post IV contrast (**c**)—synovial sarcoma within the carpal tunnel; T2 hyperintense, enhancing mass (*arrowhead*) that is displacing and flattening the median nerve (*yellow arrow*)

contrast T1-weighted fat-suppressed sequences are recommended to evaluate the postoperative changes. The aforementioned routine MRI criteria of CTS remain helpful in the assessment of the postoperative wrist. Of these findings, an increased flattening ratio is the most statistically significant difference between EDT-confirmed recurrent CTS and postoperative controls [17].

Additional statistically significant changes in the postoperative patient with recurrent CTS include the presence of perineural fibrosis, median nerve enhancement, and insufficient release of the tunnel. Fibrosis appears as extensive low-signal intensity with an ill-defined nerve margin on either nonfat-suppressed PD- or T1-weighted fast spin-echo sequences. Fibrosis is 60% sensitive, but 83% specific for recurrent CTS. Median nerve enhancement after intravenous contrast administration is considered present if the signal is higher than the level of enhancement of the thenar muscle. While not highly sensitive (40%), this is highly specific (92%) for recurrent CTS [17].

Findings indicating insufficient carpal tunnel decompression have the highest relative sensitivity for recurrent CTS in the postoperative patient population (80%). This is assessed by determining the position of the median nerve and leading flexor tendon, relative to a line joining the hook of the hamate to the ridge of the trapezium. Volar migration of the median nerve and tendon beyond this line can be considered a successful decompression. Other MRI findings such as regrowth of the flexor retinaculum, cross-sectional area of the nerve, and nerve signal intensity on T2-weighted images have not been found to be statistically significant [17] (Fig. 8.15).

Advanced MRI Techniques

Diffusion tensor imaging (DTI) is an advanced MRI technique based on the natural free diffusion of water molecules. While in free fluid, this movement can occur in any random direction. In a highly organized tissue, such as a myelinated nerve, this movement is restricted and occurs along the direction of the nerve. Abnormalities of the mean diffusivity and the direction of this diffusion reflect nerve damage and can be assessed quantitatively by using the imaging to create parameters such as apparent diffusion coefficient (ADC) and fractional anisotropy (FA). The imaging data can further be used to perform tractography, which creates a 3D image of the orientation and course of the nerves [6, 14, 18–20].

Patients with CTS have demonstrated statistically significant decreasing FA and increased ADC values compared to normal asymptomatic patients. These changes reflect a general trend of the diffusion within the nerve toward randomness, indicating nerve pathology [21–23]. Pilot studies have recently used DTI to evaluate CTS patients before and after carpal tunnel release. Naraghi et al. were

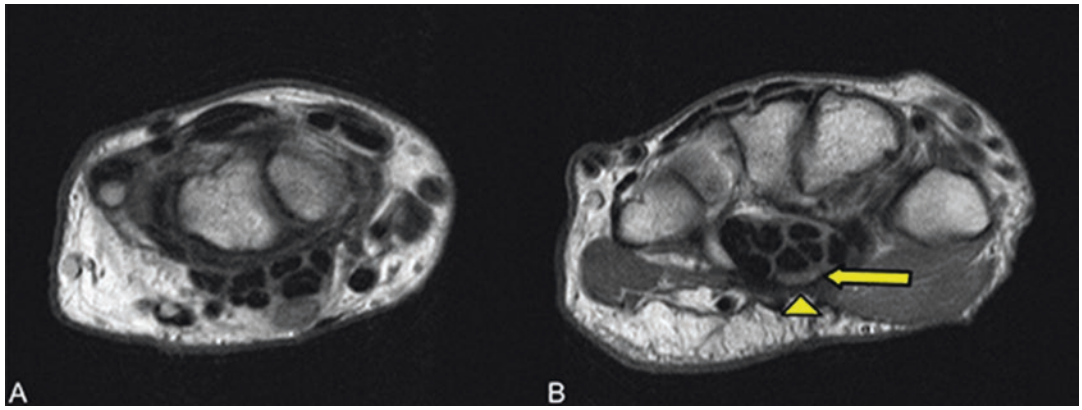

Fig. 8.15 Axial MRI T1 images at the DRUJ (**a**) and hamate (**b**)—status post carpal tunnel release with return of symptoms; residual scarring and insufficient decompression of the flexor retinaculum (*arrowhead*) and a persistently flattened median nerve (*yellow arrow*)

able to show a significant increase in FA and a decrease in ADC values associated with improvement in symptoms after decompression surgery, indicating that these diffusion changes are reversible [24]. Future studies will determine the sensitivities and specificities of DTI relative to the more commonly used MRI findings of CTS. Additionally, as normal diffusion values can vary depending on anatomic location and age, further work is needed to define normal and abnormal threshold values [25].

Ultrasound

Ultrasound has emerged as an important diagnostic tool in CTS. The superficial location of the carpal tunnel and median nerve allow diagnostic evaluation, creating images that are high in spatial resolution and image contrast, but without ionizing radiation. When using the Carpal Tunnel Syndrome 6 (CTS-6) clinical diagnostic tool as the reference standard, ultrasound has a sensitivity of 89% and a specificity of up to 90%, which is similar to EDT's sensitivity (89%) and specificity (80%) [1]. In addition, ultrasound is a relatively inexpensive, noninvasive test that has been shown to be a cost-effective alternative to EDT [26, 27].

Ultrasound Technique

Proper technique and a basic understanding of ultrasound imaging are essential in carpal tunnel imaging. A high-frequency transducer of at least 10 MHz is typically used. The patient is seated with the arm extended and the forearm supinated. The wrist should be rested on a hard flat surface and the fingers can be semi-extended. Images are obtained in both the axial and sagittal plane. Like MRI, the axial plane is the most useful for diagnostic criteria. In addition to the bony landmarks used on MRI (pisiform and hamate hook), the median nerve should be evaluated both immediately proximal to the carpal tunnel and at the carpal tunnel inlet which is defined at a level immediately deep to the proximal edge of the flexor retinaculum [27] (Figs. 8.16, 8.17, and 8.18).

An ultrasound image is produced when high-frequency sound waves emitted by the transducer interact with tissue. Depending on the tissue interfaces and impedance, the sound waves are reflected at different intensities. A strong reflection produces a "hyperechoic" signal that is bright on screen. A particularly strong reflection that can occur at bony interfaces will also produce a "shadowing" effect of any structures beyond the interface. An area that does not produce any echo is termed "anechoic" and thus will be black

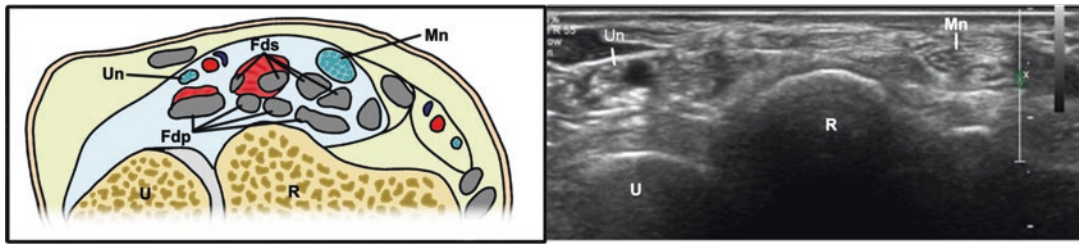

Fig. 8.16 Axial ultrasound image—normal anatomy at the DRUJ; *R* radius, *U* ulna, *Mn* median nerve, *Un* ulnar nerve, *Fdp* flexor digitorum profundus, *Fds* flexor digitorum superficialis

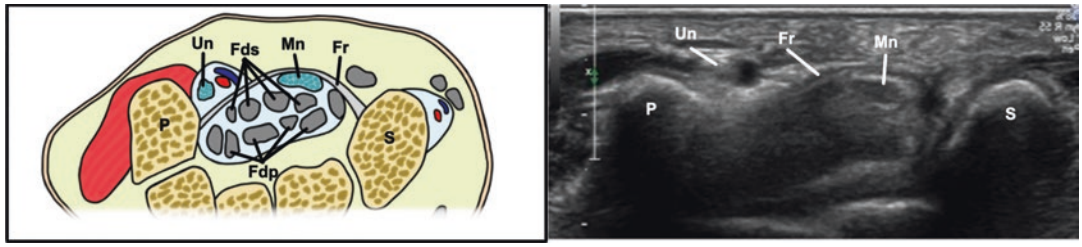

Fig. 8.17 Axial ultrasound image—normal anatomy at the pisiform; *S* scaphoid, *C* capitate, *H* hamate, *T* triquetrum, *P* pisiform, *Mn* median nerve, *Un* ulnar nerve, *Fdp* flexor digitorum profundus, *Fds* flexor digitorum superficialis, *Fr* flexor retinaculum

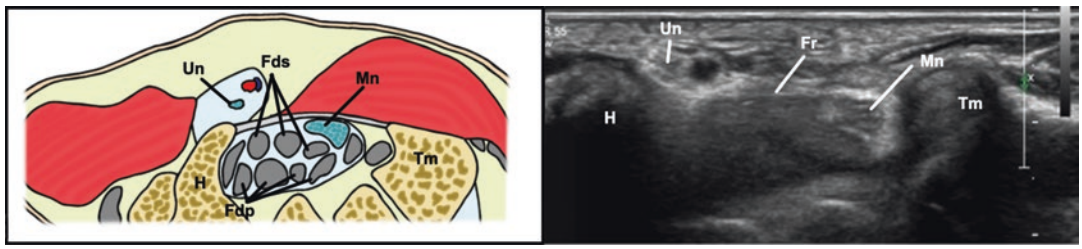

Fig. 8.18 Axial ultrasound image—normal anatomy at the hamate hook; *Tm* trapezium, *Td* trapezoid, *C* capitate, *H* hamate, *Mn* median nerve, *Un* ulnar nerve, *Fdp* flexor digitorum profundus, *Fds* flexor digitorum superficialis, *Fpl* flexor pollicis longus, *Fcr* flexor carpi radialis, *Fcu* flexor carpi ulnaris, *Fr* flexor retinaculum

on the screen. An area with a weak or low reflection is termed "hypoechoic" and is dark on the screen [28]. Normal tendons are hyperechoic or bright on ultrasound, and the fibrillar-like architecture of the longitudinal tendon fibers is well depicted. A confounding artifact is "anisotropy." When a fibrillar structure like a tendon is imaged at a plane that is angled as little as 5° perpendicular to the probe, the structure can lose its hyperechoic appearance and appear artificially hypoechoic or dark.

The normal median nerve will have an internal fascicular pattern on ultrasound, characterized as a "honeycomb" appearance. The individual nerve fascicles will be hypoechoic or dark and outlined by hyperechoic connective tissue. Mass lesions within the carpal tunnel can have varied echogenicities based on internal composition (Fig. 8.19). Color and power Doppler settings on the ultrasound can be used to depict blood flow patterns that are superimposed on the baseline grayscale imaging [28]. Applying this color

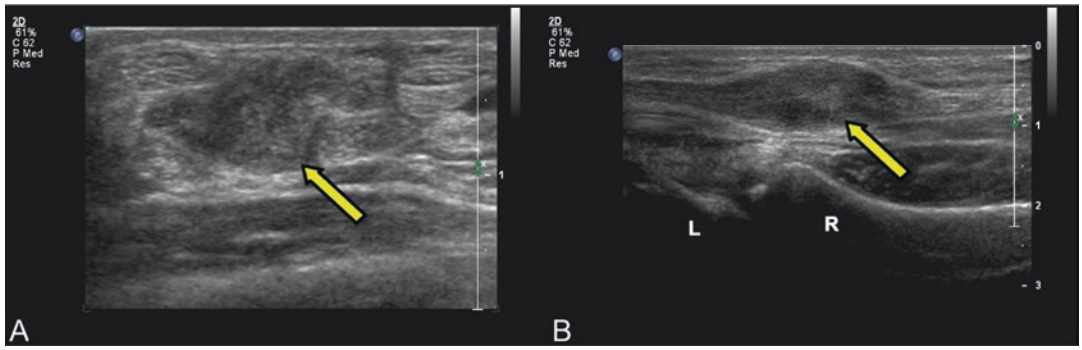

Fig. 8.19 Axial ultrasound image in the axial (**a**) and sagittal (**b**) planes—nerve sheath tumor of the median nerve (*yellow arrow*); *R* radius, *L* lunate

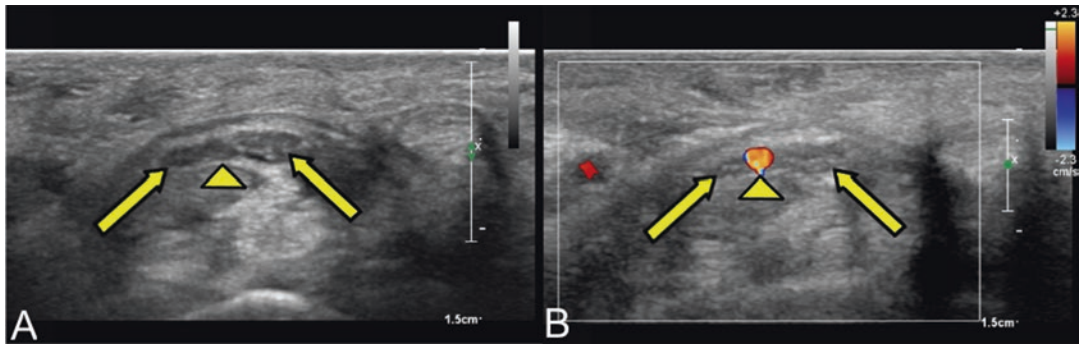

Fig. 8.20 Axial ultrasound image 2D gray scale (**a**) and color Doppler (**b**)—Bifid median nerve (*yellow arrow*) with persistent median artery (*arrowhead*)

Doppler setting is especially helpful in identifying vascular lesions, variant vascular anatomy, and tissue hyperemia (Fig. 8.20).

Although ultrasound of the carpal tunnel can depict similar MRI criteria used in CTS, the most commonly evaluated parameter has been the median nerve cross-sectional area. Using the circumferential trace mode on the ultrasound screen, the cross-sectional area of the median nerve can be measured. A widely accepted cutoff cross-sectional surface area for CTS with the highest sensitivity and specificity is 10 mm^2, measured at the carpal tunnel inlet or pisiform. This sensitivity and specificity is highly comparable to EDT [1, 27–30] (Fig. 8.21).

Other parameters unique to ultrasound can be supplemental to the cross-sectional measurement of the median nerve. In particular, color and power Doppler imaging can be used in the routine ultrasound examination to detect the presence of intraneural vascularity, which would indicate the presence of inflammatory changes within the nerve. While this phenomenon has been less studied than surface area measurements, studies have shown the sensitivity and specificity to be as high as 83% and 89%, respectively [31] (Fig. 8.22). Additional studies have observed restricted median nerve mobility in CTS, during passive flexion and extension of the digits [32]. This is thought to be due to fibrosis or adherence of the median nerve to the retinaculum. Real-time ultrasound allows for this dynamic evaluation. Subjective assessments of this restricted mobility have been shown to be specific (86%) with high interoperator reliability [33]. Since hyperemia, fibrosis, and median nerve-restricted movement

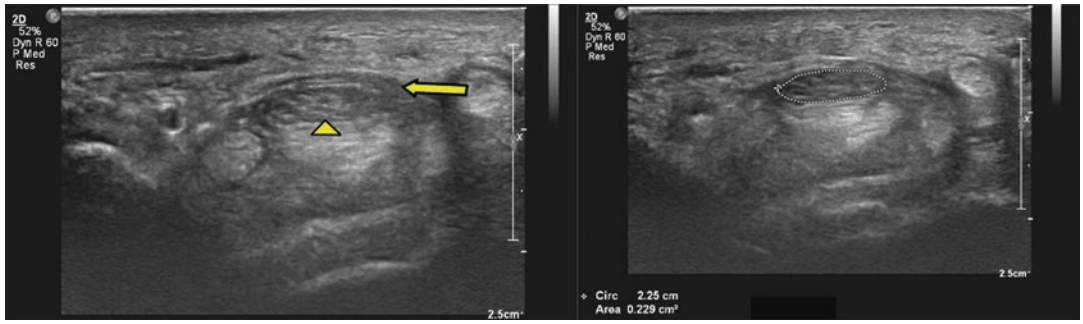

Fig. 8.21 Axial ultrasound image—median nerve enlargement (*arrowhead*) and flexor retinaculum thickening and bowing at the carpal tunnel inlet. The cross-sectional area >10 mm^2 is highly sensitive and specific for CTS

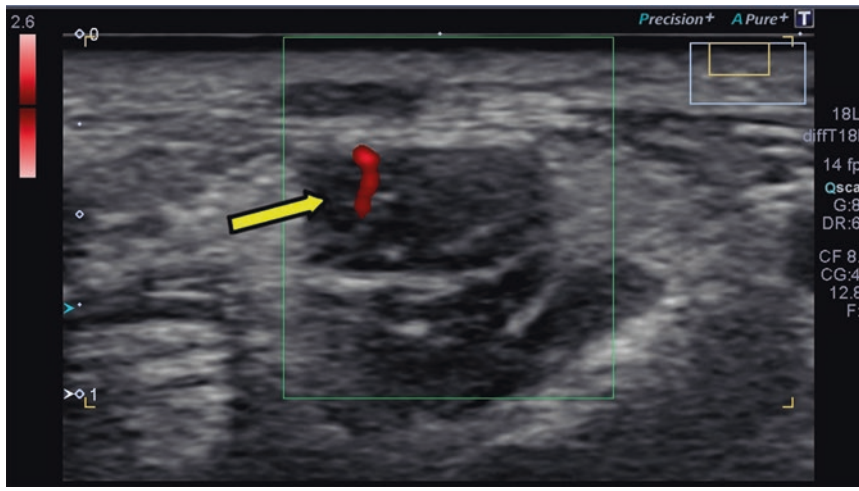

Fig. 8.22 Axial ultrasound image—median nerve enlargement with intraneural vascularity by color Doppler (*arrow*). *Image provided courtesy of Toshiba America Medical Systems, Inc.*

are likely later-stage findings of CTS, this may account for the relatively lower sensitivity of the ultrasound findings when compared to the cross-sectional area measurement. Despite this, when taken in combination with surface area, these findings can improve the sensitivity and accuracy of ultrasound.

Flexor retinacular bowing and median nerve flattening ratios are measured in a similar fashion as MRI. These parameters have been studied less than other ultrasound findings, but recent studies have demonstrated lesser sensitivities (63% and 44%), specificities (60% and 85%), and poor interobserver reliability [33]. This may be due to the technical challenges of evaluating the distal carpal tunnel and the oblique and changing course of the median nerve.

Postoperative Assessment

In the postoperative patient, the conventional ultrasound parameters of CTS can be used to assess treatment response. As the cross-sectional area of the median nerve has been found to decrease over a period of 4–12 weeks after surgical release, this measurement has particular importance [34]. Additional assessment of the flexor retinaculum and perineural fibrosis can also be made (Fig. 8.23).

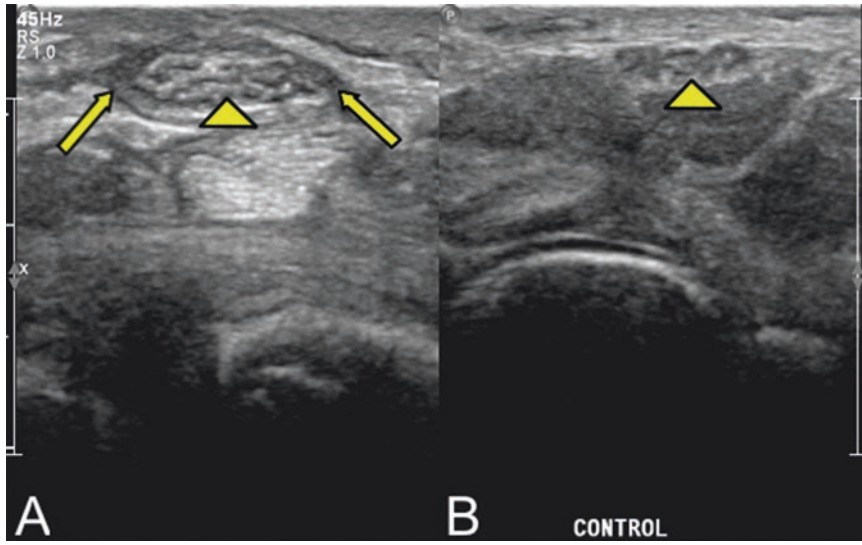

Fig. 8.23 Axial ultrasound image—postoperative patient with recurrent CTS symptoms. Note the relative enlargement of the nerve (*arrowhead*) and the surrounding scar tissue (*arrow*) about the nerve on the postoperative wrist on the left (**a**) relative to the contralateral asymptomatic wrist on the right (**b**)

Ultrasound Elastography: Emerging Ultrasound Technology

Ultrasound elastography is a method that allows the qualitative visual or quantitative measurement of soft tissue stiffness. By applying a low-frequency strain or compression, the mechanical properties of a selected tissue can be analyzed by its tendency to return to its original size and shape. In CTS, the focal demyelination and axonal degeneration can lead to a fibrotic response of the nerve. Additionally, there can be an increased carpal tunnel pressure in CTS. Both factors can create an overall stiffer nerve, which can be detected by ultrasound elastography. There are currently several elastography techniques such as strain elastography, acoustic radiation force impulse, transient elastography, and shear wave elastography. Each method has its strength and weakness. Strain elastography has been the most widely studied procedure for musculoskeletal applications. The degree of strain or elasticity is converted into a color-coded map that is superimposed on the traditional grayscale ultrasound image (Fig. 8.24). Early published reports suggest that strain elastography may have a sensitivity and specificity that is comparable to cross-sectional surface area measurements in the diagnosis of CTS. Further studies are needed to evaluate ultrasound elastography and its application in CTS; however, initial results are promising [35–38].

Conclusion

The current recommendations for the diagnosis of CTS have reiterated the importance of obtaining an accurate patient history and physical exam, as well as performing EDTs in the appropriate clinical scenarios [2]. Although radiologic imaging is not recommended for routine use, recent advancements in MRI and ultrasound have increased their importance. A variety of different imaging findings have been found in CTS with varied sensitivities and specificities and thus should be taken as a whole when evaluating this clinical diagnosis. In MRI, median nerve enlargement, nerve flattening, flexor retinacular bowing, and increased nerve signal are findings typical in CTS. While similar findings can be seen in ultrasound, cross-sectional area enlargement has demonstrated a particularly high sensitivity and specificity. Both ultrasound and MRI are also

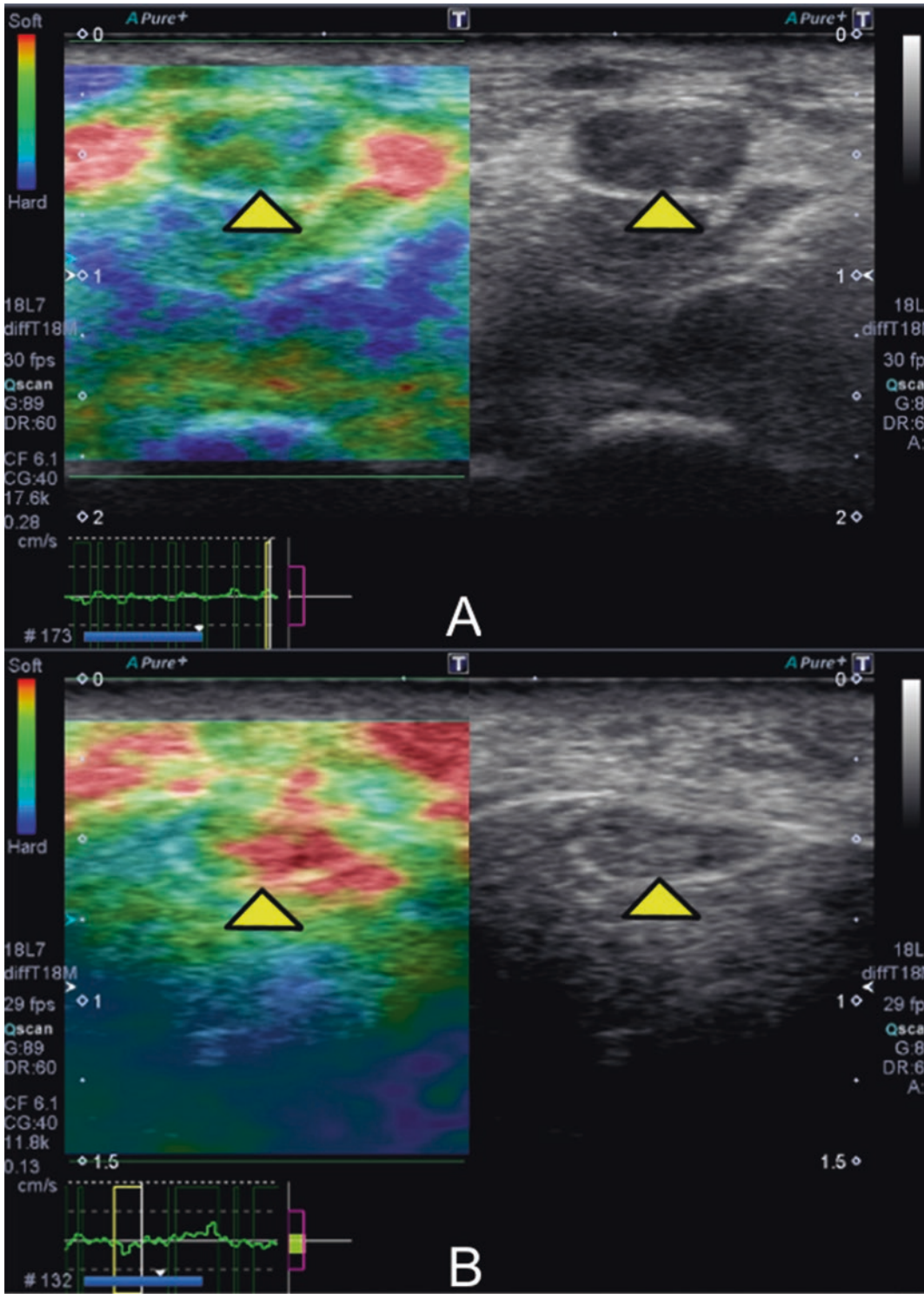

Fig. 8.24 Ultrasound strain elastography—CTS patient (**a**) with an enlarged median nerve (*arrowhead*) and color mapping on elastography indicating increased nerve stiffness (*blue*) compared to a normal asymptomatic patient (**b**) with a normal size median nerve (*arrowhead*) and color mapping on elastography indicating a soft (*red*) nerve. *Image provided courtesy of Toshiba America Medical Systems, Inc.*

helpful in identifying alternative causes of nerve compression, which include ganglion cysts, mass lesions, and infectious or inflammatory flexor tenosynovitis. Variant anatomy, which can affect surgical planning, can also be readily identified. Future research will continue to determine if there will be greater role of these modalities in the routine diagnostic evaluation.

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9 Severity Scoring Systems for Carpal Tunnel Syndrome and Outcome Tools

Elham Mahmoudi and Kevin C. Chung

Introduction

Although carpal tunnel syndrome (CTS) is the most common wrist and hand disorder [1–3], much controversy still exists regarding standardization of its treatments and outcome measures [4]. CTS occurs following compression of the median nerve within the carpal tunnel [1] and is associated with severe pain, numbness, and tingling in the affected hand [5, 6]. Traditionally, clinical evaluation of CTS focused on measuring neuromuscular impairment of the nerve [5, 7], manifested by reduced sensibility and grip strength [2, 7]. However, owing to the fact that CTS symptoms may not necessarily be accompanied by physical changes in sensation and strength of the median nerve in the hand [3, 5], assessing the severity of CTS and the outcomes of treatment has remained a challenge [8]. More recently, in addition to the traditional set of physical measurements [5, 9], physicians have started employing subjective methods such as questionnaires that place more emphasis on outcomes that matter the most to patients [10, 11]. Health outcome questionnaires, whether administered verbally by the physician at the clinic or self-administered by the patient, are examples of subjective tools used for assessment of severity of symptoms and functional status in CTS [10–13].

Today, more than ever, the healthcare system is constrained by limited resources and increasing demand. Thus, medicine is under stringent scrutiny to not only deliver high-quality care but to do so in a cost-effective way [14]. Additionally, with the establishment of the Patient-Centered Outcomes Research Institute (PCORI) under the Affordable Care Act (ACA) [14], and recognition of the patient as an active participant in medical decision-making, health outcome questionnaires have become important tools for inclusion of patients' perspectives. This chapter will explore and evaluate available assessment tools, particularly health outcome questionnaires commonly used to measure CTS severity and treatment outcomes.

E. Mahmoudi (✉)
Department of Family Medicine,
The University of Michigan Health System,
Ann Arbor, MI, USA

University of Michigan, North Campus Research Complex, 2800 Plymouth Rd, Building 16, Room G024W, Ann Arbor, MI 48202, USA
e-mail: Mahmoudi@med.umich.edu

K.C. Chung
Section of Plastic Surgery, Department of Surgery,
University of Michigan Medical School,
Ann Arbor, MI, USA

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Assessment of Severity of Symptoms and Optimal Treatment Option

Treatment suggestions for CTS depend on a physician's assessment of a patient's history and severity of symptoms [15, 16]. If symptoms are mild to moderate and CTS is diagnosed early, nonsurgical methods including wrist splinting, nonsteroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen, or injection of corticosteroid drugs such as cortisone may reduce the inflammation and alleviate some or all of the symptoms, either temporarily or over the long term [3]. If, however, the symptoms have become severe, surgery may be the most effective option [3]. Despite the high prevalence of and extensive body of literature on CTS [17, 18], perhaps because there is no easy way of determining the severity of the condition, debate, and controversy regarding assessment and treatment of CTS continue [19]. Thus, most physicians choose to apply a combination of tools in their assessments of severity and effectiveness of treatment (Fig. 9.1) [19].

Objective Measurement Tools

In order to check the health of the median nerve, and usually when symptoms of CTS are severe enough for the patient to be considered for surgery, electrodiagnostic studies are performed [20]. There are two types of electrodiagnostic nerve tests: (1) nerve condition velocity (NCV) measures the speed of electricity as it passes through a nerve and (2) electromyogram (EMG) checks the electrical activities of nerves and muscles [21]. Based on these test results and the patient's history of CTS, the symptom severity scale of the condition will be defined as mild, moderate, or severe [7]. Nerve tests are expensive and painful for patients; many physicians argue that patients may not need to go through these tests [7, 19].

Subjective Measurement Tools

In addition to objective measurement tools, there are a variety of subjective tools that physicians may use to assess the severity of CTS [7]. For example,

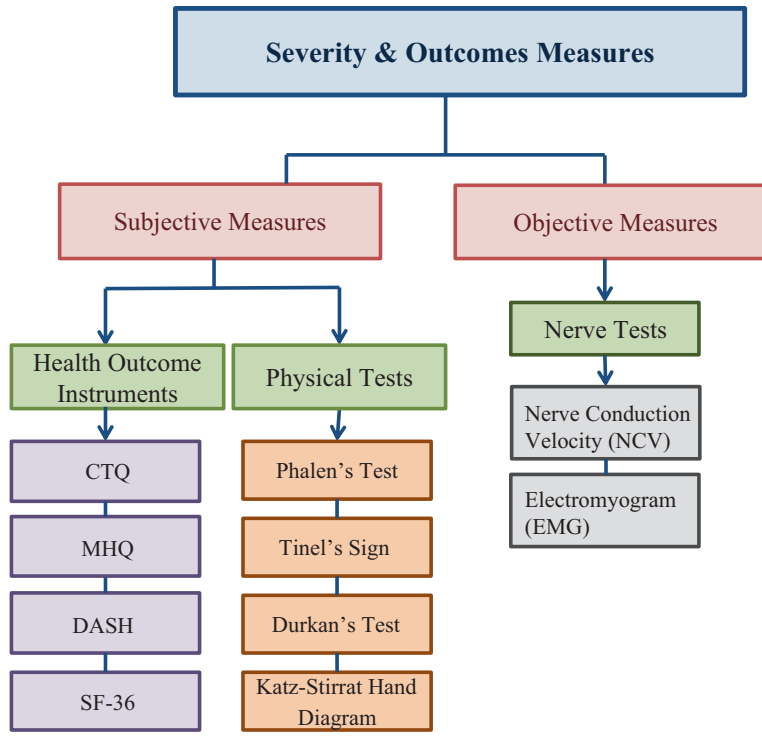

Fig. 9.1 Severity and outcome assessment tools for carpal tunnel syndrome

Table 9.1 Description of subjective clinical tests for diagnosis and evaluation of the severity of carpal tunnel syndrome

Name	Description
Phalen's test (wrist flexion test)	Patient is asked to hold their wrist in complete flexion for 1 min with the forearm held vertically. If pain, numbness, or tingling of the median nerve is reported within 1 min, the test will receive a positive score
Tinel's sign	Performed by tapping the patient's median nerve in six different locations with examiner's index and middle finger. Administration of taps travels proximally from the transverse carpal ligament to the proximal wrist crease. If tingling or burning is reported by the patient, the test will receive a positive score
Durkan's carpal compression test	Performed by examiner placing patient's thumbs over the median nerve in the area where it crosses under the transverse carpal ligament and exerting pressure for 30 s. If pain, numbness, or tingling is reported within the 30 s, the test will receive a positive score
Katz-Stirrat hand diagram	Performed without the assistance of an examiner. It involves asking the patient to look at a diagram of a hand and report, in reference to the diagram, which location they experience pain, numbness, or tingling. Locations on the diagram can be scored according to a designated table of criteria

common clinical provocative CTS tests include Phalen's test [22], Tinel's sign [22, 23], the Durkan's carpal compression test (CCT) [24], or the Katz-Stirrat hand diagram [7, 25] (Table 9.1).

Qualities of a Good Severity Measurement Tool for CTS

Although most traditional CTS tests have been performed commonly in clinical settings, assessments of their validity, reliability, and responsiveness do not necessarily yield the same results [25]. For example, research shows no correlation between the severity of CTS and results of the Tinel's, Durkan's carpal compression, and Katz-Stirrat hand diagram tests [7]. Phalen's test was the only test to show a positive association between results of the nerve conducting test and severity of CTS [7]. Higher CTS severity scores are positively associated with a higher probability of the Phalen's test being positive [7]. Reliability of these tests ranged from moderate (0.51 for Tinel's sign, with a confidence interval of 0.13–0.88) to excellent (0.95 for the Katz-Stirrat hand diagram, with a confidence interval of 0.84–1.00) [7].

Outcome Assessment Tools

In developing any health status questionnaire, there is a tradeoff between breadth and depth of measurement [26]. Generic health outcome questionnaires seek to evaluate health using a broad perspective, ranging from physical to social health. For example, the 36-Item Short-Form Health Survey (SF-36) evaluates eight different domains of health and well-being without being related to any specific illness [27]. Generic questionnaires are usually useful when comparing health status across various conditions [28]. On the other hand, questionnaires that were developed to measure health outcomes related to a specific condition such as CTS or rheumatoid arthritis seek to evaluate symptoms and functions that are very specific to an illness (more depth and less breadth). For example, the Carpal Tunnel Questionnaire (CTQ) evaluates all major symptoms or functions that are specifically related to CTS (e.g., hand and wrist numbness or pain at night) [10]. For health surveys measuring general health status, such as the SF-36, breadth is more important than sensitivity toward a specific illness [26]. On the other hand, for illness-specific questionnaires such as the CTQ, the focus is more on sensitivity to changes in conditions specific to carpal tunnel [7, 9, 29, 30].

Outcome questionnaires have been developed to examine the responsiveness of treatment for CTS in a standardized and non-biased way. A good outcome questionnaire should be reproducible, valid, reliable, and responsive to changes in symptom relief and functioning status (Table 9.2)

Table 9.2 Properties of a validated health outcome questionnaire

Name	Meaning	Examples of statistical tools for measurement
Reproducibility	Reproducibility or test-retest shows repeatability of the instrument, meaning that instrument yields the same results if used among the same population at two different but close time intervals	• Measurement error (ME) indices coefficient of repeatability (CR) • Smallest real difference (SRD) • Pearson coefficient • Intraclass correlation coefficient (ICC)
Internal consistency	Internal consistency shows the degree of homogeneity among all the items included in a scale. It is measured by calculating the interclass correlations within each scale	• Cronbach's alpha
Validity	A valid instrument should be logically and theoretically acceptable and accurately measures what it is supposed to measure. Sensitivity and specificity of an instrument determines its validity	• Receiver operating characteristic (ROC) curve analysis • Correlation analysis • Regression analysis
Responsiveness	Responsiveness is an instrument ability to detect change over time. Responsive instrument should be sensitive enough to detect meaningful change in outcome measures of interest before and after the treatment	• Paired *t*-test • Effective size • Standardized response mean (SRM) of effect size • Responsiveness-retrospective (RR) coefficient of effect size
Ease of use	Ease of use refers to the time it takes for the subject to fill out the questionnaire and its ease of use. It also refers to other administrative complexities related to the questionnaire such as scoring system	NA

[26, 30, 31]. With a direct annual cost of more than one billion dollars, carpal tunnel release is the most common surgical procedure performed on the hand [10]. Although patients with CTS are mostly concerned about symptom relief and improvement in hand function [31], up until 1993 the responsiveness of the treatment, including surgical procedures, had been mostly assessed by using physical/objective measurement tools such as nerve studies [10, 31]. Because it was primarily the surgeons who had performed the operations who conducted the outcome studies, the probability of bias was relatively high in supporting the success of the surgical treatment [4]. In this section, we will describe and compare the health questionnaires commonly used to assess the severity and treatment outcomes of CTS. First, we will describe each of the following questionnaires: (1) the Carpal Tunnel Questionnaire (CTQ); (2) the Michigan Hand Questionnaire (MHQ); (3) the Disability of Arm, Shoulder, or Hand Questionnaire (DASH); and (4) the 36-Item Short-Form Health Survey (SF-36). We will then use properties associated with validated questionnaires to evaluate commonly used health instruments [4, 32].

Carpal Tunnel Questionnaire (CTQ) [10]

Brigham and Women's Carpal Tunnel Questionnaire (CTQ) is an example of a disease-specific questionnaire designed to evaluate CTS [4]. The CTQ, developed by Levine et al., contains two separate scales: (1) symptom severity and (2) functional status [10]. Severity of CTS is measured using an 11-item multiple-choice questionnaire, focusing on pain, numbness, tingling, and nocturnal symptoms. Each item is scored from 1 (none or mild) to 5 (severe). The mean of all 11 scores is reported as the overall symptom severity of CTS. To measure functional status, an 8-item functioning questionnaire measures a range of activities [10]. Each listed activity is scored from 1

(no difficulty) to 5 (cannot do at all). A higher score on both scales shows a higher severity or a more limited hand/wrist function [10].

A multidisciplinary team of hand surgeons, rheumatologists, and CTS patients developed the CTQ; it contains all essential properties of a valid health instrument: reproducibility, internal consistency, validity, responsiveness, and ease of use (Table 9.2) [32]. The main advantage of this questionnaire is that it is focuses on symptoms and functions most often observed among CTS patients, so it is the most sensitive and responsive questionnaire for CTS. Pearson correlation coefficients of above 90% indicate excellent reliability/reproducibility attributes for both sections of this questionnaire [10]. In contrast, because it is disease specific, the CTQ does not allow for comparisons among different conditions [4].

Regarding validity of the questionnaire, a high correlation between mean scores obtained from the two sections of the test, severity of symptoms and function status, shows that patients with more severe scores had more function limitations. However, the correlation scores between both severity of symptoms and function status and traditional objective tools such as nerve conducting tests show low or poor correlation. For example, the correlation between the result of symptom severity evaluated by the CTQ and the two-point discrimination test, using the Spearman coefficient, was 0.15 and statistically not significant [10]. This is not an indication of low validity of the questionnaire; the provocative and nerve conducting tests and the CTQ capture different outcomes and should be used as complementary tools [10–12, 29].

With the average effect size of 0.82, the CTQ proved to be a responsive tool in measuring clinical outcome changes [10]. Additionally, patients' satisfaction with the result of treatment was associated with significant improvement in symptom relief and function status [10].

Michigan Hand Questionnaire (MHQ)

The MHQ is a 57-item hand-specific questionnaire with six different domains that can be administered all together or in isolation [33]. The six domains of the questionnaire include (1) function, (2) activities of daily living, (3) pain, (4) work performance, (5) aesthetics, and (6) patient satisfaction [33]. The MHQ is widely used for various hand disorders [34] and has been translated into many different languages and used in other countries [35, 36].

Patients are asked to answer each question for each domain using a scale of 1–5 [33]. The sum of scores for each domain can total up to 100. With the exception of the pain domain, in all other domains a score of 0 represents the worst outcome and score of 100 represents the best [33, 37]. Like DASH, the MHQ can also be used for other hand disorders [38, 39]. However, because it covers hand and the wrist in the global assessment, it is more specific. The MHQ is the only hand questionnaire that distinguishes between the two hands and can be used to compare the severity of symptoms and function of one hand with the other [30].

Like DASH, the MHQ also has a 12-item brief MHQ to reduce the burden of answering long questionnaires for patients [40]. Both the MHQ and brief MHQ have been proven to be reliable, valid, and responsive hand outcome instruments and used to assess effectiveness of treatments for different hand disorders including CTS [30, 39, 40]. The MHQ has many advantages over other similar hand questionnaires. The MHQ is specific to hands but not to any specific disorder; this gives the questionnaire a desirable depth and adequate breadth. Additionally, having different domains makes it flexible and responsive for each specific disorder. For example, in assessment of CTS, the aesthetics domain can be excluded without affecting the results of the questionnaire [30]. Also, because the MHQ distinguishes between the two hands makes it possible to compare the outcomes of the affected hand with the unaffected hand. Most importantly, because the MHQ can measure outcomes of all hand and wrist conditions (e.g., CTS, carpometacarpal thumb arthritis, rheumatoid arthritis of hand, etc.), it can be utilized in comparative effectiveness studies across various conditions.

Disabilities of the Arm, Shoulder, or Hand Questionnaire (DASH)

DASH is a 30-item self-administered questionnaire that was designed to measure physical function and severity of symptoms in patients with any upper extremity musculoskeletal disorder [41–43]. DASH was developed to fill the gap in longitudinal assessment of patients with one or multiple upper extremity disorders or injuries [41]. DASH contains two main domains: (1) symptoms and (2) function status, including physical, social, and psychological functioning [43]. Patients are asked to choose the level of difficulty of doing an activity or severity of a symptom, using a five-point Likert scale, with a higher score indicating a greater level of severity and disability [41]. To calculate the DASH total score, one needs to add all the responses (ranging between 1 and 5) and subtract 30 from the total; then, the total has to be divided by 1.2 to get a DASH score out of 100 [41]. If more than three items are not answered (missing), the overall DASH score cannot be calculated [41]. DASH combines questions related to symptom severity and functioning into one single questionnaire. The total score ranges from 0 to 100, with 0 representing perfect functioning and 100 representing the worst symptoms and disability [43]. Examples of activities include preparing a meal, pushing a heavy door, and making a bed. The functioning portion of the questionnaire includes general questions regarding pain, weakness, or tingling of the arm, shoulder, or hand, ranging from none to extreme [41].

DASH has been translated into many different languages and used widely in other countries [42]. Late in 2005, a shorter version of DASH, an 11-item questionnaire called QuickDASH, was developed to ease the burden of answering too many questions for the patients [44]. Both the DASH and QuickDASH questionnaires have proven to be reliable, valid, and responsive to clinical changes for upper extremity injuries and disorders (Table 9.3) [42, 46].

The main advantage of DASH is that it is one questionnaire that can be applied to all upper extremity disorders, including CTS [10, 29, 30]. DASH is particularly useful for the assessment of upper extremity disorders in which the combination of symptoms and function can be assessed in one scale. However, DASH is a generic upper extremity questionnaire, which makes it less sensitive in assessing CTS responsiveness to treatment simply because symptoms specific to CTS improve more quickly than function outcomes [29, 30]. Thus, the combined scoring system of DASH for symptoms and function outcomes reduces the responsiveness of the questionnaire compared with the CTQ or the MHQ. This is because DASH puts more emphasis on the functional aspects of upper extremity disorder than on the severity of symptoms [12]. Additionally, DASH does not distinguish between the two hands, so one cannot use the questionnaire to compare the unaffected hand with the affected one [47].

Table 9.3 Standardized response means (SRM) of the SF-36, the DASH, the MHQ, and the CTQ subscales 4 or 6 months after carpal tunnel release

Questionnaire	SRM[a] (After 3 months) s)	SRM[b] (After 6 months)
SF-36		
Physical	0.4	
Bodily pain	0.5	
DASH	1.1	0.7
MHQ		
Function		0.6
Activities of daily living		0.5
Work		0.5
Pain		0.9
Satisfaction		1.1
CTQ		
Function	1.05	
Symptom	2.01	
Total	1.66	

[a]Data obtained from the study by Manktelow et al. (2004) [45]

[b]Data obtained from the study by Kotsis et al. (2005) [30]

36-Item Short-Form Health Survey (SF-36)

The SF-36 was developed in 1992 to be used not only in clinical practice but also in population research studies and health policy evaluations

[26]. The SF-36 evaluates eight domains of health and well-being: (1) limitations of physical activity, (2) limitations in social activities, (3) limitations in usual role activities due to physical health, (4) pain, (5) mental health, (6) limitations in usual role activities due to mental health, (7) vitality (energy and fatigue), and (8) perception of general health [26]. The SF-36 uses the Likert scale—a psychometric method commonly used in questionnaires for scaling responses [48]. The interpretation of the results is based on the assumption that the averaged scored items represent the underlying health status that is being measured [27, 49]. The goal of SF-36 is to validly and precisely report the relevant differences and changes in health status and well-being [50].

Assessment of Common Outcome Questionnaires for CTS

During the last decade, various questionnaires have been developed to assess severity of symptoms, function status, and outcomes of treatment for CTS and other illnesses [10, 26, 33, 43]. In this chapter, we reviewed a few of the most common instruments, ranging from a completely generic one such as the SF-36 to the most specific one, the CTQ, that have been used for assessment of CTS. Although these instruments proved to possess all the properties of validated questionnaires, there are small variations among them when used to examine CTS. For example, research indicates less variability among hand outcome questionnaires such as the Carpal Tunnel Questionnaire (CTQ), the Michigan Hand Questionnaire (MHQ), and Disabilities of the Arm, Shoulder, and Hand (DASH). Compared with the SF-36 as an example of a generic questionnaire, hand and upper extremity questionnaires appear to be more responsive (Table 9.3) [29, 30, 51]. Physicians, researchers, and patients prefer the short forms of both DASH and the MHQ [40, 46]. The main versions of these two hand questionnaires take a longer time to complete. In addition to taking less time to complete, the short forms are similarly reproducible, valid, reliable, and responsive [40, 46]. Thus, they are the preferred instruments compared with their original versions. Considering the high prevalence of CTS and the importance of patient-centered health outcomes, depending on the context of the research, use of the appropriate outcome instrument is pertinent (Table 9.3).

Possible Future Direction

Thomas Bayes (1702–1761), an English statistician, mathematician, and philosopher, is mostly known for his work on probability [52]. According to his theory, the likelihood of having a particular condition can be estimated based on the previous probability of having that condition [53]. In statistics, this is called posterior probability [53]. From a clinical practice, posterior probability may allow a physician to mathematically combine a sequence of tests, avoiding unnecessary physical tests [53]. Theoretically, this approach adjusts for all sensitivities and specificities in the final probability value [53]. Thus, it may prove a valuable technique to help avoid expensive or uncomfortable physical exams such as nerve conduction tests (NCS) for diagnosis of CTS. For example, O'Gradaigh and Merry applied the Bayesian posterior probability technique to examine its validity among patients suspected of having CTS [54]. Prospectively, their algorithm proved to be reliable and had the same accuracy as NCS in diagnosing CTS patients [54]. Particularly for conditions with a high prevalence, such as CTS, Bayesian probability may be a useful technique in reducing the time, cost, and dissatisfaction involved in diagnosis and treatment [55–58].

Summary

The role of reliable and validated outcome instruments in measuring various health outcomes such as severity of symptoms, function status, health-related quality of life, and patient's satisfaction with the undertaken treatment have become increasingly acknowledged. Over the past decade, there has been a tremendous effort by physicians,

policy makers, and researchers to increase assessment and accountability in medicine. The increasing demand of our aging population and our limited resources give rise to the need for assessment and accountability. With an estimated annual cost of more than one billion dollars, CTS is the most common upper extremity disorder. Today, despite the tremendous progress during the 1990s in development of assessment and outcome questionnaires, controversy surrounding the treatment of CTS still remains. Future research using Bayesian probability algorithms may help streamline severity assessment and standardize treatment for CTS.

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Unusual Causes of Carpal Tunnel Syndrome

10

Laura Lewallen and Marco Rizzo

Background

Carpal tunnel syndrome is the most common peripheral neuropathy in humans and has a prevalence of 3.7% of the US general population [1, 2]. While most cases are idiopathic, there are several well-known conditions which are often associated with carpal tunnel syndrome. These include pregnancy, hypothyroidism, diabetes, obesity, overuse, trauma, renal failure, and inflammatory arthropathy [3]. In all of these conditions, it is compression, entrapment, irritation, or global compromise of the nerve (as in diabetes) that leads to symptoms [3]. However, many of the more rare etiologies are not as familiar to most physicians, but are important to consider when caring for these patients. The mechanism of causing neuropathy can vary from compressive, inflammatory, infectious, or traumatic.

L. Lewallen • M. Rizzo (✉)
Department of Orthopedic Surgery, Mayo Clinic, 200 First St. SW, Rochester, MN 55905, USA
e-mail: Rizzo.marco@mayo.edu

Compressive

Tumors

Various space-occupying lesions have been identified as rare causes of carpal tunnel syndrome. Wu et al. reported a small series of patients [4] with carpal tunnel symptoms due to tophaceous gout (10), tenosynovitis (7), and tumors (8). In a recent study, Martinez-Villen et al. identified nonneural tumors or tumorlike lesions in 22 (5.3%) of 414 patients surgically treated for a nerve compression syndrome of the hand and forearm [5].

Benign tumors such as lipoma may cause secondary compression [6] and in rare cases may arise from the flexor tenosynovium [7, 8]. Intraneural lipomatous tumors have also been described [9]. These lesions will require decompression of the nerve from within the epineurium.

Fibroma of tendon sheath, though quite rare, is another benign tumor that should be considered. The typical presentation is a slowly enlarging, painless mass [10]. Males are more often affected, particularly in the 40–60-year-old range [11]. These tumors are usually well circumscribed, attached to the tendon or tendon sheath. Identifying the correct diagnosis and underlying cause are crucial, as release of the transverse carpal ligament alone may not predictably relieve symptoms or solve the primary problem in these cases. Excision of the mass is necessary to prevent recurrent symptoms.

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Ganglion Cysts

Ikeda et al. [12] describe a case of a 34-year-old patient who presented with rapidly progressive symptoms of numbness, pain, and weakness, as well as changes on EMG. Ultrasound revealed a ganglion compressing the median nerve. She underwent carpal tunnel release and ganglion excision; her symptoms resolved. Cysts may compress the motor or digital branch of the median nerve and in some cases may affect both the median and ulnar nerves [13]. Particularly in patients with rapidly progressive symptoms, the presence of a ganglion cyst should be considered. Physical exam may underestimate the size of these lesions as they often track down to the joint. Magnetic resonance imaging (MRI) or ultrasound can confirm the diagnosis and delineate the size of the lesion. Successful treatment hinges on decompression or excision of the lesion.

Foreign Body

It is possible for a foreign body to cause atypical synovitis and subsequently carpal tunnel syndrome, though only a few cases have been described. In one case report, a patient was found to have a piece of wood compressing the median nerve [14]. On exam, one should carefully inspect for signs of an entry wound and palpate for any abnormal masses. It is also important to clarify details of the history regarding exposure to specific materials. Ultrasound is a helpful tool to rule out such possibilities, bearing in mind that certain foreign objects are not visible on plain X-rays. Once the location of the object has been determined, removal is recommended.

Amyloidosis

Patients with amyloidosis may develop protein deposition in the flexor tendon sheath, resulting in median nerve compression. Deposition in the transverse carpal ligament is also possible, leading to thickening of the ligament. One recent study found that symptoms were bilateral in 97% of cases [15]. These patients usually respond poorly to steroid injections. MRI may show thickening due to amyloid deposition. Further assessment to confirm the diagnosis includes Congo red staining and immunohistochemical studies performed at the time of surgery. Amyloidosis should be considered in the differential particularly in patients with bilateral symptoms, refractory to conservative measures.

Calcific Tendinitis

Similarly, calcium accumulation (as seen in calcific tendinitis) can cause CTS. While most common in the flexor carpi ulnaris, calcium deposition may occur in a variety of areas, including the flexor tendons and carpal bones. Previous studies have found this condition to be the most common in patients between 30 and 60 years old [16]. Females are more often affected than males, and the dominant hand is more often involved [17].

Presentation may resemble infection or inflammatory conditions, with symptoms including erythema, localized pain, and swelling [18]. CRP may be elevated. AP and lateral X-rays are often unremarkable, depending on the size of the mass. Oblique views can be helpful. Advanced imaging, with CT or MRI, is often indicated to visualize the areas of involvement. In cases of acute CTS due to calcium deposition, treatment requires not only decompression of the nerve but also resection of the calcifications if possible.

Inflammatory Conditions

Gout

Gout is another less common but important condition to consider. Patients with chronic, long-standing gout are particularly at risk, as the large tophi may result in mass effect and subsequent symptoms [19]. Deposition in the transverse carpal ligament, median nerve, or carpal tunnel floor can occur. Tophaceous gout may also affect the flexor tendons themselves, causing stiffness, flexion contracture [20, 21], and tendon infiltration [22].

Serum urate levels aid in the diagnosis. Wrist joint or tendon sheath aspiration is also recommended. Fluid should be sent for crystal analysis with polarized light microscopy. Urate crystals are needle shaped and negatively birefringent. Preoperative MRI can help define the location and size of the lesions. CT is helpful if calcifications are present. Surgical decompression is recommended, in addition to medical management of the hyperuricemia. These patients are at increased risk of recurrence. It is also important to recognize that carpal tunnel syndrome may be the first manifestation of gout.

Calcium Pyrophosphate Dihydrate (CPPD) Crystal Deposition

Similarly, several case reports describe patients with CPPD crystal deposition or pseudogout [23]. In addition to the more common sites including the TFCC and DRUJ, calcifications of the flexor tendons may occur. The floor of the carpal tunnel and epineurium of the median nerve are other potential areas of involvement.

Calcifications are typically visible on plain films. The carpal tunnel can be particularly helpful. Chondrocalcinosis and degenerative changes of the joints are an associated finding in many of these patients and may be a clue to the correct diagnosis. Crystal analysis is recommended for further evaluation. In contrast to gout, CPPD crystals are rhomboid shaped and positively birefringent on polarized light microscopy.

Infection

A number of infectious organisms have been known to cause carpal tunnel syndrome. The mechanism appears to be similar regardless of the organism, due to the mass effect from the inflammatory process. Case reports of roundworm [24], atypical mycobacterium [25], and histoplasma capsulatum [26] [27] have been described. Adequate treatment hinges on eliminating the mass effect.

Trauma

Several types of direct and indirect trauma may lead to carpal tunnel syndrome, either acutely or in a delayed fashion. Distal radius fractures are perhaps the most common example, associated with acute carpal tunnel syndrome in 5.4–8.6% and delayed carpal tunnel syndrome in 0.5–22% of cases [28]. Possible causes include direct trauma to the nerve, entrapment of the nerve due to displaced fracture fragments, and/or increased canal pressures secondary to hematoma. A high index of suspicion is crucial when evaluating these patients, as a delay in diagnosis can have devastating consequences. Urgent surgical release and fracture fixation may be necessary in symptomatic patients or those with progression of symptoms.

A recent case control study by Dyer et al. examined risk factors for acute CTS in patients with a distal radius fracture [29]. These authors found that greater translation of fracture fragments, seen in higher energy injuries, was associated with a higher risk of developing acute CTS. A threshold value was identified in only one subgroup of patients, females younger than 48 years old, with 35% translation. This suggests that prophylactic carpal tunnel release may be indicated in some patients.

Less common traumatic causes include both bone forearm fractures and elbow dislocation. A thorough physical exam is necessary in all trauma patients. Indirect causes such as blunt trauma or hemorrhage are also important. For example, patients on chronic anticoagulation or hemophiliacs are particularly at risk [30].

Congenital/Anatomic Variants

A number of anatomic variants exist, involving both the bony structures and the soft tissues. Preoperative X-rays are helpful to identify patients with bony abnormalities potentially contributing to their symptoms. Accessory carpal bones [31], coalitions (pisiform-hamate) [32], and osteophytes (of the trapezium) have been described [33]. It is reasonable to obtain preoperative CT or

MRI in such cases, to further define the bony structure for planning purposes.

Several authors have identified anomalous muscles contributing to carpal tunnel syndrome. The palmaris longus is one example. The original cadaveric work was done by Reimann et al. in 1944. While distal variations of this muscle seem to be more common, Basu et al. report a case of a dual tendon, central muscle belly variant [34]. Reversed palmaris longus [35] and palmaris profundus are also possible [36]. Barutcu et al. report a series of three patients with bilateral carpal tunnel syndrome due to an anomalous transverse carpal muscle visualized intraoperatively [37]. Ultrasound and MRI may appear normal. In many cases, such variations are first identified intraoperatively, underlining the importance of careful dissection.

A bifid median nerve is another possibility. Due to the increased cross-sectional area, compression in the carpal tunnel can occur [38]. Advanced imaging, including MRI or ultrasound, is helpful though not routinely used by some authors. Median nerve variations are important to keep in mind particularly during endoscopic release of the carpal tunnel, to decrease the risk of iatrogenic injury.

Iatrogenic cases of carpal tunnel syndrome also occur in children. Batdorf et al. reported a series of 20 patients diagnosed over a 30-year period [39]. These authors recommend stepwise management, similar to adult patients, with activity modification and bracing, injections, and finally surgery for refractory cases.

Conclusion

Presented here are a number of rare causes of carpal tunnel syndrome. As described, these cases are often more complicated and difficult to diagnose. Therefore, appropriate treatment may be delayed in some cases as release of the transverse carpal ligament is not always the solution in these patients. These examples highlight the importance of a thorough history (including occupational, social, and travel) and detailed physical exam. In some cases, carpal tunnel syndrome may be the first manifestation of an underlying systemic condition, warranting further evaluation. Advanced imaging such as ultrasound or MRI should be considered in some cases.

A 62-year-old female patient with rheumatoid arthritis developed progressive numbness, tingling, and pain in the right thumb and index finger, 26 years following right total wrist replacement (Fig. 10.1a, b). She subsequently underwent tenosynovectomy and carpal tunnel release (Fig. 10.1c). Severe compression and flattening of the median nerve were observed intraoperatively (Fig. 10.1d). A significant amount of tenosynovitis and foreign body reaction due to metal wear was present (Fig. 10.1e–i). The patient went on to wrist fusion less than 1 year later.

A 45-year-old female with a history of Hodgkin's disease and long-standing carpal tunnel symptoms presented to the emergency department with acutely worsening, severe right wrist pain several days following an EMG. Physical exam and EMG findings were consistent with carpal tunnel syndrome. X-rays were unremarkable (Figure 10.2a). An ultrasound was also performed which showed no fluid collection. There was concern for evolving CRPS; therefore, thorough evaluation was performed including CT and MRI. Both studies showed abnormal calcification along the volar wrist (Fig. 10.2b–d, e–g).

The decision was made to proceed with debridement and carpal tunnel release. Intraoperatively, a significant amount of fluid was found surrounding the FPL tendon sheath and underneath the nerve. Calcification was also present along the FPL tendon sheath (Fig. 10.2h–k). The area was carefully debrided and specimens were sent for pathology and cultures. The pathology report showed calcifying synovitis. Cultures were negative. The patient's symptoms resolved by 3 months postoperatively.

A 48-year-old right-hand dominant female from Iowa with a history of Sjogren's syndrome and interstitial lung disease presented with a 5–6-month history of right wrist swelling and paresthesias. She described constant numbness and

tingling along the radial aspect of the hand, exacerbated by activities such as driving, typing, or holding a phone. She also reported weakness of the right hand. The patient had been previously treated with splinting and a carpal tunnel corticosteroid injection 2 months prior to presentation. The injection provided relief for approximately 1 month; however, her symptoms returned.

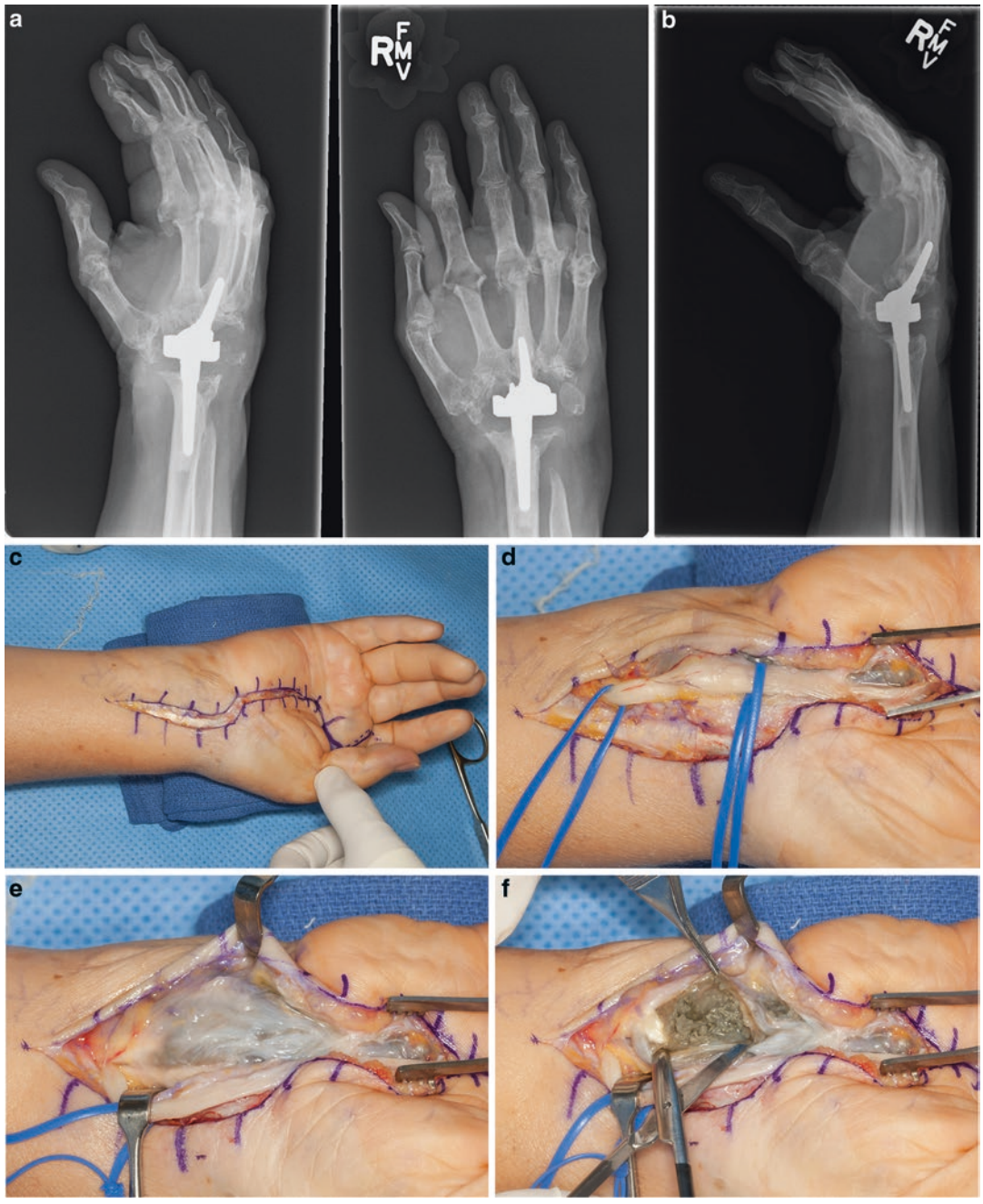

Fig. 10.1 (**a**–**j**) Foreign body reaction

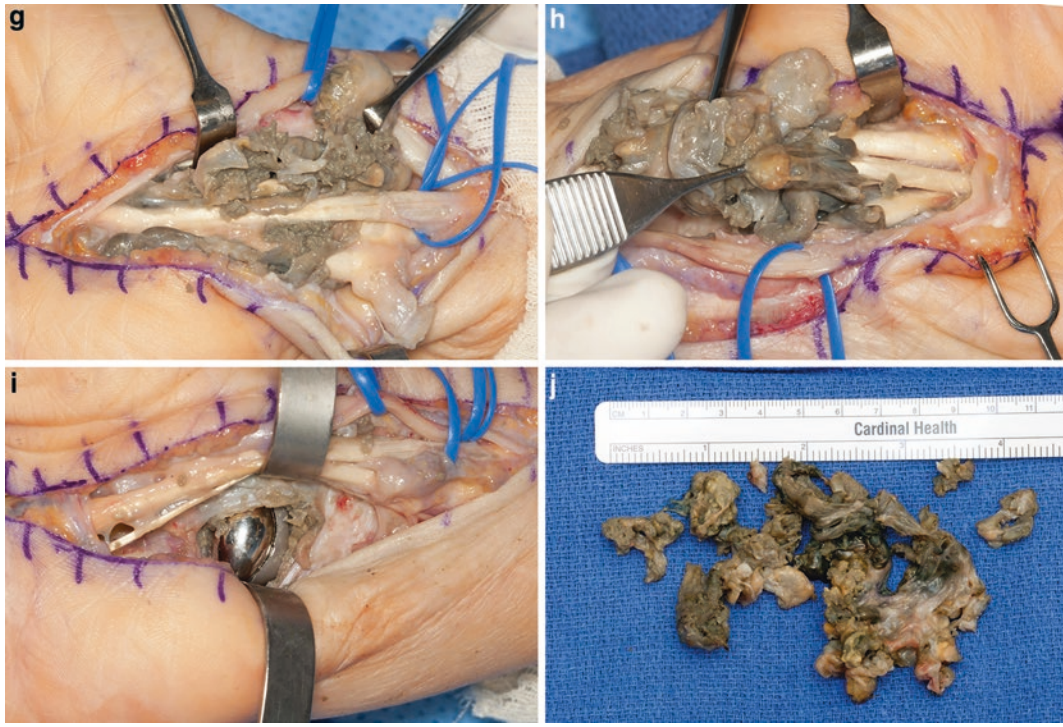

Fig. 10.1 (continued)

On physical examination, the patient had significant swelling along the volar wrist, extending through the palm and into the thumb. Carpal tunnel compression test was positive on the right and negative on Tinel's sign bilaterally. She was found to have weakness of thumb opposition (2.3 kg on the right, 4.6 kg on the left), as well as grip (4 kg on the right, 20 kg on the left). Two-point discrimination was 4–5 mm throughout all digits. Range of motion of the wrists was symmetric. EMG findings were consistent with carpal tunnel syndrome. X-rays were unremarkable (Fig. 10.3a, b). MRI showed extensive tenosynovitis (Fig. 10.3c–f).

The decision was made to proceed with carpal tunnel release and tenosynovectomy (Fig. 10.3g–i). Pathology and culture specimens were obtained at the time of surgery (Fig. 10.3j–k). The pathology report showed "non-necrotizing granulomatous inflammation of the right wrist flexor tenosynovium and FPL tenosynovium." Initial culture results were negative. However, 2 weeks later cultures revealed *Histoplasma capsulatum*. Therefore, the patient was subsequently admitted to the hospital for intravenous antifungals. After consultation with our infectious disease colleagues, the patient was treated with intravenous AmBisome for 2 weeks, followed by oral itraconazole for 3 months.

Fortunately, the patient's symptoms improved over time. The pain, swelling, and numbness had nearly completely resolved at the most recent follow-up visit. This case illustrates the importance of careful evaluation and consideration of these unusual conditions. A detailed occupational, travel, and social history is also essential.

A 13-year-old female was involved in an ATV accident and sustained distal radius/ulna fractures. She presented with numbness in the median nerve distribution. Initial X-rays showed 100% displacement and 80° of dorsal angulation (Fig. 10.4a, b). Closed reduction was performed in the emergency department (Fig. 10.4c, d). The decision was made to proceed with operative fixation. Intraoperatively, the median nerve was visualized and found to be tented and under a significant amount of stretch (Fig. 10.4e, f). The nerve was carefully dissected from its interposition between the radius and ulna fracture fragments. ORIF of the fractures was then performed (Fig. 10.4g, h).

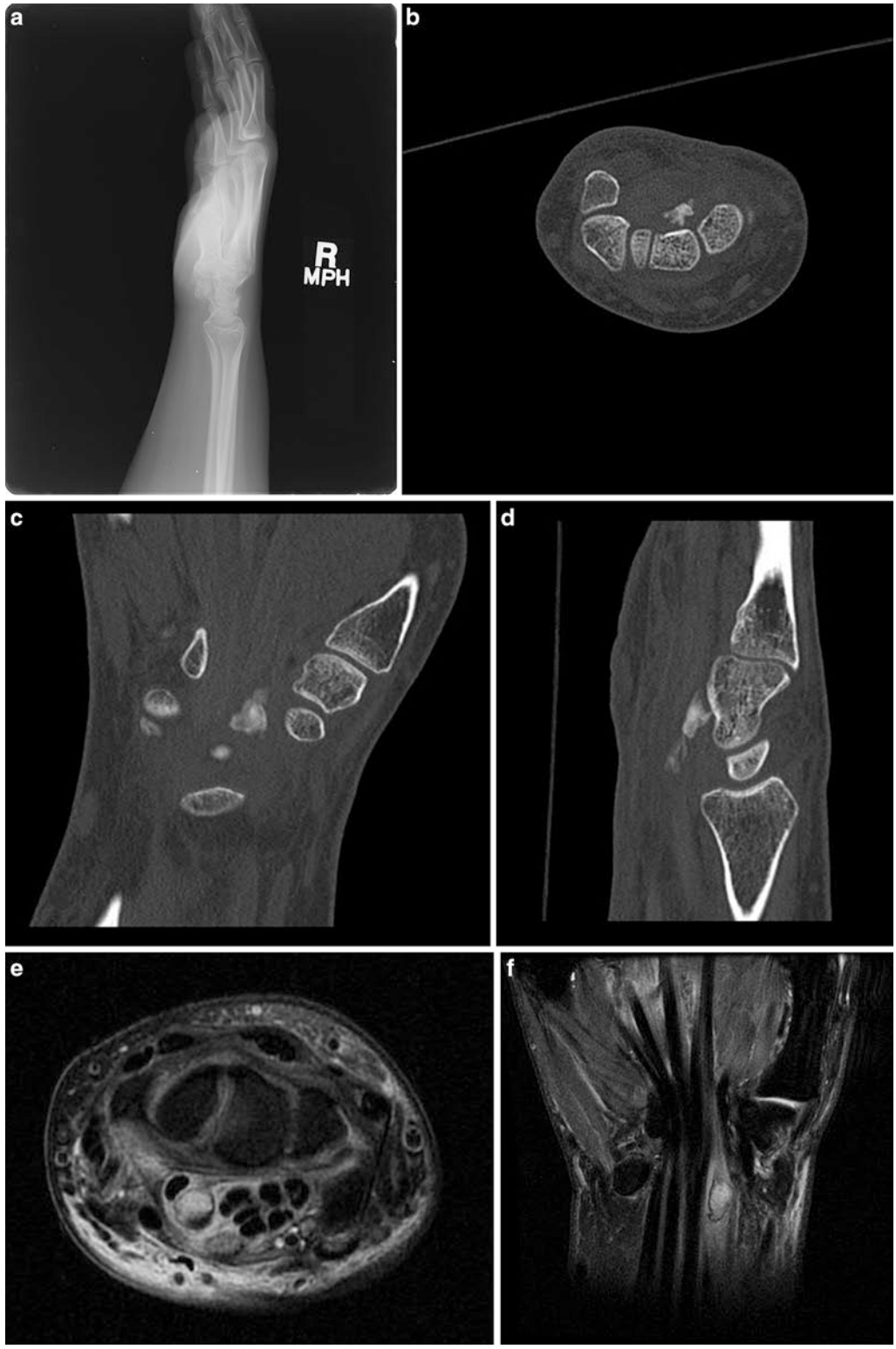

Fig. 10.2 (**a**–**k**) Calcific tendinitis

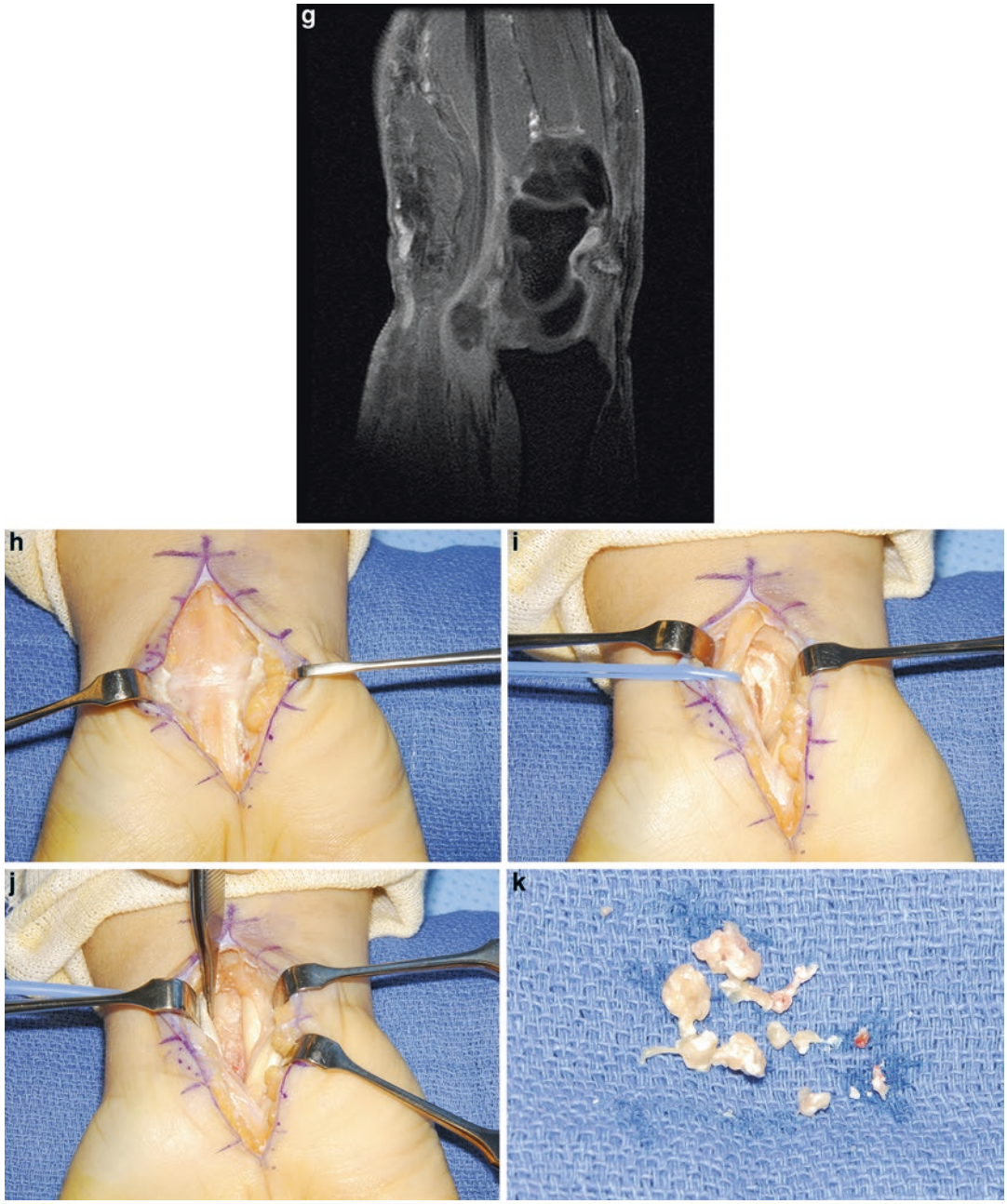

Fig. 10.2 (continued)

The fractures went on to heal uneventfully (Fig. 10.4i, j). The patient's nerve function gradually improved over time. At the time of the last follow-up (2 years from injury), two-point discrimination was 7 mm in the thumb and 5 mm in the other digits bilaterally. Tinel's sign over the median nerve was negative. She was able to make a full fist and had symmetric wrist flexion/extension as well as pronation/supination.

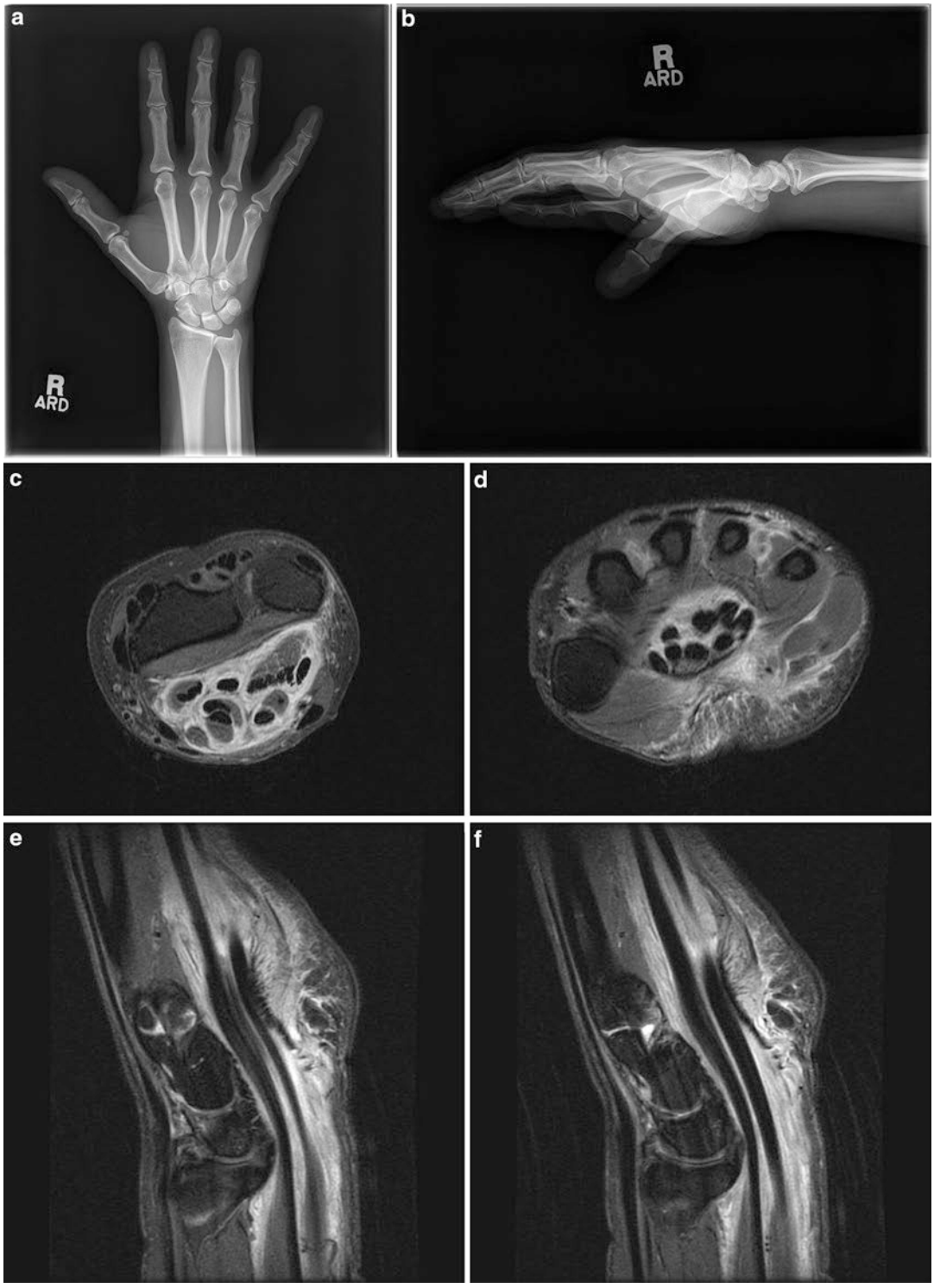

Fig. 10.3 (**a**–**k**) Histoplasma capsulatum

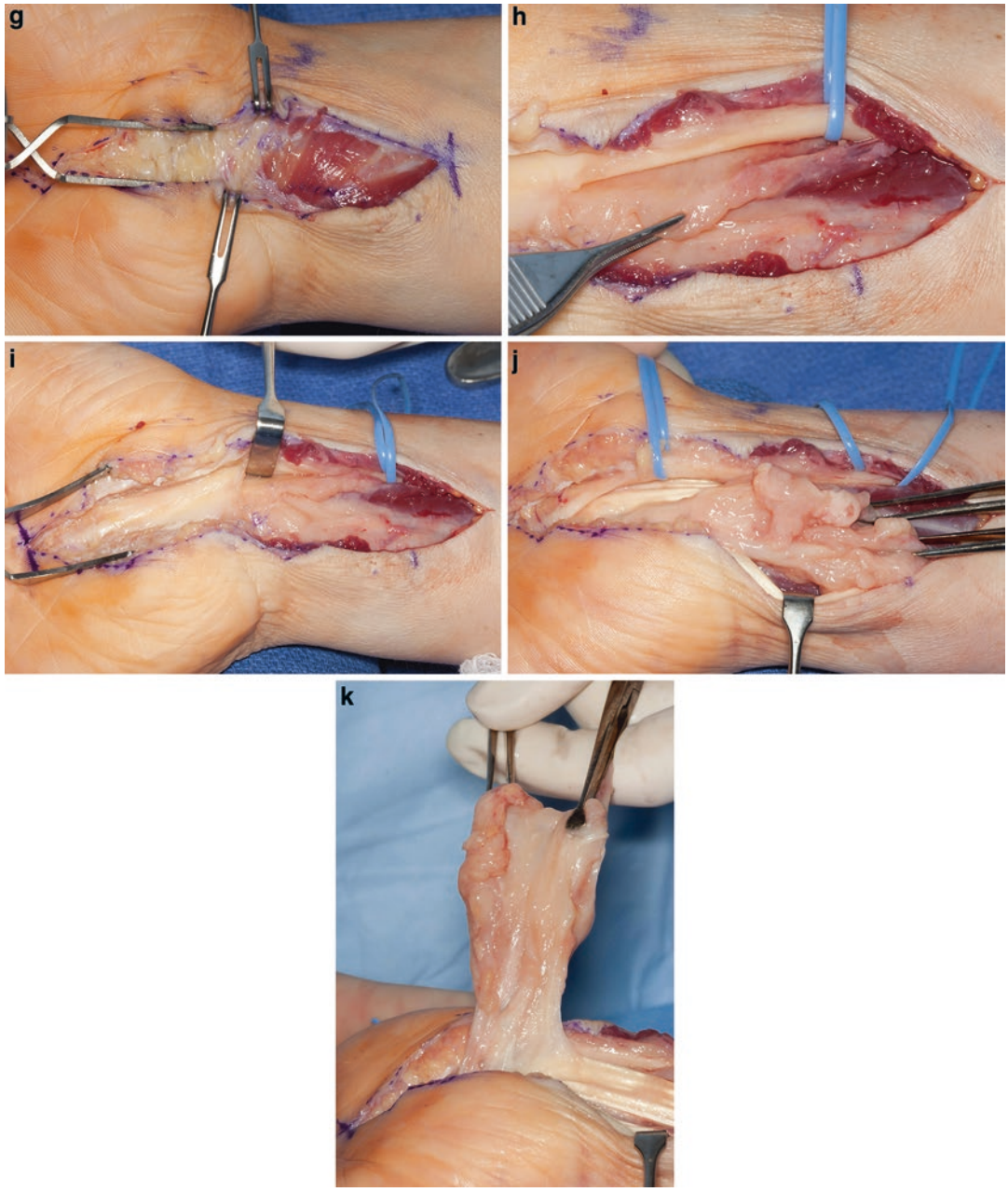

Fig. 10.3 (continued)

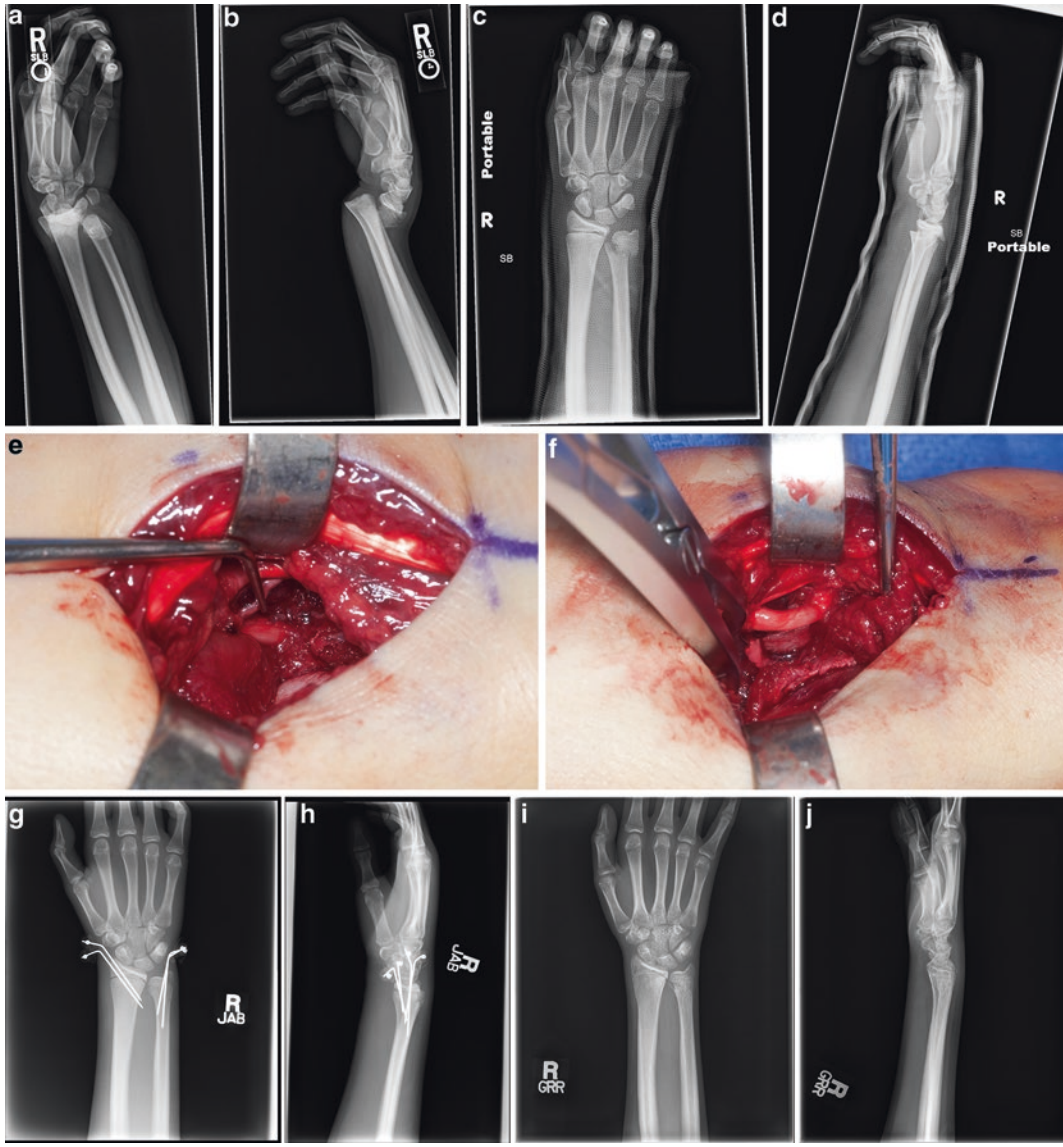

Fig. 10.4 (**a**–**j**) Trauma

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11 Nonoperative Options for the Management of Carpal Tunnel Syndrome

Loree K. Kalliainen

Introduction

Management of carpal tunnel syndrome (CTS) is reasonably straightforward at the end of the disease spectrum: patients with minimal symptoms and only rare interference with activities of daily living need no treatment, and surgery should be strongly considered when symptoms persist or rapidly worsen despite a reasonable course of nonsurgical care or if muscle atrophy is present. There is no universally agreed-upon treatment paradigm for patients with mild to moderate CTS. People may have symptoms which wax and wane over decades: they may delay seeking professional evaluation and treatment, they may present for care at different stages of their disease, and they may be treated with conservative measures with intervening asymptomatic periods [1].

Care may be provided by a primary care physician, a neurologist, a physical medicine specialist, an occupational or physical therapist, or a surgeon. If the disease is felt to be work related, patients may be referred to an occupational medicine physician. Patients can easily be seen by physicians in three to four different fields for management of this very common disease. Despite the high prevalence of CTS, practitioners in various specialties spend little time interacting with one another to discuss the scientific literature and compare philosophies of care. If there is lack of multidisciplinary consensus on key elements of care, patients may receive information regarding causation, correlation, and treatment that can be inadvertently conflicting. Physicians have inherent biases about treatment: surgeons see the benefit of relatively rapid treatment response and lasting effect, but nonsurgeons may view surgery with a less benevolent eye. As one author stated, patients "can always *submit* to surgical therapy if necessary" (italics mine) [2].

When considering if and when to intervene, it is ideal to understand the natural history of a disease. Padua et al. [3] followed 196 patients with mild to moderate idiopathic carpal tunnel syndrome for up to 15 months and found spontaneous improvement in the symptom severity score (SSS) element of the Boston Carpal Tunnel Questionnaire (BCTQ) in 34% of patients, lack of progression of symptoms in 45%, and worsening in 21%. Similar patterns were seen in the functional status score (FSS) (23% improved, 61% were stationary, and 16% worsened), pain (26%, 62%, and 12%, respectively), and electrodiagnostic tests (27%, 57%, and 16%, respectively). They identified several factors predicting disease worsening: bilateral symptoms, advancing age, and a positive Phalen test. Despite issues

L.K. Kalliainen (✉)
Division of Plastic Surgery, University of North Carolina, 7043 Burnett Womack Building, Campus Box 7195, Chapel Hill, NC 27599-7195, USA
e-mail: Loree_Kalliainen@med.unc.edu

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related to poor sensitivity and specificity, having a positive Phalen test at the initial assessment decreased the odds of spontaneous symptomatic resolution by 60%. A similar 24-month study was performed by Ortiz-Corredor et al. [4]. Of 189 people initially evaluated in their clinic, 57 (30%) had had a treatment intervention within 2 years (splint, injection, or surgery). Of the remaining 132 patients, they found clinical improvement in 48%, lack of progression in 29%, and deterioration in 23%. Electrodiagnostic studies showed improvement in 25%, stability in 67%, and deterioration in 8%. These outcomes support a minimalist approach in the initial management of the majority of patients with carpal tunnel syndrome.

Successful treatment of carpal tunnel syndrome, whether nonoperative or operative, should improve symptoms and limit nerve degeneration by decreasing pressure in the carpal tunnel, thereby improving vascular supply of the nerve and gliding of tendon and nerve relative to one another [5]. Given that anywhere from 23 to 48% of patients with mild to moderate CTS may spontaneously improve, studies looking at treatment efficacy should be powered to take this into account. Numerous nonoperative options for symptom relief are available; this chapter will review the literature regarding those options.

Treatment Outcomes

Outcome assessment tools have increasingly become patient centered [6]. Rather than solely focusing on clinicians' views of what constitutes treatment success or failure, current philosophy of care focuses more on the patient's experience. Though many scales have been used primarily for research purposes, incorporation of outcome measures into clinical practice is feasible [7]. Documentation of treatment efficacy will likely increasingly be required by healthcare systems and payers. For CTS, the Boston Carpal Tunnel Questionnaire scales (symptoms severity scale, SSS, and functional status scale, FSS) are more sensitive and specific than more generic functional scales such as the SF36 [8, 9]. Other scales validated for use with CTS are the Michigan Hand Outcomes Questionnaire and the short form of the Disabilities of the Arm, Shoulder, and Hand (QuickDASH) [9]. The majority of recent CTS studies have used the BCTQ to evaluate treatment effects and a ten-point visual analog scale (VAS) to assess pain.

Physical exam assessments may include pinch and grip strength, Semmes-Weinstein monofilaments for light touch, moving and static two-point discrimination, manipulation of objects (Jebsen Hand Function Test), and electrodiagnostic studies [5]. Electrodiagnostic tests don't always correlate with patient's complaints [10], and cost and inconvenience make them less likely to be obtained for routine post-treatment evaluations. The most recent clinical practice guideline of the American Academy of Orthopaedic Surgery for carpal tunnel syndrome was less prescriptive regarding the necessity of obtaining electrodiagnostic tests in suspected cases of carpal tunnel syndrome [11], and recent surveys of upper extremity surgeons have found that it is becoming more acceptable to substitute a physical exam for electrodiagnostic exams [12, 13].

The majority of the studies discussed in this chapter focused on management of mild to moderate idiopathic carpal tunnel syndrome. Inclusion criteria were adult patients with symptoms of median nerve dysfunction in the hand for at least 1–2 months and positive electrodiagnostic tests showing mild to moderate changes. Electrodiagnostic severity of CTS was generally defined per criteria described in Padua [3]. Mild CTS is characterized by abnormal sensory latency, moderate CTS has abnormal motor latency with or without abnormal sensory latency, and severe CTS has absent sensory latency with concomitant muscle atrophy. Unless otherwise noted, exclusion criteria included patients with severe CTS; metabolic derangements associated with an increased risk for carpal tunnel syndrome (diabetes mellitus, hypothyroidism, pregnancy, obesity, gout, fibromyalgia, rheumatoid arthritis, and osteoarthritis); inability to take a drug being tested; prior treatment(s) for carpal tunnel syndrome; history of upper extremity trauma; polyneuropathy; cervical radiculopathy; bleeding

dyscrasia; cardiac, renal, or hepatic disease; and the inability to give consent to participate in research. Study weaknesses included lack of use of a validated outcome measure in older studies, small sample sizes, and short follow-up periods. Efforts were made to include studies of moderate- to high-level evidence. When interpreting questionnaire outcomes, it is important to keep in mind the principle of the minimal clinically important difference (MCID) as differences may be statistically significant rather than clinically important [14, 15]. For the SSS, Özyürekoğlu et al. [14] found that a decline of ≥1.04 points may be clinically important.

Splints

There is reasonable evidence supporting the use of splints in patients with mild to moderate CTS, but long-term studies are limited. Baker et al. [16] performed one of the larger studies on splinting. They randomized 124 patients to four groups of splinting/stretching combinations to be done for 4 weeks, six times a day. Outcome data included the BCTQ and the DASH. The study was appropriately powered. Patient adherence was reasonable and improved with education. At the conclusion of the study, 66% of the patients had improved symptoms and 34% had improved function. The subgroup with the highest level of improvement used a general splint and did lumbrical stretches. The initial improvements were maintained at a 24 week follow-up. An additional 25% of the original patient cohort went on to have surgery at 24 weeks.

Baysal et al. [17] did a prospective, randomized trial of three treatments: splinting and range of motion exercises; splinting and ultrasound; and splinting, range of motion, and ultrasound. Group sizes were small (24, 16, and 16 patients, respectively). Treatment lasted for 3 weeks. Electrodiagnostic tests were done pretreatment and at two times post completion. All groups had significant improvement at the immediate and 2-month periods, and outcome was best in the splint/range of motion/ultrasound group with 62% of patients having good to excellent outcomes. The effect wore off to some degree, and by the 11-month follow-up visit, no patients in the splint/ROM group maintained good or excellent results. In another study with relatively long follow-up, Povlsen et al. [18] splinted 75 people with CTS. At 3 months, 52 (69%) were satisfied with splinting, and 17 (31%) wanted surgery. At 36 months, the satisfaction rates had flipped: only 25% were still satisfied with the splint and 75% weren't. Ultimately, 41% of the original 75 study participants had surgery.

In the 2009 AAOS treatment guidelines for CTS, moderate (B level) evidence was found for night splinting [19, 20]. Night splinting in a neutral position was compared to no intervention in 50 subjects (25/group). Splints were worn for at least 6 h a night for 6 months. Electrodiagnostic tests, the BCTQ, and physical exam were assessed pre-intervention and at 3- and 6-month time points. The dropout rate was high in both groups: 36% of the control group did not complete the 6-month evaluation; 28% of the splint group did not finish. Five subjects in the control group were known to have had surgery within the 6-month period (20%) compared to one in the splint group (4%). This suggests that splinting has enough benefit to satisfy patients with mild to moderate disease, whereas monitoring only can be less appealing. Of the treatment recommendations in the clinical practice guideline, splinting has the highest surgeon adherence rate: approximately 98% of hand surgeons prescribe splints as an initial therapy for patients with CTS [12].

Manual Therapy

As tissue adherence and synovial proliferation are putative causes of CTS, tissue massage may improve local blood flow and promote differential motion between tendon and nerve, decreasing traction on the nerve. The placebo effect might be presumed to be higher in this class of treatments as massage is often a relaxing and pleasant experience. If psychological factors are magnifying the negative experience of pain, manual therapy may be creating indirect benefits

rather than having discrete effects on the carpal tunnel or median nerve.

Bongi et al. [21] performed manual therapy on 22 patients. (41 hands) for twice a week for 10–15 min a time for 3 weeks [21]. The BCTQ and electrodiagnostic tests were performed at the end of treatment and after 24 weeks. There was no change in electrodiagnostic values, but the BCTQ improved at the 24-week assessment. Patients noted less paresthesia, pain, night waking, and hand sensitivity at the 24-week time point.

Burke et al. [22] randomized subjects to standard soft tissue manipulation (n = 12) or a patented technique using metal tools to mobilize tissues (n = 14). Outcome measures were electrodiagnostic tests, BCTQ, and physical exam; and the evaluator was blinded to the treatment group. The treatment duration was for 6 weeks, and outcomes were measured at the end of therapy and 3 months later. Electrodiagnostic latency was improved, but there were no changes in provocative maneuvers (Phalen and Tinel) or in two-point discrimination in either group. Improvements in strength and motion to the level of the contralateral "normal" wrist were present in both groups, and these changes were maintained at the 3-month evaluation. At both time points, subjects in both groups were satisfied or very satisfied; none were dissatisfied. Though there were no detectable differences between the treatments, the authors felt that the improved variables supported the proposed mechanism of action behind the therapy.

Elliott and Burkett [23] performed a quasi-experimental study with a pre-/post-design. Twenty subjects were recruited for twice-weekly 30-minute massages for 6 weeks. Outcomes were measured at baseline and then at 2-, 6-, and 10-week intervals with the BCTQ, two-point discrimination, provocative tests, and a pressure sensor. Significant differences were found at all time points for the BCTQ. The Phalen and Tinel tests improved as did two-point discrimination. Pain tolerance (as measured by the pressure sensor) also improved but could not be standardized due to differences in sex and habitus.

Nerve/Tendon Gliding

The purpose of nerve/tendon gliding exercises is to theoretically improve differential motion between tissues, decrease edema, and improve axonal transport and vascular supply to the vasa nervorum [24–26]. Horng et al. [26] used ultrasound (US) to compare median nerve architecture during tendon gliding in subjects with (n = 73) and without (n = 53) CTS. Demographics between groups were the same except for educational level and household income (higher in the control group). All electrodiagnostic findings were different between groups. People with CTS had higher levels of pain. The cross-sectional areas of median nerves in people with CTS were larger than controls in all hand positions of the tendon gliding exercises. The only difference between groups in the flattening ratio (ratio of long to short axis of the median nerve) was when the hand was in the straight and hook positions. The fist position was associated with compression of the median nerve in both groups. The hook and fist positions promote tendon gliding between the flexor digitorum superficialis and profundus but may irritate the median nerve.

The evidence of usefulness of tendon and nerve gliding in reducing symptoms of CTS is not compelling, and though it is unlikely to cause harm, it hasn't shown demonstrable benefit. Early studies have been challenging to compare due to poor study design, wide confidence intervals, low numbers, and high dropout rates. McKeon and Yancosek [27] did a systemic review of six studies; none demonstrated a significant benefit of nerve and tendon gliding over standard care (primarily splinting). More recently, Kim [28] did a review of RCTs looking at tendon and nerve gliding for mild or moderate CTS. Only four Cochrane A and B quality studies were included. Interventions included exercise and variety of splints. All interventions improved FSS and SSS, but none of the included studies looked at nerve/tendon gliding exercises alone.

Akalin et al. [29] prospectively randomized subjects to one of two groups: continuous splinting for 4 weeks (n = 14) or splinting and nerve/

tendon gliding for 4 weeks ($n = 14$). Outcomes at 8 weeks post-treatment were assessed by physical exam and the BCTQ. Good to excellent outcomes were noted by 72% of patients treated with splinting, and 93% of patients treated by splinting and nerve and tendon gliding. The difference was not significant. Significant improvements were noted in the SSS and FSS in each group, but there were no between-group differences except improved pinch strength in the nerve/tendon glide group.

Brininger et al. [30] randomized 61 subjects to four groups: a neutral wrist and MCP splint with and without an exercise program and a wrist cock-up splint with and without an exercise program [30]. Evaluations using the BCTQ, the Moberg test, and grip and pinch were performed at baseline and then at 4 and 8 weeks. Fifty-one subjects completed the study. Splints were to be worn at night only and exercises were to be done at least three times a day. Significant improvements were found in both the SSS and the FSS. The neutral wrist and MCP splint was more effective in decreasing symptoms than the wrist cock-up splint. Symptom reduction was maintained for the 8-week period. Doing the exercises did not provide additive benefit to splinting. Adherence to therapy in all groups was high. Heebner and Roddey [24] randomized 60 subjects into "standard" care (education, splinting, and tendon gliding, $n = 28$) or standard care plus nerve mobilization focusing on the median nerve ($n = 32$). The nerve mobilization consisted of standing arm's length from a wall, putting the hand fingers down on the wall, and turning the head away from the wall until a sensation was felt. Subjects had one teaching session and follow-up was done at 1 and 6 months. Outcomes were not significant for the DASH, the BCTQ, or the effect of nerve mobilization.

Exercise

Moderate to vigorous exercise has been associated with significant reduction of morbidity and mortality in more than 20 chronic conditions [31], and it seems intuitive that improved overall health would improve both the physical symptoms of carpal tunnel and negative psychological effects of chronic pain. Hypertension, diabetes, obesity, depression, poor overall health, and a sedentary lifestyle are associated with carpal tunnel [32–34].

A Cochrane review by Page et al. [35] summarized current evidence on exercise and nerve/tendon gliding. A total of 16 studies met inclusion criteria of randomized or quasi-randomized studies comparing exercise and gliding with nothing, placebo, or other exercise/gliding option. Because of study heterogeneity, the authors couldn't pool data. Many of the studies had short follow-up, small numbers, and subjective outcomes. Only one of sixteen studies looked at the effect of whole-body exercise on CTS; the remainder involved massage or tendon and nerve gliding. As noted in the prior section, there is little evidence that tendon and nerve gliding have significant benefit.

Garfinkel et al. [36] evaluated the effects of yoga and relaxation therapy on CTS symptoms. Subjects were randomized to a yoga program ($n = 22$), 1–1.5 h twice a week for 8 weeks or the use of a wrist splint ($n = 20$). All subjects had abnormal electrodiagnostic exams in addition to other clinical findings consistent with CTS. Wearing a splint and having prior injections were not exclusion criteria. Outcome variables included sleep disturbance, VAS, provocative maneuvers, paresthesia, numbness, grip strength, and distal latency. They were tested at baseline and at the end of the 8-week program. The yoga group had significant improvements in grip strength and significantly less pain. No changes or between-group differences were found in sensory or motor latency or sleep disturbance.

Nathan et al. [37] examined the effect of a 10-month program of supervised aerobic exercise on body mass index (BMI), body fat percentage, oxygen consumption, nonspecific symptoms, and sensory latency. Forty-one subjects started the program; 30 finished it. Subjects showed an acceptable degree of adherence to the training, completing 73% of sessions. Aerobic capacity, BMI, and body fat all improved, but there were no improvements in sensory latency or in symptoms

specific to CTS. The authors did not specify which symptoms were evaluated. No outcome tools specific to CTS were used.

Phonophoresis/Iontophoresis/ Nonthermal Ultrasound

Phonophoresis, iontophoresis, and ultrasound are commonly used modalities in hand therapy. Phonophoresis uses ultrasound for the transdermal delivery of drugs; iontophoresis uses electrical current. Phonophoresis can deliver drugs to a greater depth (2–5 cm at 1 MHz) than iontophoresis (at least 1.5 cm). Though they are used routinely, evidence supporting efficacy is minimal [38]. Recent evidence is suggestive of greater efficacy with phonophoresis than with iontophoresis.

Bakhtiary et al. [39] randomized subjects to treatment with dexamethasone delivered by phonophoresis or iontophoresis in 52 wrists in 34 patients with mild to moderate carpal tunnel syndrome. Outcome variables included pain (VAS), pinch and grip strength, and electrodiagnostics. Measurements were recorded before and 4 weeks after a 2-week treatment session (5 days a week, 10 treatments in total). Significant improvements were seen in grip, pinch, pain, latency, and amplitude. Changes were more pronounced in the phonophoresis group. Long-term effects are unknown.

Gurcay et al. [40] performed a prospective and randomized trial of three treatments: phonophoresis with 0.1% betamethasone (n = 18), iontophoresis with 0.1% betamethasone (n = 16), or a nighttime wrist splint (n = 18). Phonophoresis and iontophoresis were done 3 days a week and splints were worn every night for 3 weeks. Outcome measures were the SSS component of the BCTQ, grip strength, and the nine-hole peg test which measured dexterity. At 3 months after treatment, the SSS improved in all groups compared to pretreatment, but the only between-group difference was between phonophoresis and splinting. No differences were found with the peg test or in grip strength.

Soyupek et al. [41] compared splinting (n = 23) to phonophoresis with either diclofenac (n = 23) or 0.1% betamethasone (n = 28). Phonophoresis was done 5 days a week for 3 weeks. Splinting was done continuously for 15 days and then as needed. Outcomes were measured with ultrasound at the level of the pisiform, electrodiagnostics, provocative tests, VAS, and the BCTQ at baseline and after 3 months. Splints improved the SSS but not the FSS. Phonophoresis improved pain intensity and the SSS. If patients had positive Tinel and Phalen tests, phonophoresis with steroid improved both the SSS and the FSS. Phonophoresis and diclofenac only improved the SSS. The median nerve CSA decreased after phonophoresis treatment with steroids. No changes were seen in electrodiagnostic studies in any group. No correlations were identified between findings on ultrasound and the BCTQ scores or provocative tests. There were no correlations between electrodiagnostic tests and the BCTQ.

Ebenbichler et al. [42] used pulsed, nonthermal ultrasound in a randomized and prospective fashion on 90 subjects. Ultrasound (n = 45) and sham ultrasound (n = 45) were used for 7 weeks: 5 times a week for 2 weeks and then 2 times a week for 5 weeks. Validated outcome measures were not used. Electrodiagnostic exams and physical exams were performed at baseline, after ten sessions, and after the final session. Final follow-up was performed after six more months. There was early loss of 24% of patients due to noncompliance or symptom severity. Symptom improvement was significantly greater in the active treatment group at all time points. Complete or satisfactory improvement was experienced by 68% of subjects at the end of treatment in the treatment group and 38% of the sham group. At the 6-month time period, the treated subjects experienced continued improvement, and 74% had complete or satisfactory improvement compared to 20% of sham-treated subjects. Long-term improvements in grip and pinch strength and sensory and motor latency were also seen in the active treatment group.

Laser

Low-level light therapy (LLLT) has been used in clinical settings for almost 50 years, but it remains poorly accepted. LLLT has been used to aid in wound healing, reduce inflammation, improve hair growth, reduce pain, improve cognitive function in total brain injury, and reduce musculoskeletal complaints (photobiomodulation) [43, 44]. It theoretically offers a plethora of benefits but via poorly understood mechanisms of action. It can be applied using a wide assortment of parameters which have not been globally standardized. Studies of LLLT to treat CTS have had the usual limitations of short follow-up, small sample sizes, and no agreed-upon treatment regime.

In a prospective and randomized trial, Dincer compared wrist splints ($n = 36$), splints and US ($n = 30$), and splints and LLLT ($n = 36$). Outcome variables included BCTQ, patient satisfaction, VAS, and electrodiagnostic studies. Subjects in the splint group were instructed to wear standard splints at night and as needed during the day for 3 months. Subjects in the US and LLLT groups had treatments 5 days a week for 2 weeks. Assessments were done at baseline and then at 1 and 3 months following treatment. Statistical improvements were observed in the BCTQ and VAS assessments, but the differences were very small in the splint only group. The mean changes at the third month for the SSS were 0.25 for splinting, 0.95 for US, and 1.66 for LLLT. As per the suggestion of Özyürekoğlu et al. [14], the LLLT improvement is likely the only one to meet MCID criteria [14]. Differences in VAS were likewise more pronounced in the LLLT group with a drop of 4.45 in pain at the third month compared to 3.2 in the US group and 0.67 in the splint group. All patients had baseline VAS score of 6. The degree of satisfaction ("completely" or "almost") was highest for LLLT and US groups at 3 months: 61% of LLLT group, 53% of US, and 17% of splints.

Pratelli et al. [45] compared laser to fascial manipulation. Fascial manipulation (FM) is deep massage which aims to decrease pain by improving gliding and reducing viscosity of the extracellular matrix. Forty-two subjects (70 hands) were included. The female to male ratio was lower than is generally seen in studies of CTS (29 women, 13 men). Fascial manipulation subjects ($n = 35$) were treated for 45 min one time a week for 3 weeks. LLLT subjects ($n = 35$) were treated 5 times for 10 min each session using an infrared (78–830 nm) laser set at 1000–3000 mW. Outcomes were assessed with the VAS and BCTQ at baseline and at 10 days and 3 months after the end of treatment. Within and between groups, differences were found in SSS, FSS, and VAS at both follow-up times. VAS decreased from six at the start in the FM group to 0.71 at the end and LLLT decreased from 5.51 to 5.03. The evaluator was blinded to the treatment group. As this study included 45% men, sex bias may have been introduced. As there are no widely agreed-upon laser settings, and because fascial manipulation is inherently difficult to standardize, it is difficult to compare these findings with other studies.

Fusakul et al. [46] used a randomized, double-blind, placebo-controlled study to explore the effects of LLLT on CTS. Fifty-six subjects per group were randomized to LLLT and a splint or to sham laser and a splint. The treatments were done 3 times a week for 5 weeks to mimic the normal duration of hand therapy. Outcomes were evaluated at 5 and 12 weeks following completion of the treatments. The laser was a gallium-aluminum, arsenide laser (810 nm) set at 50 mW. Each group showed improvements in VAS, BCTQ, and grip and pinch strength, but the only difference between the groups was the SSS at 5 weeks. This difference disappeared at the 12-week assessment. There were no meaningful differences in the electrodiagnostic tests. Treatment response ratings had no differences at any time points.

Acupuncture

Acupuncture has been used in Asia for thousands of years, but it has yet to be widely accepted in the sphere of Western medicine. Primary concerns with the therapeutic use of acupuncture have been related to an unclear mechanism of action and finding an ideal placebo [69]. It has

been theorized that stimulation of meridian points promotes the release of endogenous opioids leading to relaxation, pain relief, and improvement of sensorimotor dysfunction. The data thus far is mixed on the effectiveness of acupuncture in the treatment of CTS. Sim et al. [70] reviewed randomized controlled trials in all languages. Using the Cochrane risk of bias tool, six studies were felt to be of adequate quality. No differences were found between real and sham acupuncture or between acupuncture and oral steroid. Two RCTs compared acupuncture to steroid and splint or steroid alone, and both were in favor or acupuncture. All studies had poor methodology as noted by lack of details regarding randomization, ethics approval, low statistical power, uncertain methods of blinding, and lack of details in attrition and complications. *Deqi* is the desired sensation of deep heaviness, pressure, warmth, and fullness achieved when acupuncture is done properly, and this was only mentioned in 3/6 studies [70].

Cox et al. [69] did a more recent review focusing on the use of acupuncture in the extremities. Using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), they found ten RCTs with low risk of bias to review. Three looked specifically at the use of acupuncture in the management of CTS. They were unable to pool data because of heterogeneity. *Deqi* was mentioned by eight authors. Two studies found superiority of acupuncture. Khosrawi et al. [71] demonstrated superiority of acupuncture and night splints to placebo acupuncture, night splints and vitamin B using GSS, motor latency, and sensory conduction velocity. Yang et al. [72] found that acupuncture is superior to oral prednisolone in a 4-week study. The areas of improvement were symptom resolution and latency at 13 month. The third study by Kumnerddee and Kaewtong [73] favored electroacupuncture compared to night splinting over 5 weeks. They found that different types of acupuncture worked differently in different conditions.

Hadianfard et al. [74] performed a randomized controlled trial with ethics approval. The control group was treated with custom night splints for 4weeks and ibuprofen 400 mg three times a day for 10 days ($n = 25$). The intervention was acupuncture with standardized techniques for 4 weeks ($n = 25$). Outcomes were assessed with electrodiagnostics, the BCTQ, and VAS. All outcomes were significantly in favor of acupuncture. No complications were experienced with acupuncture; five in the control group had non-serious gastrointestinal side effects.

Napadow et al. [75] found that the limbic centers of people with chronic pain may respond differently to acupuncture than healthy people without evidence of CTS. They compared acupuncture-naïve people with CTS ($n = 13$) to healthy age and sex-matched controls without CTS ($n = 12$). Acupuncture was performed 3 times a week for 3 weeks and then 2 times a week for 2 weeks. The *deqi* response was present. Functional MRI (fMRI) scans showed differences in activity in limbic areas in people with CTS compared to controls before and after a course of acupuncture.

In a well-designed RCT, Yao compared acupuncture ($n = 21$) to sham acupuncture ($n = 20$) [76]. Both groups wore night splints. Both groups had improvements in the carpal tunnel self-assessment score, but there was no difference between true and sham treatment. Improvements were maintained for 3 month. No differences were found in tip and key pinch.

Yang et al. [77] did an RCT (2009) comparing treatment with 4 weeks of prednisone with 4 weeks of acupuncture. GSS and nerve conduction velocities were measured at baseline and two (GSS only) and 4weeks after treatment. This study was different in that patients were monitored for a month prior to inclusion to see if they were in a spontaneous improvement phase. Both groups improved with treatment, but there was no difference between prednisone and acupuncture in GSS or most electrodiagnostic parameters. The authors then did a long-term follow-up of the 70 subjects 7 and 13 months later. Nerve conduction studies were repeated at 13 months. Of 35 subjects in the steroid group, 3 had had surgery. Of the 35 in the acupuncture group, 1 had had surgery. The steroid group subjects' improvements in the GSS had been lost, and the improve-

ments associated with acupuncture had persisted. Recurrent symptoms were noted in 2.6% of subjects in the acupuncture group and 28% in the group treated with steroids at month 7 and in 10.5% and 41%, respectively, at month 13. Motor and sensory latencies were better in month 13 in the acupuncture group. They hypothesized that there may be been ongoing improvement in inflammation and local blood flow.

Ergonomics

The field of ergonomics as is related to CTS has little supportive data. The principles of maintaining good posture, working in a comfortable and safe setting, and avoiding unnecessary strain are reasonable goals [80], but there is little evidence showing that applying recommended changes will reduce CTS symptoms. Risk factors for hand and wrist dysfunction in the workplace are complex, multifactorial, and not clearly or necessarily related to physical factors. They include personal, organizational, biomechanical, and psychosocial elements. Petit et al. [81], in a large prospective survey of working adults, determined likely risk factors for CTS: female sex, increasing age, using the hand for high-force activities in cold environments or extreme postures, and pay based on piecework or automatic rates. As in other studies, no relationship was found with keyboard use. O'Connor et al. [82] did a Cochrane review in 2012 looking at various ergonomic interventions for the treatment of CTS. Data was limited to two RCT or quasi-RCTs with a total of 105 subjects. The use of an ergonomic keyboard was associated with decreased pain at a 3-month endpoint in a small study of 25 people, but no change was seen in hand function or sensory latency. A larger study showed no difference in pain after 6 months using an ergonomic keyboard compared to a standard one. Schmid et al. [83] investigated the effect of computer-mouse shape and ergonomic pads on carpal tunnel pressure in 21 subjects with mild or moderate CTS. Carpal tunnel pressures were measured with an epidural catheter. Baseline pressures were elevated (47–66 mmHg) but the ergonomic measures did not decrease them.

Steroid Injections

The short-term effectiveness of corticosteroid injection in improving the symptoms of CTS has been found to be supported in the literature [20, 47, 48].

Green [49] studied the effects of steroid injections on recurrence and the need for surgery in a large series of patients with CTS. Unlike many current studies, he did not exclude patients with comorbidities. He injected 233 patients (281 hands) with local anesthetic followed by 8 mg of dexamethasone. Follow-up ranged from 6 to 45 months in 199 patients. Complete or good relief of symptoms was experienced by 81% of patients. Symptoms began to recur after 2–4 months but were less bothersome. Eleven percent had no recurrence for 10–45 months. Forty-six per cent went on to have surgery with 94% having good relief. The study was underpowered to correlate electrodiagnostic findings with injection or surgical outcomes. Ninety-three percent with abnormal latency had good to complete response to surgery. Eighty-six percent with normal latency but with carpal tunnel symptoms had good result from surgery. Injections were more effective in relieving pain rather than reversing numbness.

Khosrawi et al. [50] compared splinting alone to splinting and steroid injection with 40 mg of methylprednisolone in a randomized fashion. Twenty-two subjects were treated with a splint and 21 with splint and steroid for 12 weeks. Outcomes were measured with the BCTQ, a patient satisfaction score, and electrodiagnostics. The splint was worn full time. Significant improvement was seen in both groups, but the FSS showed more benefit in the steroid group at 12 weeks.

Atroshi et al. [51] used injected methylprednisolone to treat CTS in a randomized, double-blind, placebo-controlled fashion. Their study was designed to look at effects at 1 year postinjection with a saline placebo (n = 37) or one of two doses of methylprednisolone: 80 mg (n = 37) or 40 mg (n = 37). Patients had failed a 2-month course of splinting prior to entry into the study and were offered the chance to have surgery 3 months after enrollment if the injections were not helpful. Primary outcomes were the SSS at 10

weeks and conversion to surgery by 1 year. They also looked at the time to surgery, the change in SSS at 1 year, QuickDASH, SF36, and SF 6D scores and treatment satisfaction at 10 weeks and 1 year. Grip strength, Semmes-Weinstein, electrodiagnostic test, and two-point discrimination were measured at 5 weeks. The SSS at 10 weeks was significantly improved in the methylprednisolone groups compared to placebo, but it improved in placebo as well. Patients who decided to have surgery at 3 months all had worse SSS at 10 weeks than those who did not have surgery. At 1 year, 73% of 80 mg methylprednisolone, 81% of 40 mg methylprednisolone, and 92% of placebo patients had had surgery. The difference was only significant between placebo and 80 mg methylprednisolone patients. The time to decide to have surgery was longer in the methylprednisolone groups than in the placebo group. No serious adverse effects were seen. The effect of methylprednisolone on SSS was greater for patients who had worse electrodiagnostic scores at baseline.

At a population level, Sears et al. [52] analyzed the use of steroids and operative procedures for CTS. Most patients did not have steroid injections prior to surgery. If the patient had a single injection of steroid, they had a 39% chance of having carpal tunnel surgery. If the patient had multiple steroid injections, the probability of surgery increased to 44–47%. Carpal tunnel release was performed within a year (median 4.3 months) of an injection in 77% of patients. Comorbidities associated with having surgery for CTS included age, diabetes, hypothyroidism, osteoarthritis, obesity, renal failure, congestive heart failure, drug abuse, rheumatologic diseases, and pregnancy.

The combination of procaine and triamcinolone injections to decrease pain, theoretically by stabilizing sodium channels and decreasing abnormal excitability, was done by Karadas et al. [53]. Procaine was used due to its potential for increased effectiveness in nerve membrane stabilization, possibly related to a high pKa. Twenty-two people with CTS were injected with 40 mg of triamcinolone and 4 ml procaine HCl followed by two injections a week for two more weeks with procaine HCl only. Electrodiagnostic studies were done at the beginning and 2 months later. Other outcomes were the VAS, SSS, FSS, and ultrasonic anatomy of the median nerve (AP, transverse, CSA). All patients had statistically significant improvements at 2 months in the BCTQ, VAS, and median nerve CSA. The VAS decreased from 9.7 to 2.8, and the CSA decreased from 0.13 cm^2 to 0.11 cm^2. Electrodiagnostic latencies and amplitude improved.

Local Anesthetic Agents (Topical)

To capitalize on the potential beneficial effects of local anesthetics on membrane stability while avoiding risks of injury to the median nerve related to injections, several authors have proposed the use of topical anesthetic patches. The ease of applying a patch would likely be attractive to patients who wish to avoid injections or cannot or do not want to take oral medications. Nalamachu et al. [54] randomized 40 patients with CTS to either a 5% lidocaine patch or steroid injection (40 mg methylprednisolone). All patients had positive electrodiagnostic studies. Patches were changed daily for 4 weeks, and up to three patches could be used to cover the volar wrist. Outcomes were assessed with a brief pain inventory and patient and global clinical impression of improvement. Eighty percent of patients randomized to the patch were very satisfied or satisfied compared to 59% of patients who had had an injection. Using the clinician global impression of change, 88% of patch patients and 74% of injection patients improved.

A second randomized parallel-group study by Nalamachu et al. [55] compared a 5% lidocaine patch to 500 mg naproxen taken twice daily for 6 weeks. Of 100 subjects, 52 were randomized to the patch group and 48 to naproxen. People with diabetes mellitus were not excluded and comprised 10–12% of people in each group. There was a high withdrawal rate: 9 in the patch group and 14 in the naproxen. There were two treatment related adverse events in the patch group and 14 associated with naproxen. All were mild to moderate. Despite the above, both treatments

were effective in decreasing symptoms. The clinical global impression of improvement was higher for the patch, and there was a trend toward an increased number of people in the very satisfied/satisfied group in favor of the patch which did not reach significance.

Oral Steroid

Patients may prefer oral medications to injections. As with topical agents, oral medications also have decreased risk of nerve injury caused by an injection. Studies to date, though, show less effect on carpal tunnel symptoms with systemic oral steroids than with local injections. Mishra et al. [56] randomized subjects to 20 mg/day prednisolone for 2 weeks followed by 10 mg/day for 2 weeks (n = 35 hands) to splinting at night and as much as possible during the day (n = 36). All had abnormal electrodiagnostics and were assessed with the BCTQ. Both treatments were associated with significant improvement in the BCTQ and latency at 1- and 3-month periods. The FSS component was better in the steroid group than the splint group at 1 and 3 months, but the SSS did not differ between groups.

Wong et al. [57] compared steroid injection to oral steroids in a placebo-controlled, randomized, double-blind fashion. All participants had abnormal electrodiagnostic exams. They were assigned to an oral placebo for 10 days along with a 15 mg methylprednisolone injection (n = 30) or 25 mg of oral prednisolone a day for 10 days and a saline injection (n = 30). The Global Symptom Score (GSS) was used. This scale ranges from 0 to 10 where 0 is symptom-free and 10 is severe symptoms in five categories: pain, numbness, paresthesia, weakness/clumsiness, and/or night waking. The range is 0–50, and it was recorded at baseline and then at 2, 8, and 12 weeks. Significant improvements were found at 8 and 12 weeks in the injection group. Baseline scores were not different but began spreading apart until the 8- and 12-week assessments.

Chang et al. [58] evaluated several oral medications to see if any had a beneficial effect on symptom reduction in CTS. All patients had abnormal electrodiagnostic tests. The GSS was used to evaluate outcomes. Patients were randomized to 4 weeks of placebo (n = 16), 4 weeks of diuretic (trichlormethiazide, 2 mg/day) (n = 16), 4 weeks of a sustained release nonsteroidal anti-inflammatory drug (NSAID-SR) (n = 18), or 2 weeks of prednisolone at 20 mg/day and then 2 weeks at 10 mg/day (n = 23). The study was double-blind. At 2 weeks, steroid was more effective than other three groups in symptom reduction. At 4 weeks, steroid was better than placebo, but there were no significant differences between steroid, diuretic, and the NSAID-SR. This study had weaknesses of small sample type, short follow-up, and a weak study design.

In a study several years later, the same group randomized a larger group of patients to one of two doses of steroids: 2 weeks of prednisolone at 20 mg/day followed by either 2 weeks of 10 mg/day prednisolone (n = 53) or by 2 weeks of placebo (n = 56) [59]. There was a high attrition rate in each group: 11 in the group with 4 weeks of steroids and 20 in the steroid and placebo group. Five patients in the 4-week treatment group (10%) and 9 in the 2-week treatment group (16%) had surgery within a year using an intent to treat analysis. Follow-up was done at baseline and then at 1, 3, 6, 9, and 12 months. GSS scores trended downward fairly equally in each group. At month 12, the reduction was approximately 60%—a moderate improvement per the GSS scoring system. Electrodiagnostic exams were done at all points if there was symptomatic improvement. In these patients, studies showed maintained improvement in latency and velocity at 1 year. There were no significant differences between groups and so the shorter course of steroid is likely adequate if chosen.

Nonsteroidal Oral Medications

Gabapentin

Gabapentin has been increasingly used in the management of neuropathic pain via inhibition of calcium channels [60]. Other proposed actions include pain inhibition via noradrenergic pathways

and reduction of inflammatory agents. Erdemoglu [61] and colleagues treated 41 patients with CTS with gabapentin at standard doses ranging from 300 to 3600 mg/day. The BCTQ was used at baseline and 1, 3, and 6 months. Side effects related to the medication were seen in 27% of participants but were not severe enough to cause cessation of use. There were statistically significant but minimal improvements in the SSS (2.9 ± 0.74 to 2.05 ± 0.78) and slightly larger changes in the FSS (5.61 ± 1.38 to 3.81 ± 1.61). Larger studies would be needed before this treatment could be widely recommended.

Diuretics

The use of diuretics in carpal tunnel syndromes has been done to theoretically decrease the volume of tissue within the carpal tunnel. Very little material in the literature supports this thesis. Heathfield and Tibbles [62] treated 35 patients with mild to moderate CTS with a thiazide diuretic twice daily 6 days a week. This was published in the form of a preliminary communication and never appeared in a long-form paper. Doses were adjusted to effect, and patients were followed until symptom-free for 2 months. By 1 month, 29 of 35 (83%) were symptom-free or much improved. Of the 6 who didn't improve, 4 were "cured" with a splint, and 2 had surgery. At 3 months, 19/29 (66%) were symptom-free, and 10 had relapsed. At final follow-up visits up to 13 months later, 16/29 (46%) remained symptom-free. The findings in this paper may have become adopted as, in a survey of hand surgeons in 1987, 15% reported using diuretics as a nonoperative treatment for patients with CTS [63].

Pal et al. [64] performed a randomized double-blind placebo-controlled study using bendrofluazide (n = 41 hands) or placebo (n = 40 hands) for 1 month in patients with mild to moderate CTS. The outcome measure was not a validated scale (0–5, 0 being no improvement and 5 having full recovery). Of patients treated with diuretic, 54% had no improvement, of patients treated with placebo, 50% had no improvement. A smaller percentage had full or near full recovery: 10/41 (24%) in the diuretic group, 7/40 (18%) in the placebo group. People who were treated with diuretic and improved did have improved sensory and motor latencies at 4 weeks and 6 months.

Pyridoxine (Vitamin B6)

Aufiero et al. [65], in a review of the use of pyridoxine for the treatment of CTS, discussed potential mechanisms of action of action of vitamin B6 [65]. It is involved in protein synthesis and metabolism within nerves and a deficiency has been hypothesized as a causal agent for the disease. It is known also that excessive amounts of pyridoxine can be neurotoxic. Prospective randomized studies with adequate power have failed to show a connection between B6 supplementation or deficiency and electrodiagnostic studies or symptomatic improvement in patients with carpal tunnel syndrome.

Spooner et al. [66] performed a randomized, placebo-controlled study on 35 patients with idiopathic CTS [66]. Outcomes were assessed with the SSS and electrodiagnostics at baseline and 12 weeks. A dose of pyridoxine routinely used in studies, 200 mg/day, was used in 18 subjects, and 17 received a placebo. There was improved swelling and less pain with motion in the treatment group, but no differences were seen in night waking, numbness, tingling, or on electrodiagnostic studies. The outcome measure was a 5-point scale with 0 being asymptomatic and 4 having "a great deal" of symptoms. It was not a validated measure; and differences, especially with swelling, were statistically significant but very small (2.1 ± 1.6 to 1.3 ± 1.4).

Vitamin D

Much attention has been paid recently to the multisystem effects of vitamin D deficiency. It has been linked to a wide array of medical conditions including neurodegenerative disorders, diabetic neuropathy, and nonspecific chronic pain [67]. Vitamin D receptors on small nerve fibers may

play a role in the development or exacerbation of CTS. No consistent relationships have been found between vitamin D levels and CTS, and we cannot yet make specific recommendations about replacement to ameliorate symptoms of neuropathy. To examine the potential relationship, Gürsoy et al. [67] measured the circulating metabolite, 2(OH)D, in patients with clinical symptoms of CTS (n = 108) and asymptomatic healthy controls (n = 52). Outcome measures included electrodiagnostics, the BCTQ, and fasting blood levels of 2(OH)D. The BMI of people with CTS was significantly higher than controls (29 vs 26). People with clinical CTS had lower 25(OH)D levels compared to controls (9.21 + 6.32 vs 15.76 + 11.85), but in that group, 47% had no electrodiagnostic evidence of the disease. Vitamin D was lowest in subjects with negative electrodiagnostics and highest in controls. No correlation was found between vitamin D and the BCTQ scales, pain scores, or BMI. From this work, we can only assume a more complex relationship than initially envisioned.

Lee et al. [68] excluded subjects with normal electrodiagnostic studies and measured blood levels of 25(OH)D in 135 women who had had carpal tunnel releases. Thenar atrophy was present in 22 and mean symptom duration was 27 months. Age-matched asymptomatic controls (n = 135) were recruited from the hospital's disease prevention program. A second control group of 135 women with symptoms of non-carpal tunnel upper extremity neuropathy was also recruited to see if there were commonalities in subjects with neuropathy. The only significant finding was of a higher incidence of CTS in vitamin D-deficient women under age 50 (66% compared to 28% incidence in subjects 50 years and older). They theorized that vitamin D may be neuroprotective in younger women.

As people attempt to find less invasive methods of treatment for chronic musculoskeletal conditions, traditional medicines are increasingly being studied. Potential concerns lie in irregularity in compilation, uncertain bioactivity and mechanisms of action, and lack of adequately powered human studies. Eftekharsadat et al. [78] used *Eremostachys laciniata*, an herb with anti-inflammatory and analgesic properties to treat mild and moderate CTS. Patients were randomized to topical application with the herb or a placebo for 4 weeks. Both groups were treated with night splints. Outcomes included grip strength, VAS, and electrodiagnostic tests. In the herbal group, palmar prehension, VAS, and motor and sensory latency improved over placebo.

Hashempur et al. [79] performed a randomized double-blind placebo-controlled trial of *Linum usitatissimum* L. (linseed or flaxseed) oil. It contains alpha linolenic acid and may inhibit mediators of inflammation and fibrosis. Topical application and night splints were used. The BCTQ and electrodiagnostic tests were used for outcome measurements. Differences were seen within and between groups, but the effect sizes were small, and it is unlikely that the statistical difference is clinically significant. No complications related to treatment were observed.

Conclusions

Nonoperative treatments have been shown to improve symptoms of mild to moderate CTS as well as electrodiagnostic findings. Night splints, corticosteroid injections, and therapeutic modalities are the most likely to provide short- to medium-term relief. There is intriguing evidence pointing toward central nervous system changes associated with acupuncture. Manual therapy, nerve and tendon gliding, and general aerobic exercise appear to have fewer direct effects on CTS, but exercise is so beneficial to global health that the indirect effects on CTS may be larger than we have been able to detect. Topical and oral agents appear to have few benefits for the patient with CTS. Ergonomic modifications also have little evidence to support their use as a treatment of CTS.

Given the combination of fluctuating presentation of symptoms of carpal tunnel syndrome and the ease with which conservatively managed patients may be lost to follow-up, patient education is crucial. If symptoms are progressing without response to conservative measures, surgical treatment should be strongly considered.

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Open Techniques for Carpal Tunnel Release

12

David R. Veltre

Introduction/History

The first recorded open carpal tunnel release surgery was described by Dr. Learmonth in 1933 [1]. In his landmark paper, he described two cases of median neuropathy treated by dividing the transverse carpal ligament. Twelve years later, Cannon and Love published their review of 38 surgical releases of the transverse carpal ligament [2]. Along with the promising results of this first series of surgically treated carpal tunnel syndrome, the paper gave us the first accurate illustration of the anatomy and a depiction of carpal tunnel release surgery. In 1966, Phalen cemented carpal tunnel syndrome as a treatable condition with excellent operative outcomes in his series of 354 successful operations [3].

Since the work of these pioneers, our understanding of the anatomy and pathophysiology of carpal tunnel surgery has improved, but the general principles of treating carpal tunnel syndrome have remained the same. The surgical incision has evolved from transverse, zigzags, oblique, and curved incisions [3, 4] to the "mini" and standard longitudinal incisions currently utilized today. Initially, extensive debridement including extensive neurolysis and synovectomy of flexor tendons within the canal was performed along with the release of the transverse carpal ligament. Today, those adjunct procedures have largely been abandoned due to complications such as neuromas, paresthesias, and skin adhesions [5, 6].

Despite the fact that the use of endoscopic carpal tunnel surgery has increased dramatically since its introduction in the late 1980s, open carpal tunnel release surgery remains the gold standard and the most commonly performed procedure to treat carpal tunnel syndrome [7, 8]. Initially, endoscopic carpal tunnel release was proposed as a technique to eliminate pillar pain and get patients back to work earlier. However, endoscopic surgery did not eliminate the issue of pillar pain and no study has shown long-term clinical superiority [9–14] compared to open carpal tunnel surgeries. Additionally, endoscopic techniques have been shown to cause incomplete release of the transverse carpal ligament up to 50% of the time [15]. Although some functional improvement such as grip and pinch strength has been seen early in the post-op period with endoscopic technique compared to open techniques, these benefits disappear by 3 and 6 months [16]. Overall, with questionable long-term clinical significance and the added complications related to the limited visualization in endoscopic tech-

D.R. Veltre (✉)
Orthopaedic Surgery, Boston University Medical Center/Boston Medical Center,
850 Harrison Ave, Dowling 2 North, Boston, MA 02118, USA
e-mail: david.veltre.md@gmail.com

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niques including iatrogenic nerve injury and incomplete release, open carpal tunnel release surgery remains the preferred treatment for idiopathic carpal tunnel syndrome.

Anatomy

A strong knowledge of the anatomical structures of the carpal tunnel and its surrounding structures is essential to avoid complications and iatrogenic injuries. The carpal tunnel is an oval-shaped channel on the volar aspect of the wrist. It is bordered ulnarly by the hook of the hamate; radially by the trapezium, scaphoid, and flexor carpi radialis retinaculum; dorsally by the arch of the carpal bones; and volarly by the transverse carpal ligament (Fig. 12.1). The transverse carpal ligament is 1–3 mm thick and 3–4 cm wide as it crosses transversely over the carpal tunnel. Within the carpal tunnel, there are nine extrinsic flexor tendons from three muscles (flexor digitorum superficialis, flexor digitorum profundus, and flexor pollicis longus) and the median nerve. The median nerve sits on the volar and radial aspect of the carpal tunnel just ulnar to the flexor pollicis longus tendon.

Prior to entering the carpal tunnel, the median nerve gives off its palmar cutaneous branch. The palmar cutaneous branch of the median nerve branches off from the median nerve from the radial aspect of the nerve 6–11 cm proximal to the distal wrist crease [17]. It travels distally together with the median nerve then passes volar to the carpal ligament to the undersurface of the palmar aponeurosis where it then divides into branches to the palmar skin supplying sensation to the radial and lateral aspect of the palm at the base of the thumb.

After the median nerve exits the carpal tunnel, the median nerve gives off its terminal branches including the recurrent motor branch and common digital nerves. The recurrent motor branch of the medial nerve typically wraps around the transverse carpal ligament to innervate most of the thenar muscles (abductor pollicis brevis, the superficial head of the flexor pollicis brevis, and opponens pollicis). The terminal branches of the median nerve divide into the digital nerves that provide sensation to the thumb, index, middle, and radial half of the ring finger (Fig. 12.2).

Outside of the carpal tunnel, it is important to be aware of the other important neurovascular structures in the vicinity of the palmar wrist. The ulnar nerve passes superficial and ulnar to

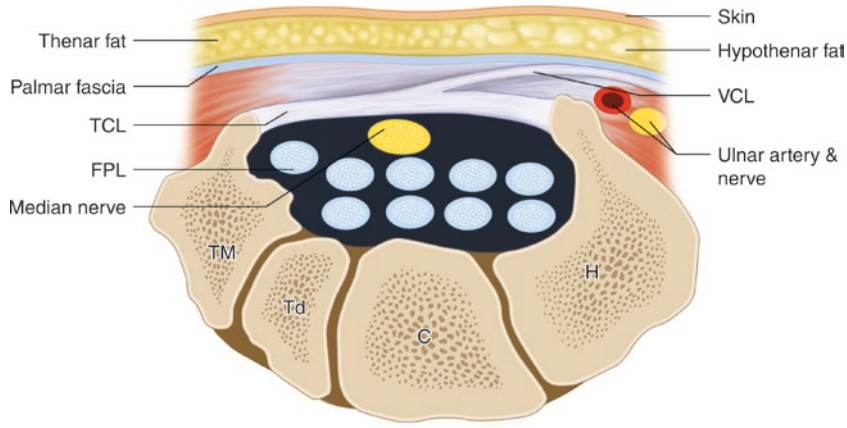

Fig. 12.1 Anatomy of carpal tunnel

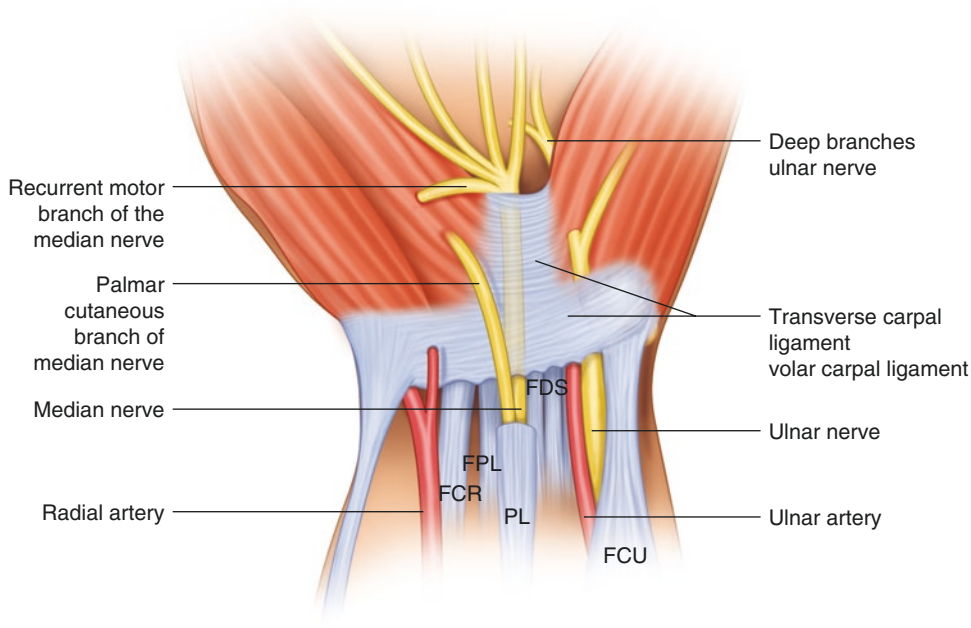

Fig. 12.2 The palmar cutaneous branch of the median nerve lies radial to the median nerve and ulnar to the flexor carpi radialis tendon. The motor branch of the median nerve branches off of the median nerve after the carpal tunnel in most cases

the transverse carpal ligament. It bifurcates into sensory and deep motor branches in Guyon's canal. Its sensory branches provide sensation to the ulnar aspect of the hand, the small finger, and the ulnar aspect of the ring finger. The deep motor branches innervate the interosseous muscles, the third and fourth lumbricals, the hypothenar muscles, the adductor pollicis, and the medial head of the flexor pollicis brevis. Both the radial and ulnar arteries provide arterial supply to the hand. In most cases (88%), the dominant blood supply to the hand is from the ulnar artery via the superficial arch. The other 12% of the time the dominant blood supply is from the deep palmar arch as a continuation of the radial artery. The deep palmar arch anastomoses with the deep branch of the ulnar artery. It lies 1 cm proximal to the superficial arch, and its location can be estimated by drawing Kaplan's cardinal line (a line drawn from the distal edge of the abducted thumb to the hook of the hamate). The deep palmar arch is approximately one finger breadth superficial from that line (Fig. 12.3).

Anatomical Variations

After the median nerve exits the carpal tunnel, it divides into its many terminal branches. There are numerous anatomical variations of the branching of the median nerve that the operating surgeon should be aware of. In 1977, Lanz dissected 246 cadaver hands and found 29 variations of the median nerve that he categorized into four groups [18]. Group I consisted of variations of the recurrent motor branch which was initially subdivided into three described variations: extraligamentous, subligamentous, and transligamentous [19]. The extraligamentous

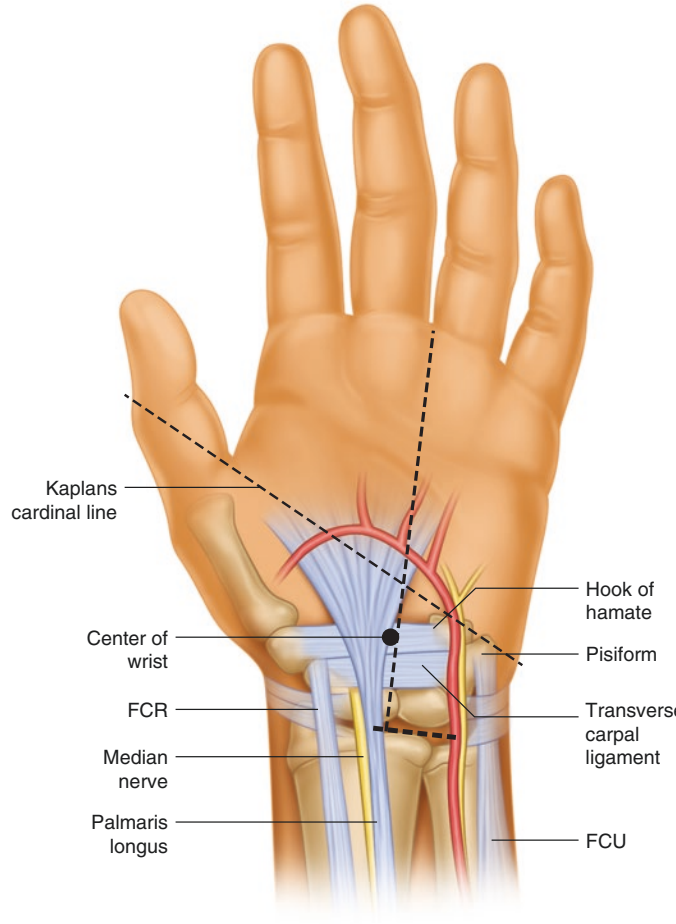

Fig. 12.3 Volar Wrist Anatomy

pattern is found in the majority of people and is therefore considered normal anatomy. In this pattern, the recurrent motor branch arises from the median nerve distal to the transverse carpal ligament to innervate the thenar muscles. In the subligamentous variation, the recurrent motor branch leaves the nerve within the carpal tunnel and bends around it at the distal aspect of the retinaculum. The transligamentous variation branches off within the tunnel and penetrates directly through the transverse carpal ligament before innervating the thenar muscles. This last transligamentous variation is of particular importance due to the compression within the retinacular fibers or iatrogenic injury from a retinaculum release. There have been reports of more rare patterns of the recurrent branch including where the branch takes off from an ulnar and anterior location [20] or branches that have a course superficial to the transverse carpal ligament [21]. However, further studies have confirmed that an extraligamentous pattern is found in 80–90% of cases [22–24] (Fig. 12.4).

The other median nerve groups described by Lanz include accessory branches of the median nerve at the distal carpal tunnel (Group II) found in 7.2% of cases, a high division of the median nerve at the level of the forearm (Group III) found in 2.8% of cases, and accessory branches of the median nerve branching proximal to the carpal tunnel (Group IV) found in 1.6% of cases. The majority of these branches leave the median nerve radially. Therefore, at surgery the nerve should be approached from the ulnar side to

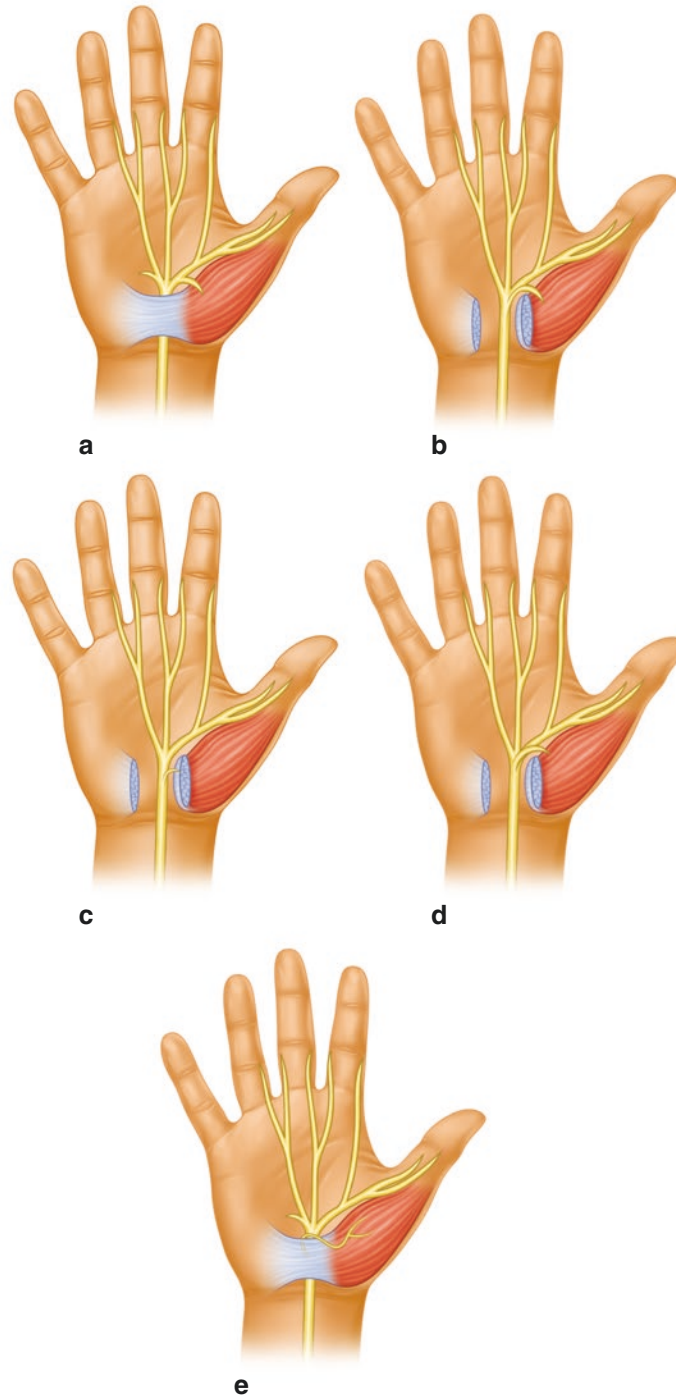

Fig. 12.4 Group I: Variations of the recurrent motor branch of the median nerve: Extraligamentous (**a**), subligamentous (**b**), intraligamentous (**c**), branch from ulnar aspect (**d**), and traversing over transverse carpal ligament (**e**)

minimize injury to the nerve or its branches. However, rare variations of branches dividing from the ulnar side of the median nerve [18] or a bifid median nerve where the nerve is seen in two distinct compartments within the carpal tunnel [25, 26] have been described.

Abnormalities within the tunnel are not limited to the median nerve. Anomalies of the tendons are rare, although elongated or additional muscle bellies of flexor digitorum superficialis have been described [27–32]. Women have been found to have elongated bellies of flexor digitorum superficialis and profundus extending into the carpal tunnel more often than men [33]. The osseous anatomy of the tunnel has also been associated with an increased risk of carpal tunnel syndrome. Hypoplastic variants of the hook of the hamate have been found to be more common in a group with carpal tunnel syndrome than in a group without carpal tunnel syndrome [34].

Surgical Technique

An open carpal tunnel release allows excellent visualization of the transverse carpal ligament and the contents of the carpal tunnel. Most open carpal tunnel releases today are performed through a "mini-open" surgical approach [7], but many are still performed through a standard open technique. The decision of the type of approach is dependent on the patient, surgeon preference, and the visualization in the OR. Regardless of the length of the incision, all open carpal tunnel releases follow the same basic steps: setup and anesthesia, skin incision, palmar fascia incision, transverse carpal ligament release, carpal tunnel inspection, and closure.

Setup and Anesthesia

Carpal tunnel surgery begins with the selection of the appropriate surgical setting and anesthesia for the patient. Options for anesthesia include full sedation/general anesthesia, conscious sedation with local anesthesia, intravenous regional anesthesia (Bier block), or "wide-awake anesthesia" [35, 36]. The type of anesthesia used is a multifactorial decision involving the surgeon preferences, patient factors including potential comorbidities, availability of facilities, and experience of the anesthesia and surgical staff. According to a recent survey of hand surgeons, most surgeons use intravenous sedation with local anesthesia (43%), followed by a Bier block (18%) and general anesthesia (11%) [7].

Elective carpal tunnel surgery does not require local or systemic antibiotics. Numerous studies support low infection rates in the hand without the use of perioperative antibiotics. Multicenter studies evaluating elective soft tissue hand surgery [37] and specifically elective carpal tunnel surgery [38] have shown no statistical difference in infection rates with or without preoperative antibiotics. The overall infection rate is very low, and even in high-risk populations such as diabetic patients, antibiotic use did not decrease the rates of infection.

A tourniquet can greatly aid the surgery by minimizing bleeding and providing excellent visualization of the surgical field. The decision of whether or not to use a tourniquet is dependent on the surgeon's preference and the clinical situation. A tourniquet can cause pain and may be contraindicated in patients with fistulas or who are at increased risk for clot formation. If a tourniquet is used, regional anesthesia blocks or a double tourniquet can be used and changed at 10 min so that the patient does not experience pain. If a tourniquet is not used, adding to epinephrine to the local anesthetic can provide sufficient vasoconstriction to maintain a dry surgical field [39, 40].

The patient is placed supine with his or her arm on a hand table. After appropriately cleansing the extremity, the wrist is prepared for surgery. Often a "lead hand" is helpful in positioning the hand. The appropriate anatomy and surgical landmarks are identified and labelled including Kaplan's line as described previously in this chapter. The appropriate surgical instruments are collected and placed on the surgical field.

Skin Incision

The skin incision in an open carpal tunnel release surgery is placed longitudinally over the ulnar aspect of the carpal tunnel as identified by its

anatomical landmarks. The incision should avoid crossing the distal wrist crease at a right angle as it may result in a hypertrophic and painful scar. The incision is oriented longitudinally to avoid the potential injury to the palmar cutaneous nerve branch and has better exposure compared to a transverse incision [41].

For a primary carpal tunnel surgery, the mini-open technique is the preferred approach. A longer, standard open skin incision is indicated in patients who require more proximal exposure or exploration of the canal such as in patients with gout or amyloidosis. An incision started as a mini-open incision may be extended to a standard incision based on the need for additional visualization or exposure.

Standard Open Skin Incision

The standard longitudinal incision is a straight or curvilinear (parallel to the thenar crease) incision at the base of the palm. The straight incision begins distally at the Kaplan cardinal line and extends proximally toward the distal wrist crease along an axis defined by the radial aspect of the ring finger for approximately 3–4 cm (Figs. 12.5a and 12.6a). It should pass 3–5 mm ulnar to the thenar crease in most patients. If a curvilinear incision is desired, it should be parallel and ulnar to the thenar crease. The incision should avoid crossing the distal wrist crease to prevent a painful hypertrophic scar. However, if more exposure is needed proximally, the incision can be extended in a zigzag fashion across the wrist in an ulnar direction (Fig. 12.5a).

Mini-Open Skin Incision

Initially described by Bromley in 1994 [42], the "mini-open" technique has gained rapid popularity and clinical acceptance as a way to minimize incisional pain and scarring while allowing adequate visualization of the carpal tunnel. The skin incision for the mini-open technique begins distally at

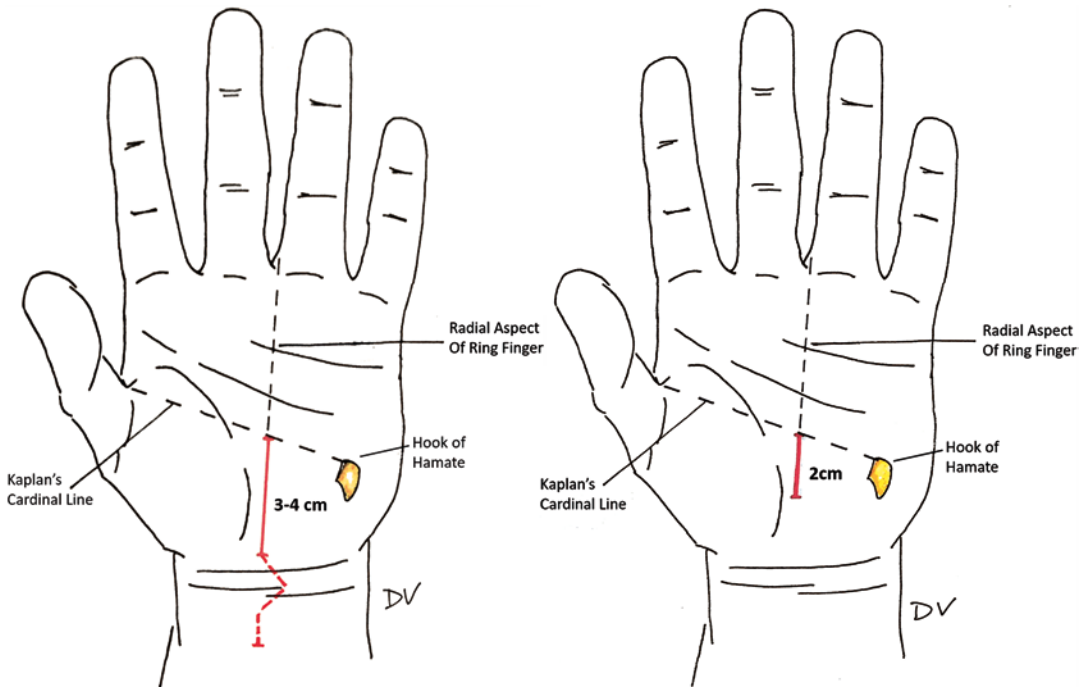

Fig. 12.5 (**a**) Standard open incision with optional extension proximal to wrist crease (*dotted line*) (*left*) and (**b**) mini-open incision (*right*)

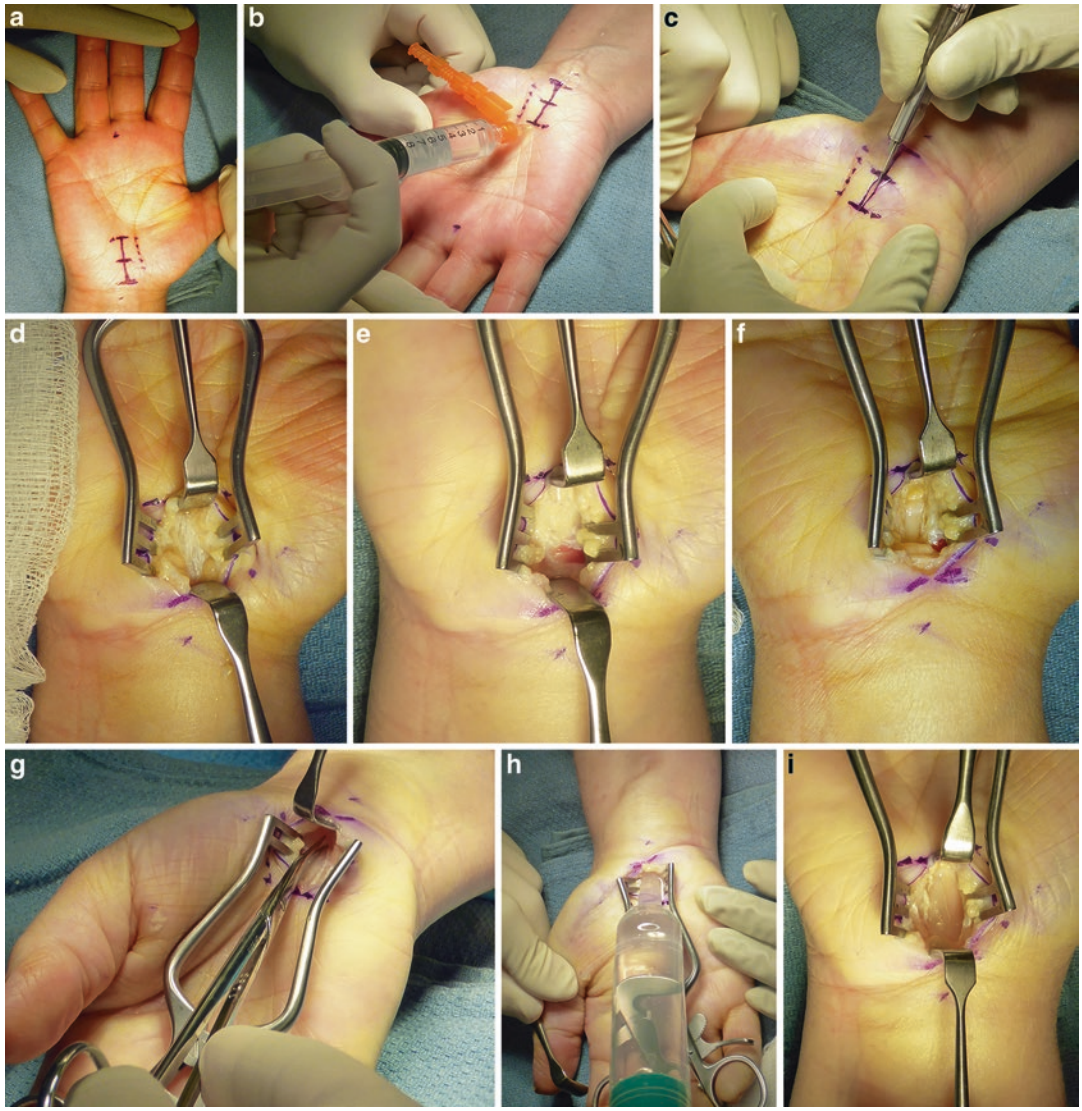

Fig. 12.6 (**a**) The incision of a standard open carpal tunnel release. (**b**) Injection of local anesthesia epinephrine can be used as part of the anesthesia for the procedure or to help with postoperative pain control. Epinephrine can be added to the injection to provide a bloodless field if not using a tourniquet. (**c**) Incision is made with a scalpel through skin and subcutaneous tissue. (**d**) Beneath the subcutaneous fat, the palmar fascia is exposed. The fibers of the palmar fascia run longitudinally and can be distinguished from the fibers of the transverse carpal ligament which run transversely. (**e**) A small incision in the transverse carpal ligament is made exposing the median nerve (seen here at proximal aspect of wound). (**f**) The transverse carpal ligament is transected proximally until the volar fat pad is visible. Dissection distal to this risks injuring the superficial palmar arch. (**g**) The transverse carpal ligament is released proximally using tenotomy scissors and a Ragnell retractor to ensure adequate visualization. (**h**) A bulb syringe can be used to inject saline into the proximal aspect of the incision. A visible collection of fluid underneath the skin indicates adequate release of the antebrachial fascia. (**i**) Excellent exposure of the median nerve after complete release of transverse carpal ligament

the Kaplan cardinal line and extends proximally approximately 2 cm (Fig. 12.5b). The incision should be along the axis of the radial aspect of the ring finger, approximately 3–5 mm ulnar to the thenar crease. If additional exposure is required, the incision can be extended proximally into a more standard open skin incision.

Palmar Fascia Incision

After the skin is incised, a layer of subcutaneous fat is exposed. The subcutaneous fat is bluntly dissected for exposure, being careful to avoid injuring superficial nerves. The palmar cutaneous nerve of the median nerve [4, 43] and occasionally its corollary of the ulnar nerve crosses in this location. Identifying and preserving these cutaneous sensory branches is thought to be the most important step in reducing painful incisional neuromas; however, it has not been shown to improve postoperative scar pain in a recent prospective randomized study [44].

A self-retaining retractor such as an Alm or a small Weitlander retractor and two Ragnell retractors can be placed to aid in visualization being careful to avoid injuring any superficial nerves. Soft tissue dissection through fatty tissue is continued down to expose the palmar fascia (Fig. 12.6d). The fibers of the palmar fascia are oriented longitudinally and should be incised in line with their fibers under direct visualization for the entire length of the skin incision. The retractors are repositioned underneath the palmar fascia, and the transverse carpal ligament is exposed.

Transverse Carpal Ligament Release

Deep to the palmar fascia lies the roof of the carpal tunnel, the transverse carpal ligament (TCL). The TCL must be clearly visible and exposed to avoid injuring an intraligamentous variation of the recurrent motor branch of the median nerve. The TCL should be approached carefully and a small incision should be made with a scalpel or beaver blade (Figs. 12.6e and 12.7a). Once an opening is created, the TCL is divided longitudinally, perpendicular to the orientation of its fibers with a sharp blade or tenotomy scissors. The incision should be near the ulnar aspect of the TCL directed toward the ring finger to avoid the recurrent branch of the median nerve.

The incision is extended distally under direct visualization until the volar fat pad around the superficial arch is encountered (Figs. 12.6f and 12.7b). The volar fat pad is a reliable anatomic landmark that ensures that the ligament has been released completely [45]. The incision is then extended proximally and inspected for complete transection of the ligament. In a mini-open incision, the incision may need to be extended to ensure complete transection of the transverse carpal ligament.

Attention is now directed toward the antebrachial fascia located just proximal to the wrist crease. A release of the antebrachial fascia, particularly in the case of connective disease where the fascia may be thickened, can help prevent recurrence of carpal tunnel syndrome [46]. To release the fascia, the incision may need to be extended if using a mini-open technique. The surgeon will be positioned at the end of the hand table to ensure excellent visualization. The fascia is divided from distal to proximal using a No. 15 blade or tenotomy scissors approximately 2.5 cm proximal to the wrist crease on the ulnar side of the palmaris longus tendon (if present) (Figs. 12.6g and 12.7c). To confirm that the fascia is released, a bulb syringe can be placed in the proximal aspect of the incision and water injected into the distal volar forearm. The water pressure should cause a visible bulge underneath the skin, known as the "Stein sign", confirming that the antebrachial fascia is released (Fig. 12.6h).

Carpal Tunnel Inspection

With the transverse carpal ligament released, the median nerve should be completely exposed (Fig. 12.6i). The carpal tunnel should be examined

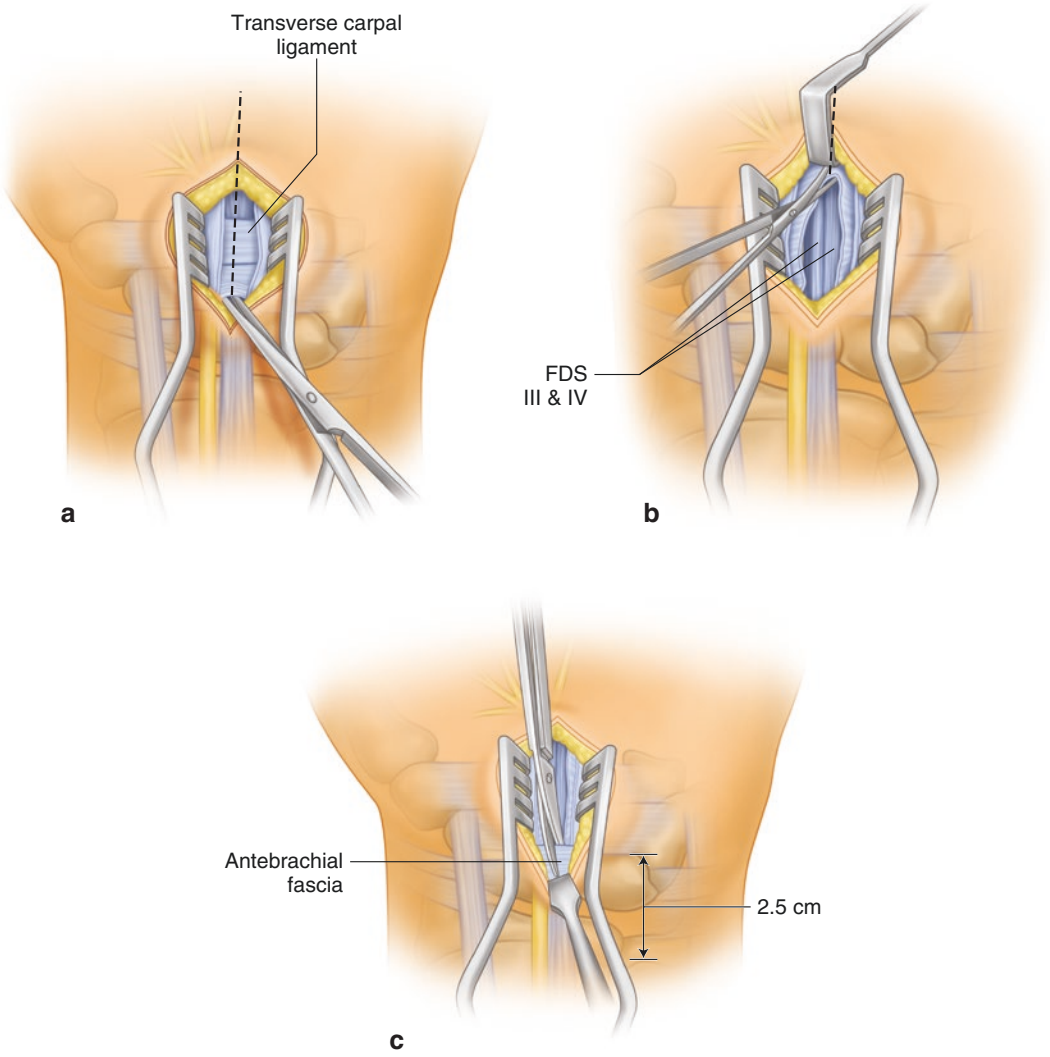

Fig. 12.7 (**a**) Exposure of transverse carpal ligament—modify image to show vertical incision and blade instead of scissors making cut. (**b**) Release of TCL. (**c**) Release of antebrachial fascia

for irregularities of the nerve and surrounding soft tissues such as tumors, aberrant muscles, or thickened synovium. Often this is performed by sliding a smooth instrument, such as a freer elevator, alongside the nerve to unsure that it is free proximally or distally. If an intraligamentous variation of the recurrent motor branch of the median nerve is found, the branch should be carefully released from the transverse carpal ligament. Additional procedures such as internal neurolysis, epineurotomy, and tenosynovectomy are rarely indicated and should not be a routine part of primary carpal tunnel release [47–49].

Closure

After the release has been completed, the tourniquet is deflated, and bipolar electrocautery can be used for hemostasis. The skin is closed with nylon sutures. A long-acting anesthetic (bupivacaine) can be injected into the incision for

postoperative comfort. Often this injection is performed prior to the initial incision.

Postoperative Care

Immediately following surgery, the patient is placed in a soft dressing. Historically, after surgery patients were placed in a splint to protect the wound and prevent the flexor tendons from bow stringing through the now open transverse carpal ligament. However, a recent study found no difference in outcomes between a postoperative light bandage or a bulky dressing with a volar splint left in place for 48 h [50]. Accordingly, only 29% of recently surveyed hand surgeons use a postoperative orthosis, down from 37% 3 years prior [51] and 82% of hand surgeons in 1987 [52].

Patients can be safely discharged without the need for postoperative antibiotics. Postoperative infections from carpal tunnel surgery are rare and are not significantly decreased with the use of antibiotics [37, 38]. After surgery, the patient can remove the dry dressing and shower 3 days postoperatively. Patients should begin range of motion exercises for the elbow, wrist, and digits early in the postoperative period to prevent stiffness. To prevent a painful scar, desensitization techniques, such as percussion or friction massage, and scar massage should be initiated early following surgery.

Surgical sutures are removed at the first follow-up appointment 10–14 days after surgery. At our institution, no specific restrictions are given to the patients postoperatively, and gradual resumption of activity and use of the hand is encouraged. Over the next 4–6 weeks, most patients have resumed normal activities. A final follow-up appointment is scheduled for 6 weeks to evaluate healing and outcomes. Formal rehabilitation programs with physical therapists have not been shown to improve the functional recovery compared to home therapy exercises in all patients [53, 54]. We therefore reserve formal rehabilitation programs only for patients who develop pillar pain or are slow to recover.

Outcomes and Complications

Open carpal tunnel surgery is an extremely effective treatment for carpal tunnel syndrome. Most studies report the long-term symptomatic improvement between 75 and 90% [55–59]. Although carpal tunnel surgery has proven to be safe and reliable, complications do occur. Complications from carpal tunnel surgery can be thought in three different categories: persistent symptoms, recurrent symptoms, and new symptoms.

Persistent Symptoms

The most common complication of carpal tunnel surgery is the persistence of symptoms, occurring in up to 20 percent of patients [60]. There are three primary reasons for persistent symptoms after a carpal tunnel release. The most common reason is incomplete division of the transverse carpal ligament or antebrachial fascia. It has been suggested that surgeries with less visualization such as the mini-open or endoscopic techniques are more susceptible to this type of complication, particularly because the distal retinaculum is the most common site of incomplete release [61, 62]. Inadequate visualization can also lead the surgeon to miss space occupying lesions such as a ganglion or tumor that can compress the nerve and replicate the symptoms of carpal tunnel syndrome.

Another reason for persistent symptoms would be median nerve compression proximal to the wrist. While there may be compression of the nerve at the carpal tunnel, damage to the nerve may occur at an area proximal to the tunnel such as in a cervical radiculopathy, brachial plexopathy, or another lesion such as the “double crush” phenomenon. If there is doubt about the location of the pathology, electrodiagnostic testing should be performed to locate the location of the nerve injury to localize the area of pathology. In some cases, the injury to the nerve is so profound that even if it is fully decompressed, the nerve is unable to recover.

Finally, patients who were diagnosed incorrectly with carpal tunnel syndrome would not improve after carpal tunnel release. If a patient's symptoms do not resolve, an alternate diagnosis should be investigated.

Recurrent Symptoms

Some patients may do well initially after carpal tunnel release, only to have some symptoms return. Recurrent symptoms can be divided into early and late recurrence. Late recurrence occurs years after the initial surgery and may be due to true recurrence of the pathological process causing the compression of the median nerve in the carpal tunnel. Patients with late recurrence require a full repeat work-up for their symptoms.

Early recurrences are symptoms that return weeks to months after the initial procedure. This can occur from excessive scar tissue formation forming around and compressing the median nerve. Techniques and therapy such as minimizing postoperative immobilization and appropriate range-of-motion exercises are vital in minimizing the chance for a painful or hypertrophic scar. Alternatively, symptoms may recur if the median nerve is compressed at a site proximal to the carpal tunnel such as at the antebrachial fascia or in pronator syndrome. The carpal tunnel release may unmask these symptoms of a more proximal injury.

New Symptoms

Even when the median nerve is successfully and fully decompressed at the carpal tunnel, the patient may have other painful symptoms that may occur postoperatively. Complications following open carpal tunnel release include, but are not limited to, iatrogenic injuries to the motor branch and palmar cutaneous branches of the median nerve, neuroma and hematoma formation, palmar arch injuries, tendon adhesions, and pillar pain.

Pillar pain, the term used to describe pain in the thenar or hypothenar area of the palm, in particular is a significant problem in many patients. The exact cause of pillar pain is unknown although some speculate it to be ligamentous or muscular in origin, an alteration in the carpal arch (now that the TCL is released), or due to the violation of the palmar skin, its cutaneous nerves, and palmar fascia [63]. This last theory has led many to attempt to minimize the incision in an effort to decrease pillar pain. Desensitization and nerve gliding exercises can be used to treat pillar pain. Fortunately, pillar pain does seem to improve with time, and only 6% of patients report having this pain 1 year postoperatively [64].

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Endoscopic Carpal Tunnel Release

13

Scott D. Lifchez and Joseph Lopez

Introduction

Carpal tunnel syndrome (CTS) is the most common nerve neuropathy in the upper extremity, affecting approximately 5% of the general population [1]. Characterized by compression of the median nerve by the transverse carpal ligament (TCL) at the wrist, CTS can be a fairly debilitating condition causing discomfort and/or numbness in the thumb, index, long, and ring finger and motor weakness in the hand.

The treatment of CTS has evolved significantly over the last century. Patients who fail conservative treatment with splinting, therapy, and corticosteroid injections often require surgical management. The first carpal tunnel release (CTR) was performed by Herbert Galloway in 1924 [2]. Since then, a variety of surgical techniques have been developed to release the TCL and decompress the underlying median nerve. Although the open CTR (OCTR) approach remains the most commonly utilized technique, over the last three decades, several endoscopic techniques, such as the two-portal endoscopic technique by Chow in 1989 [3], single proximal portal approach by Agee in 1992 [4], and single distal portal approach by Mirza in 1995 [5], have been developed and refined. In this chapter, we will discuss these three commonly utilized endoscopic CTR (ECTR) techniques and describe in detail the single proximal portal technique. Furthermore, we will discuss indications/contraindications, complications, and surgical outcomes of ECTR.

Indications/Contraindications

Indications for ECTR are generally similar to those for conventional OCTR (Table 13.1). Most idiopathic CTS can be treated using endoscopic techniques. However, ECTR is relatively contraindicated in several circumstances. While many argue that recurrent CTS is a relative contraindication to ECTR [6], Trumble and colleagues reported excellent results with endoscopic revision carpal tunnel release and emphasize potential benefits of this technique in appropriately selected patients [7]. Since incomplete division of the transverse carpal ligament is a primary cause of persistent CTS and may contribute to recurrence, one must be cognizant that the cause of failure of the previous surgery might be due to

S.D. Lifchez (✉)
Plastic Surgery, Johns Hopkins Bayview Medical Center, 4940 Eastern Ave, Rm A518, Baltimore, MD 21224, USA
e-mail: slifche1@jhmi.edu

J. Lopez
Plastic and Reconstructive Surgery, Johns Hopkins Hospital, 4940 Eastern Ave, Rm A518, Baltimore, MD 21224, USA

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Table 13.1 Indications/relative contraindications for endoscopic CTR

Indications	Contraindications
Idiopathic CTS	Recurrent CTS
	Anticoagulation
	Inflammatory conditions (i.e., rheumatoid arthritis, amyloidosis)
	Severe CTS[a]
	CTS secondary to fracture/trauma

CTS carpal tunnel syndrome, *CTR* carpal tunnel release
[a]Based on Sucher criteria [34]: unobtainable median sensory response, low-amplitude median mixed nerve response, and low-amplitude median compound muscle action potential with prolonged distal latency

anatomic abnormalities (e.g., compressive lesions) that cannot be visualized using an endoscopic approach. Therefore, most surgeons advocate for the conventional open technique in the setting of recurrent CTS.

Additionally, many surgeons believe that ECTR should be avoided in patients with certain preexisting conditions, including anticoagulation and inflammatory conditions such as rheumatoid arthritis or amyloidosis. Since hemostasis is a concern in the setting of anticoagulation, the conventional open approach is the preferred technique in order to avoid bleeding complications that may be better avoided by open surgical visualization. ECTR in patients with inflammatory conditions should also be approached with caution. Patients with rheumatoid arthritis or other inflammatory conditions have a higher risk of synovial lesions or other pathology which can interfere with visualization of the carpal tunnel, or occasionally even the introduction of endoscopic device at the wrist. Endoscopic technique also precludes synovectomy, which may be necessary in some of these patients. That said, ECTR can be performed reliably in inflammatory arthritis patients whose disease is quiescent [8]. ECTR should also be carefully considered in patients with a history of trauma or hand/wrist fractures, since these events can perturb the bony anatomy of the carpal tunnel. Lastly, some argue that patients with severe median nerve compression necessitating extensive neurolysis or tenosynovectomy should instead undergo conventional open CTR, as these adjunctive procedures cannot be performed via an endoscopic approach [9, 10].

Surgical Techniques

Positioning

In general, with any ECTR technique, the patient is placed supine with the arm abducted on an operating arm table. The surgeon is positioned on the medial side of the abducted arm (if right hand is the dominant hand) in order to facilitate the use of the dominant hand for maneuvering the endoscope, while the assistant is positioned on the opposite side. Some surgeons prefer to use their dominant hand for all cases (requiring them to sit on the head side of the hand table to release the nondominant hand), while others prefer to maintain their position on the axillary side of the hand table (and use their nondominant hand to release the nondominant hand of the patient).

Anesthesia

ECTR can be performed using general, regional, and local anesthesia. More commonly, regional and local anesthesia is used, with general anesthesia reserved for those unable to tolerate local or regional blocks. Several studies have examined the efficacy and the postoperative outcomes with local versus regional anesthesia. While some studies have suggested less cost and equally effective intraoperative analgesia with local-only techniques, our experience is that injection of local anesthetic into the skin over the transverse carpal ligament creates fogging of the endoscope and poor visualization, requiring an unacceptably high rate of conversion to open procedure in these circumstances [11].

In our practice, we generally use local anesthesia with IV sedation, and it is well tolerated. The distal wrist crease and proximal forearm fascia are infiltrated with a 1:1 solution of 1% lidocaine with epinephrine with 0.5% plain bupivacaine. A tourniquet is utilized, and it is inflated to 250 mmHg after local anesthesia infiltration to reduce bleeding.

Endoscopic Approaches

Currently, there are three main distinct types of ECTR techniques performed (Table 13.2). The most commonly performed technique is the single proximal portal technique, first described by Agee in 1992 [4]. This technique utilizes a proprietary device (MicroAire, Charlottesville, VA) which is composed of a 2.7-mm 30-degree-angle arthroscope, a fiber-optic light source and camera, and a handpiece with attached disposable blade cartridge into which the endoscope is inserted (Fig. 13.1A, B). The Chow dual-portal technique was introduced by James C. Y. Chow in 1989 [3]. Unlike the Agee technique, the Chow technique uses a two-port approach which creates a fixed space in which to operate. A cannula is fixed at the proximal and distal portals, and a 4-mm 30-degree endoscope with an incorporated knife is inserted at the proximal portal, which is then used to incise the TCL (Fig. 13.2a, b). Lastly, in 1995, M. Ather Mirza described a single distal portal approach which utilizes a 1.5-cm longitudinal palmar incision along the thenar crease, a standard 4-mm 30-degree endoscope, and a knife/sleeve device which is used to divide the TCL and decompress the carpal canal [5]. The

Table 13.2 Three endoscopic CTR approaches

Technique	Year of development	Description
Agee	1992	Single proximal portal approach
Chow	1989	Two-port approach
Mirza	1995	Single-distal port approach

CTR carpal tunnel release

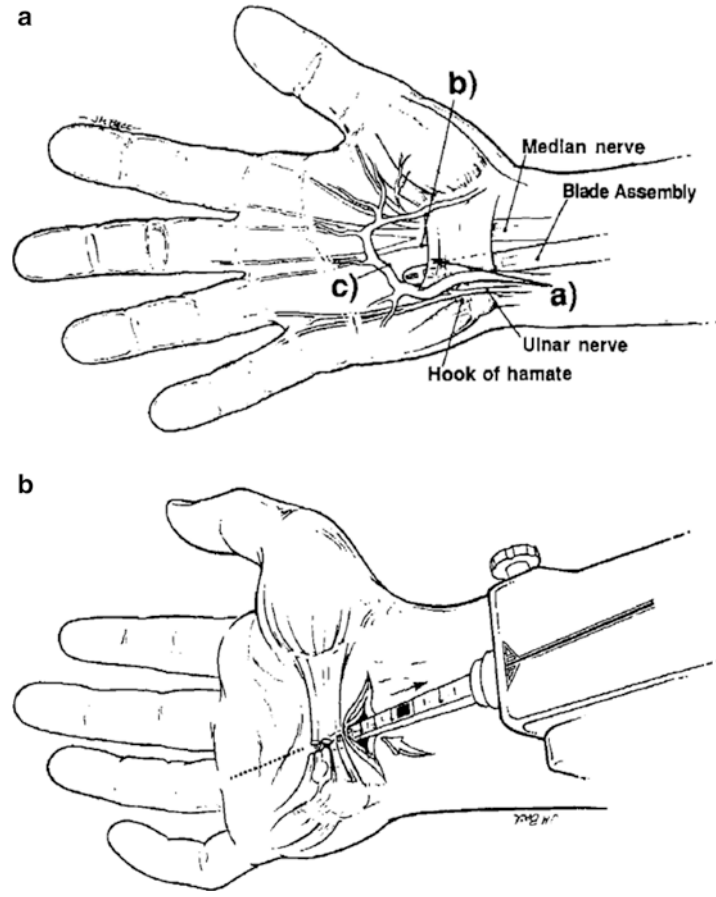

Fig. 13.1 The original description of the single proximal portal technique by Agee. (**A**) Schematic of the relative position of the endoscopic device relative to the distal edge of the TCL (**a**), ulnar limit of the median nerve (**b**), and proximal limit of the superficial palmar arch (**c**). (**B**) The device is inserted parallel to the plane of the palm and forearm

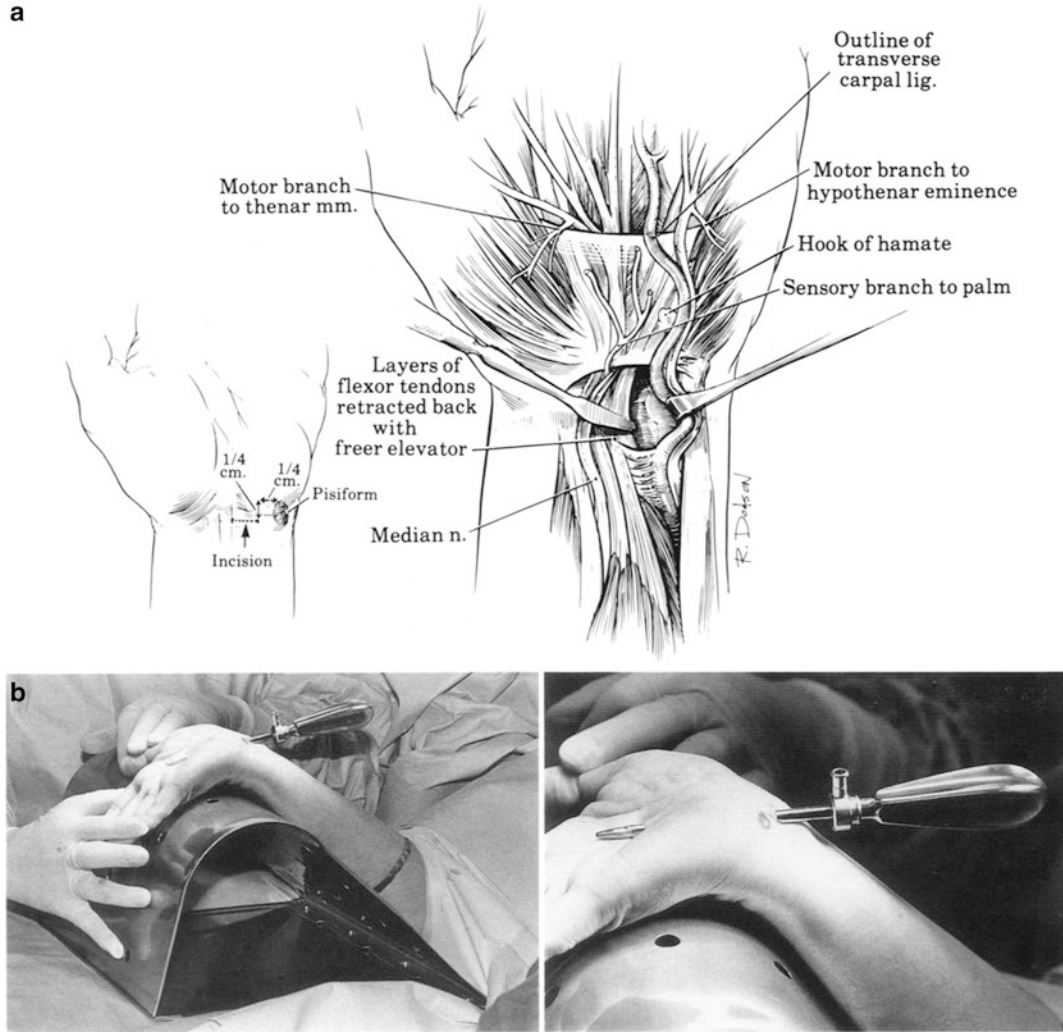

Fig. 13.2 The Chow two-portal technique. (**a**) Schematic of the cannula position relative to the volar wrist structures. (**b**) The hand positioned on the wrist extension platform with the cannula inserted

single distal portal approach can also be done using the MicroAire device (Fig. 13.3a–c) [12].

The Single Proximal Portal Technique

The senior author has extensive experience with the single proximal portal technique so a brief description of the operative technique is provided below:

1. *Incision, Exposure, Insertion*

   A 1–2-cm transverse incision is made at the proximal flexor wrist crease ulnar to the palmaris longus. Careful dissection is performed down to the antebrachial fascia using skin hooks for exposure (Fig. 13.4). The fascia is incised by creating a distal ulnarly based L-shaped flap. The distal antebrachial fascia proximal to the incision just made is divided under direct vision with scissors. Means and colleagues demonstrated that pressure on the median nerve can remain elevated even after release of the TCL if the antebrachial fascia is intact [13]. For this reason, we always include division of the distal antebrachial fascia as part of ECTR. The maneuver takes less than a minute to perform and does not add additional cost to the procedure.

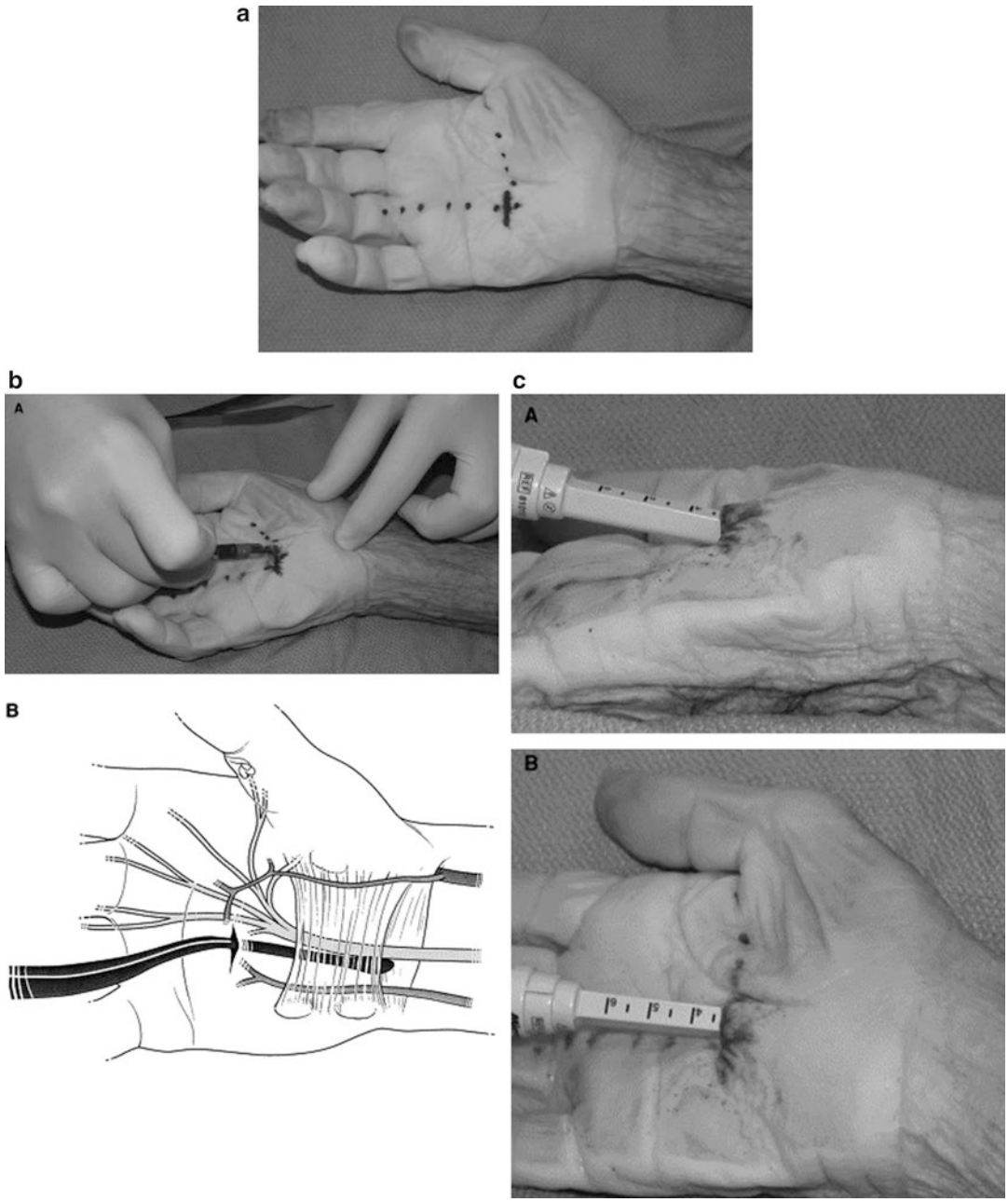

Fig. 13.3 The single distal portal technique. (**a**) The incision is placed at the intersection of Kaplan's cardinal line and the fourth ray. (**b**) Schematic of the location of the endoscope passage relative to the superficial palmar arch and the ulnar limit of the median nerve. (**c**) The endoscope is inserted into the carpal tunnel

2. *Retinaculum Incision*

A synovial elevator is passed distally several times along the axis of the fourth ray to elevate the synovium off of the transverse carpal ligament (TCL) deep surface (Fig. 13.5a, b). The endoscopic device is then inserted into the carpal canal (Fig. 13.6). With the TCL distal edge in full view on the endoscope monitor (Fig. 13.7), the TCL is divided from the distal to proximal edge using the device blade. If

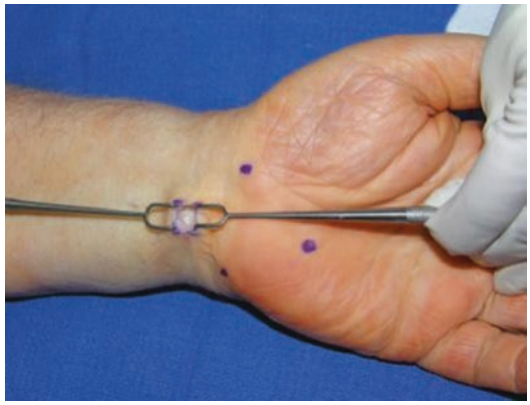

Fig. 13.4 The distal antebrachial fascia is exposed via a transverse incision of a volar crease immediately proximal to the volar wrist crease

there are any issues with visibility of the TCL, the surgical approach is then converted to an open procedure.

3. *Assessment of Release*

   Next, to ensure adequate release of the TCL, the device is reinserted and the TCL is visualized from its most distal edge to its most proximal edge for any fibers that may be tethered to the cut edges of the retinaculum. The presence of these fibers indicates that an incomplete division should be suspected. Using the device blade, the undivided TCL fibers are divided to ensure complete release, with careful attention to the location of the median nerve to avoid transection/injury (Fig. 13.8).

4. *Closure*

   The skin is closed with interrupted nylon sutures or a resorbable subcuticular suture. Prior evidence suggests that there is no difference in pain reduction or long-term cosmetic outcome with either skin closure technique [14].

Postoperative Care

Traditionally, carpal tunnel release patients were managed postoperatively with immobilization for 1–3 weeks. However, several lower-level evidence studies have demonstrated that splinting may actually slow the postoperative recovery process [15]. Therefore, most surgeons now place the hand in a large bulky hand dressing for only 1–3 days postoperatively to avoid bleeding in the carpal tunnel. ECTR patients are also encouraged to begin using the hand immediately after surgery. While some studies have found better surgical outcomes in terms of grip and pinch strength, subjective symptom measures, and functional status with immediate hand therapy [16, 17], other studies have identified this same benefit by simply allowing the patient to begin moving and light use of the hand immediately after surgery [18].

Complications

Overall, ECTR is a safe procedure. A limited number of high-level studies have explored complications following ECTR. Most reported complication rates range from 0 to 5% [19, 20]. During the early development stages of the endoscopic technique, the experience was plagued with several complications [21]. However, blade redesign, modifications to insertion techniques, and increasing surgeon experience have dramatically decreased the frequency of complications.

The most feared complication is transection or trauma to the median nerve. Although transection of the median nerve is very rare [22], some research has found higher rates of transient (non-permanent) median nerve injury after endoscopic surgery compared to open [23]. In order to minimize the risk of nerve transection or neuropraxia, surgeons must be aware of the various anatomical variations arising from the ulnar aspect of the median nerve which place the nerve at risk for iatrogenic injury.

Another feared complication after ECTR is bleeding. As with any surgical procedure, postoperative bleeding can occur due to inadequate hemostasis, resulting in swelling of the hand and an increased risk of infection. To minimize this risk, we use a bulky, soft compressive bandage for the first 24–48 h postoperatively which helps tamponade any bleeding from the wound.

To minimize any complications following ECTR, surgeons must have a low threshold for

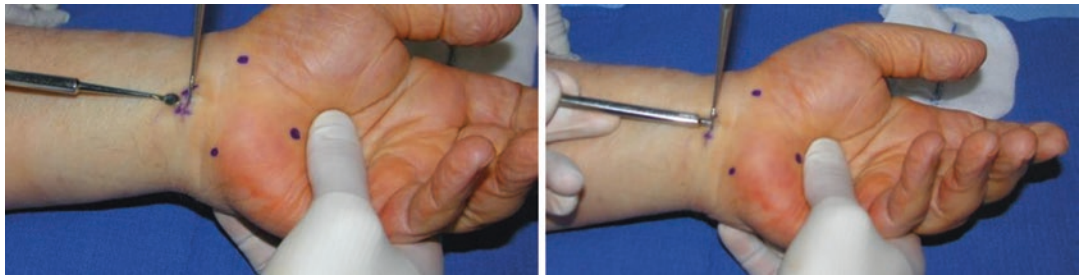

Fig. 13.5 A synovial elevator is used to free the synovium within the carpal tunnel from the deep surface of the TCL

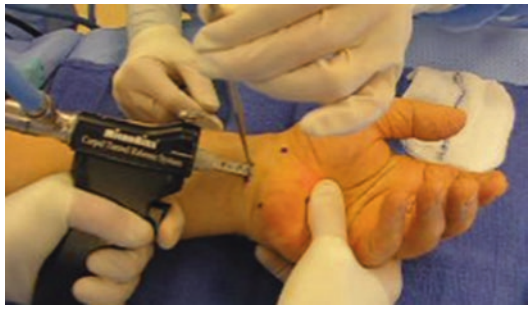

Fig. 13.6 The endoscopic device is inserted into the carpal tunnel parallel to the plane of the TCL

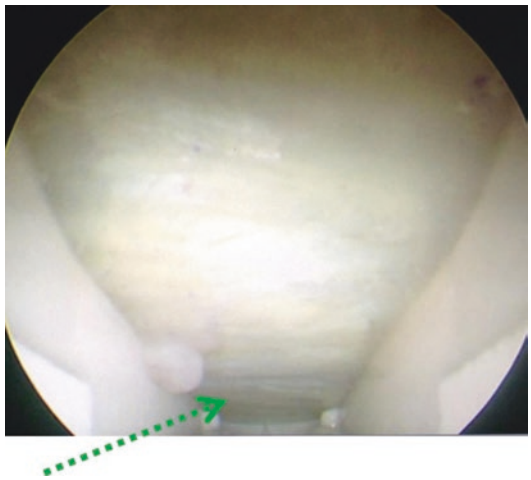

Fig. 13.7 The distal end of the TCL is identified on the monitor as the junction of the white transverse fibers of the TCL and the more yellow fat of the palm just distal to it

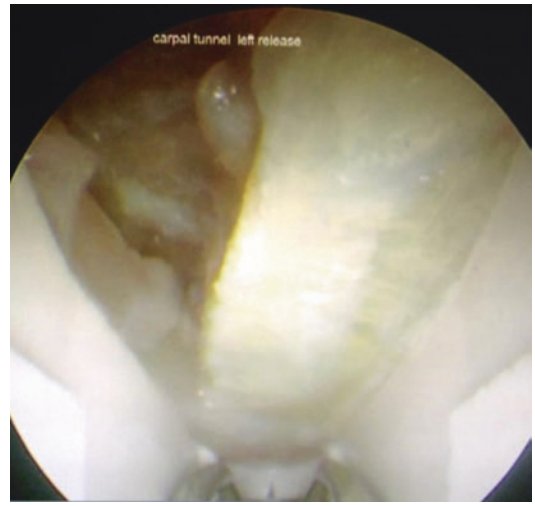

Fig. 13.8 The radial-sided cut edge of the TCL is visualized, confirming adequate release. Gentle supination of the endoscope (with the blade retracted) allows visualization of the median nerve to confirm it has not been injured

converting to an OCTR. Visibility is extremely important in ECTR, and if visibility is compromised, risk for nerve injury is increased. Thus, if bleeding minimizes visualization of the nerve, or if the surgeons experience significant resistance during the introduction of the endoscope (likely secondary to anatomical variations or synovial adhesions) [24], conversion to an OCTR is highly recommended.

In summary, ECTR is a generally safe procedure. Chow et al. published their 13-year experience with their technique and reported a 1.1% overall complication rate [25]. In another series with 14,722 patients, Hankins et al. reported only one nerve injury and a low conversion rate to OCTR (0.07%) [26]. Overall, when comparing open and endoscopic CTR, complication rates seem to be very low and similar for both procedures [27].

Outcomes

Over the last two decades, numerous studies have explored surgical outcomes after ECTR. Several of these studies have compared open versus endoscopic CTR on postoperative recovery. Multiple studies have shown that endoscopic and conventional open techniques have equivalent *long-term* functional outcomes [28, 29]. Trumble et al. performed a randomized, double-blinded multicenter trial comparing open versus single proximal portal ECTR and showed statistically significant improvement in pain and hand strength in the ECTR group when compared to the open group at 6 weeks and 3 months. However, long-term hand pain and strength at 1 year were found to be equivalent [30]. Similarly, Macdermid et al. found significantly better grip strength and pain control at 1 and 6 weeks, but these differences dissipated by 12 weeks [31]. Conversely, several studies have found similar short-term and long-term postoperative outcomes after ECTR and OCTR. A recent Cochrane Review summarized the current literature on surgical outcomes after ECTR and concluded that ECTR may "enable patients to return to work or daily activities sooner" but may not "offer better relief from symptoms in the short- and long-term compared to OCTR" [32]. Overall, the current evidence suggests that long-term relief of neuropathic symptoms, improvement in functional status, and subjective patient satisfaction are similar between ECTR and OCTR.

Conclusion

ECTR is becoming increasingly prevalent in the surgical treatment of CTS. Although initial reports described higher complications rates, the endoscopic techniques have been refined and have yielded improved surgical outcomes. Unlike other areas in hand surgery, several high-level studies have been published assessing the efficacy of ECTR. These studies, although still limited due to unstandardized outcome metrics, provide evidence that ECTR is a safe technique with excellent results, including that patients may recover faster and/or with less pain from this technique. Furthermore, studies have gone on to demonstrate that ECTR is a cost-effective procedure [33]. With increasing experience, we anticipate that ECTR will continue to increase in prevalence in the surgical treatment of CTS.

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Challenges and Complications of Carpal Tunnel Syndrome

14

Julie E. Adams and Maureen A. O'Shaughnessy

Introduction

Carpal tunnel release (CTR) is a common procedure with a relatively low complication rate ranging from 1 to 25%; however, some of those complications can be potentially devastating and may lead to reoperation in up to 12% of cases [1–5]. This chapter reviews complications following carpal tunnel release surgery, both theoretical and those cited in the literature, ranging from the common to uncommon. Having awareness and thorough understanding of the potential risks inherent to the procedure will hopefully decrease their incidence in the readers' hands. The ability to competently evaluate and manage complications is an essential part of hand surgery [6].

Complications following CTR can present clinically in various ways. Pain, redness, and erythema following CTR may be caused by infection, postoperative edema, inflammatory arthritis flare such as gout, or complex regional pain syndrome. These etiologies will be explored in further detail later in the chapter. Alternatively, the patient presenting with complaints of persistent, recurrent, or worsening symptoms suggestive of carpal tunnel syndrome (CTS) requires a different evaluation, and several factors must be considered. Among the differential diagnoses include inadequate release, recurrent carpal tunnel syndrome, incorrect diagnosis, or inadequate time for nerve recovery. Tung and Mackinnon classified indications for revision CTR into three categories: persistent, recurrent, and new symptoms [7]. These etiologies will be explored in detail in this chapter.

When these patients are evaluated, a good history is taken and a thorough physical examination is performed. Patients are queried as to their symptoms preoperatively in terms of duration, exacerbating and relieving factors, and nature of the symptoms. One cannot take shortcuts with these patients; the history and physical exam should be performed very thoroughly and objectively; and one must also take nothing for granted. A healthy skepticism about the initial diagnosis and evaluation is held as the surgeon should not assume that treatment to date has been adequate or appropriate or even that the initial diagnosis of carpal tunnel syndrome is correct. It is important to rule out other causes of numbness including generalized peripheral neuropathy or cervical spine or other compressive neuropathies. Patients are evaluated for provocative signs, two-point discrimination is assessed, and an electrodiagnostic test may be

J.E. Adams (✉)
Orthopedic Surgery, Mayo Clinic Health System,
1000 First Drive NW, Austin, MN 55912, USA

Department of Orthopedics, Mayo Clinic,
200 First Street SW, Rochester, MN 55902, USA
e-mail: adams.julie@mayo.edu

M.A. O'Shaughnessy
Department of Orthopedics, Mayo Clinic,
200 First Street SW, Rochester, MN 55902, USA
e-mail: OShaughnessy.Maureen@mayo.edu

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obtained and compared to preoperative studies (if available). Caution in interpreting electrodiagnostic testing must be used. It is unclear if electrodiagnostic testing findings of median neuropathy ever return to "normal" even after successful carpal tunnel release.

Moreover, the important concept is differentiating carpal tunnel syndrome from median neuropathy at the level of the wrist. Although it is true that the patients who have abnormal electrodiagnostic testing do better after CTR surgery than those who have normal testing, it is important to recognize that median neuropathy at the level of the wrist and CTS are two separate diagnoses. The two may coexist or exist separately. Carpal tunnel syndrome is a syndrome of pain and/or dysesthesias and/or dysfunction in the median nerve distribution that is symptomatic. Median neuropathy at the level of the wrist is an electrodiagnostic diagnosis. If the patient has altered median nerve function according to the electrodiagnostic test (median neuropathy at the level of the wrist) but is asymptomatic, the patient does not have carpal tunnel syndrome. Conversely, a patient with symptoms of CTS but a normal electrical test does have CTS. Thus, electrodiagnostic testing is not the gold standard for diagnosis of CTS but rather a tool to provide objective data about the function of the median nerve. This author often performs a diagnostic and potentially therapeutic carpal tunnel injection at the level of the wrist as patients who respond well to injection will likely respond similarly to surgical release.

In the author's practice, examination of the new patient presenting with complaints of numbness and tingling includes evaluation of cervical spine motion and wrist, elbow, and digital range of motion and provocative testing, including:

Spurling's maneuver
Elbow flexion test
Cubital tunnel compression test
Phalen's maneuver
Durkin's compression test
Reverse Phalen's maneuver
Compression over the pronator
Tinel's testing over the carpal tunnel, cubital tunnel, and pronator
Manual motor strength testing of thumb opposition, first dorsal interosseous, flexor pollicis longus, and FDP of index
Visual inspection for vasomotor changes or atrophy and prior incisions
Two-point discrimination in the median and ulnar nerve distributions (innervation density testing)
Occasional vibratory testing (threshold testing)
An even more careful examination of the patient presenting with recurrent or residual CTS symptoms is essential.

Persistent Symptoms

Persistent Symptoms: Inadequate Release

The examiner must determine if the patient initially had symptom relief for some disease-free interval but then had symptoms which returned or if the symptoms never went away or became worse. The latter is generally suggestive of inadequate release which is the most common reason for revision CTR [8–10]. Other possibilities include incorrect diagnosis, inadequate capacity or time for the nerve to recover, or iatrogenic injury to the median nerve.

Initial inadequate release is the most common reason revision CTR is required [8]. Typically, patients will present with complaints of persistent or worsening symptoms of paresthesia and pain in the median nerve distribution. They will generally relay that their symptoms were never improved following the index procedure. In contrast to patients with a nerve with limited capacity for recovery or those in whom there has been inadequate time allowed for recovery, these patients with inadequate release will often report persistent or worsening *pain* as well as numbness. The patient may be made worse, as prior to surgery, there may have been a broad area of compression, whereas after inadequate release, the nerve is compressed over a smaller segment, and thus pressure is distributed over a smaller segment leading to higher pressure at a shorter

segmental site—and worsening symptoms. In patients in whom the nerve has been damaged by prolonged compression and in whom either there is limited capacity for recovery or in whom inadequate time has passed for recovery, pain and intermittent symptoms are typically relieved almost immediately, but the constant numbness that was bothersome preoperatively will persist, either for some period of time or indefinitely if the nerve has been irrevocably damaged by prolonged compression.

Inadequate release can be avoided by taking time to adequately assess the extent of release at the index procedure. The surgeon must be careful to ensure full release of the transverse carpal ligament (TCL), especially at the distal end where it is most commonly incompletely released. The release must be continued proximally to the distal forearm fascia and distally to the thenar-hypothenar aponeurosis as these are the most common sites of residual compression and may be difficult to visualize using the mini-open or endoscopic techniques [9]. It is imperative that if any question about the adequacy of release or potential for iatrogenic injury remains, incision should be extended to fully assess the field. In the case of an endoscopic approach, if adequate release cannot be confirmed, conversion to open technique should be considered.

Many surgical complications associated with open CTR are related to inappropriately placed incisions. An adequate incision must allow adequate exposure, avoid injuring adjacent structures, and not cross the wrist flexion crease at a right angle [11]. An inadequate incision can lead to poor visualization of the TCL and possibly result in incomplete release (Fig. 14.1). A disadvantage of endoscopic technique is the limited visualization making it difficult to differentiate between nerve and synovium [8]. Some studies showed an increased rate of recurrence after endoscopic release including a study by Concannon et al. showing a statistically significant increased recurrence rate of 7% compared to 0% after open release ($p = 0.008$) [12, 13]. In contrast, Schreiber et al. found a lower reoperation rate among endoscopic release patients in a center which has a higher volume of endoscopic cases than open [14]. A recent meta-analysis has shown no statistical difference in reoperation rate between open and endoscopic technique [15]. The author in general prefers a mini-incision. The author makes an incision in line with the radial aspect of the fourth ray, extending from the

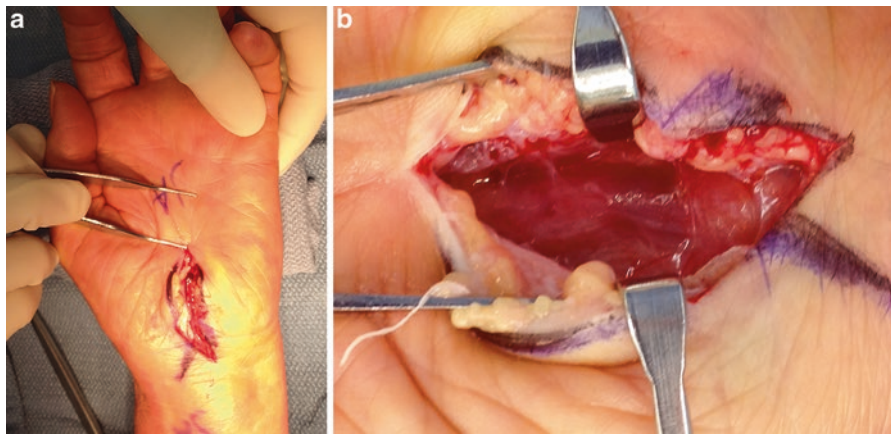

Fig. 14.1 (**a**, **b**) The initial surgical incision for carpal tunnel release in this patient was placed very distally (outlined by pickups) (**a**). Initial carpal tunnel release led to worsening burning pain and dysesthesias. Electrodiagnostic testing revealed worsened median nerve function compared to preoperatively but suggested continuity of the nerve. At time of revision surgery, a large incision was made crossing the wrist crease obliquely to ensure adequate release proximally and distally (**a**). The prior release was found to be incomplete, with an hourglass compression of the nerve proximal to the old incision (**b**). A revision carpal tunnel release was completed. The patients' symptoms slowly improved postoperatively. ©Julie Adams MD

wrist crease distally to a location that one can palpate as a soft spot which represents the end of the transverse carpal ligament (Fig. 14.2). The incision is just ulnar to the hook of the hamate and is in line or parallel to the thenar crease. Dissection proceeds to the palmar fascia which is identified and sharply incised. The transverse fibers of the transverse carpal ligament are exposed and incised. The distal forearm fascia is released under direct visualization. The adequacy of release is assessed and confirmed proximally and distally. The carpal canal is visually inspected for any masses or irregularities. In cases of revision surgery or in cases in which adequate release cannot be confirmed with the mini-incision, a low threshold is held to expand the incision and cross the wrist crease obliquely to ensure adequate exposure and release (Fig. 14.1).

Persistent Symptoms: Wrong Diagnosis

Incorrect primary diagnosis may be the etiology for apparent residual symptoms following CTR [3]. Reasons for apparent carpal tunnel symptoms fall commonly under vascular or neurological diagnoses.

Vascular

Patients with Raynaud's disease or phenomenon may have intermittent numbness in the hands typically precipitated by stress or cold. The typical "red-white-blue" discoloration accompanies the numbness which occurs following vasospasm of the small vessels. Although history is generally enough to differentiate CTS from Raynaud's, the results of various provocative tests and/or laboratory studies in the setting of phenomenon may be useful. Vascular insufficiency with occlusion of the radial or ulnar artery leading may mimic CTS [13]. An Allen's test may be performed to assess for vascular competency (Figs. 14.3, 14.4, and 14.5).

Neurological

The surgeon must consider additional sites of compression of the nerve proximally. The nerve may be compressed more proximally such as in the forearm with pronator syndrome. In pronator

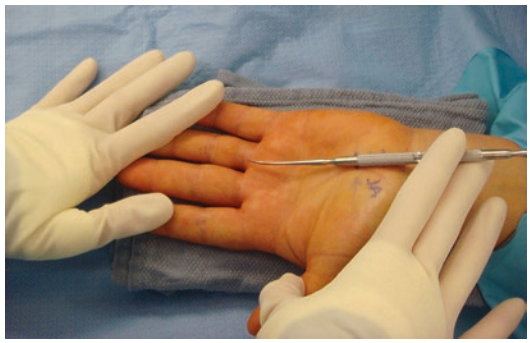

Fig. 14.2 The mini-open incision is made in line with the radial aspect of the fourth ray. Copyright Julie Adams MD

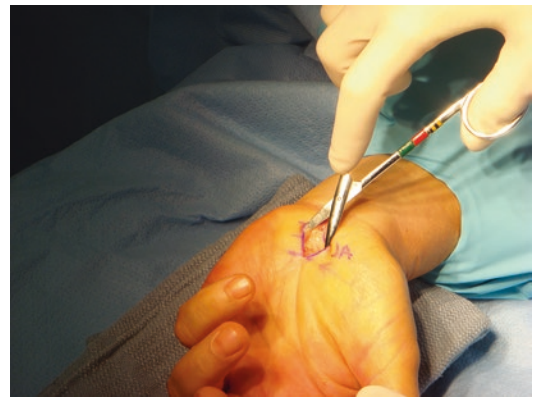

Fig. 14.3 Dissection proceeds to the palmar fascia. Copyright Julie Adams MD

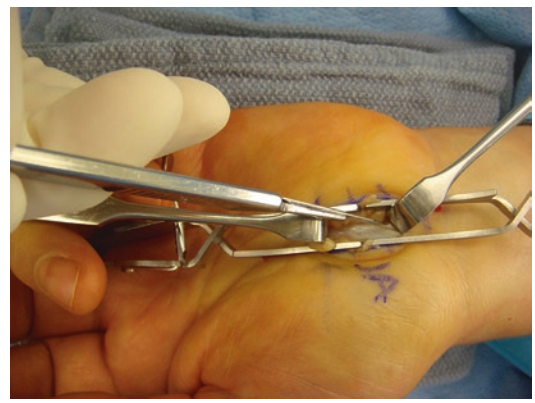

Fig. 14.4 The palmar fascia is identified and sharply incised. Copyright Julie Adams MD

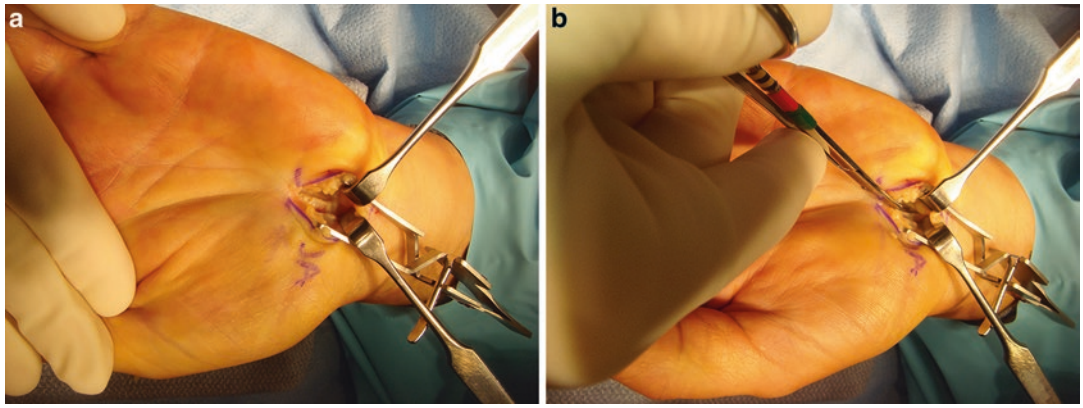

Fig. 14.5 (**a**, **b**) The distal forearm fascia is identified (**a**) and released under direct visualization (**b**). Copyright Julie Adams MD

syndrome, the patient may have symptoms of weakness in the FDP of the index and the FPL and commonly has numbness in the "palmar triangle" related to involvement of the palmar cutaneous branch of the median nerve [9]. In addition, proximal lesions in the cervical spine can be problematic [9]. The patient may have isolated proximal compression or may suffer from both CTS and a proximal lesion leading to the "double-crush" phenomenon. Patients may also suffer from generalized peripheral neuropathy, and referral to a neurologist for evaluation and possible treatment may be beneficial. Electrodiagnostic testing is helpful to determine the level of pathology and to determine the presence of generalized neuropathy.

A study by Witt and Stevens reviewed 12 patients with a diagnosis of CTS who underwent unsuccessful CTR that were evaluated in their electrodiagnostic lab [16]. In their series, ten patients did not meet electrodiagnostic criteria for CTS but were discovered to have a neurological diagnosis including polyneuropathy (five patients), motor neuron disease/ALS (four), cervical radiculopathy (three), multiple sclerosis (two), cervical spondylotic myelopathy (one), and syringomyelia (one). Only one patient had severe recurrent CTS related to postoperative scarring, and one patient had asymptomatic median neuropathy at the wrist. The authors conclude that the patients either did not have CTS or their CTS were not a clinically important factor compared to their other neurologic diseases.

Persistent Symptoms: Inadequate Time for Recovery/Delayed Intervention

Patients presenting with persistent symptoms should be counseled that a reasonable time course must pass to allow for nerve recovery. Patients should be counseled that nerve recovery, and continued symptom improvement, can be expected for up to 6–12 months after surgery, particularly in cases where the nerve was severely compressed for a long duration [6]. In the authors' practice, patients are counseled that rapid resolution of intermittent symptoms and pain is likely following carpal tunnel release surgery; however, constant symptoms take much longer to resolve, if they ever do. It is extremely helpful to obtain serial evaluations of the patient with objective data. Many patients are anxious and impatient with recovery of sensibility and fail to appreciate improvement over time. Serial evaluation and documentation of two-point discrimination are often helpful to show the patient that recovery is slowly occurring.

Unfortunately, CTR may not provide relief if the compressive damage has led to irreversible motor and sensory changes. Initial and repeat electrodiagnostic testing may be helpful to prove this if question remains. Patients who exhibit thenar atrophy, loss of opposition function, and dense sensory impairment are counseled about the advisability of proceeding with carpal tunnel release. If electrodiagnostic testing preoperatively

reveals a nonresponsive nerve study, there is limited capacity for recovery of meaningful function. Extreme caution is used in patients who have NO PAIN preoperatively, constant numbness, and a nonresponsive electrical test. These patients are unlikely to have recovery of function and usually do not benefit from surgical release. In addition, particularly in such patients who have no pain, extreme caution is used—the pain fibers of the median nerve may recover, while the sensory and motor fibers do not, leading to a painful yet continued insensate hand. To improve function, surgical options such as tendon transfer opponensplasty may be indicated for certain patients with low median nerve palsy due to long-standing CTS. Many techniques have been described to restore opposition and should be tailored to the need of the patient [17].

Recurrent Symptoms

The definition of recurrent symptoms, in contrast to persistent, has been defined as "documented carpal tunnel syndrome in which the symptoms had resolved following surgical release, but then recurred, requiring a re-release of the carpal tunnel [12]."

Jones et al. suggested that the diagnosis of recurrence should include a minimum of 6 months of a symptom-free interval before return of symptoms [9]. Cause of recurrent symptoms may be perineural or intraneural fibrosis, scarring, median nerve adherence to adjacent tissue, neuroma, median nerve subluxation, tenosynovitis, synovial proliferation, or flexor retinaculum regrowth [3, 9]. The TCL is known to reform and appear intact upon reoperation even in the case of experienced hand surgeons who have reexplored their own patients years later [8]. Incomplete release may also be the source of recurrence. Less common reasons may be amyloid deposits, rice bodies, or calcinosis [9]. Often the cause for recurrent symptoms is not clear at the time of reoperation, and in one series, no specific abnormal findings were noted in 5% of revision CTR [9]. Additional factors which have been suggested (but not proved) to contribute may include poor hemostasis, prolonged immobilization, or excessive physical therapy [9].

Evaluation

The surgeon should request the operative report from the patient's index procedure, including initial workup testing such as electrodiagnostic testing, and clinical examination documentation as well as any imaging studies. Review of these documents may provide a clue as to the cause of the recurrent symptoms. Clinical exam may show misplaced or small surgical scar. MRI or ultrasound, although rarely indicated, may be used in an appropriate setting to search for an occult mass or space occupying lesion which may be the culprit of ongoing symptoms and would be an important finding not to be missed. MRI, however, does not reliably detect evidence of incomplete release [3].

A reasonable course of nonoperative management is indicated initially including splinting, rest, injections, hand therapy, and desensitization [9]. An excellent diagnostic and potentially therapeutic intervention is carpal tunnel injection. If patients exhibit improvement following injection, the recurrent carpal tunnel syndrome is likely a cause or the cause of recurrent symptoms. If these measures fail to provide adequate relief and electrodiagnostic results worsen, the surgeon can reasonably proceed to revision CTR. The patient should be counseled that they may not get relief of symptoms if the nerve was adequately decompressed initially and if recurrent carpal tunnel syndrome is not the cause of their symptoms.

Surgical Considerations

The surgeon may consider using an extended carpal tunnel approach in the revision setting in order to fully assess the nerve. The surgeon should take care to document the integrity of the transverse carpal ligament at the time of repeat exploration, the integrity of the median nerve and its branches, as well as the presence of inflamed or hypertrophied synovium. The surgeon should consider

sending tissue samples for pathology and culture if there are any concerns at the time of surgery as atypical or fungal infections may present with hypertrophied synovium leading to CTS [18]. The median nerve is typically contained within dense scar tissue and may require careful external neurolysis or even epineurectomy, although internal neurolysis is contraindicated [9].

Controversy exists as to whether additional tissue coverage steps should be taken in the revision setting. Some advocate that if a definitive cause for the patient's symptoms is found, coverage may not be indicated [9]. However, if the nerve is found in significant scar tissue, it is reasonable to consider interposition of some type of soft tissue between the nerve and the residual TCL and the palmar skin to prevent recurrence. Local flap options include muscle (abductor digiti minimi, pronator quadratus, palmaris brevis), hypothenar fat pad flap, synovial flap, dermal graft, or use of synthetic membrane [9]. Distal flap options described include omental, reverse radial forearm adipofascial and small free muscle and fascial flaps [9]. In the authors' hands, flap coverage is rarely necessary, and we feel it may contribute to additional recurrent scarring.

Outcomes following revision CTR may not be as rewarding as in the primary setting with some studies reporting poor results and up to 95% of patients reporting persisting symptoms, while others report an overall 95% satisfaction rate [3]. A recent large series reviewing results of CTS revision found that most patients demonstrate good outcomes with reasonable improvements in pain and strength [10].

New Symptoms

Iatrogenic Nerve or Vessel injury

Nerve injury or transection at the time of surgery is a dreaded complication but can occur even in the hands of experienced surgeons [6, 8, 9, 19]. Multiple studies including a recent meta-analysis have shown an increased risk of nerve injury in endoscopic compared to open technique; however, the nerve injuries tend to be temporary neurapraxias [4, 15]. In the next section, we explore the various nerve injuries that can be associated with CTR.

Patients will typically report a history of persistent or worsening symptoms postoperatively. Thorough examination to determine level of nerve injury should be performed. Examination should document two-point discrimination for all digital nerves as well as the distribution of the palmar cutaneous branch. The examiner should evaluate for a Tinel's at the wrist, at the scar, as well as proximally in the forearm. This can help determine the presence of a neuroma or of a proximal nerve entrapment. Motor strength should be carefully examined to help determine level of injury. A clue to nerve damage is that patients may experience worsening postoperative pain secondary to nerve injury or transection. Relief of symptoms with injection of local anesthetic at the site of presumed injury has been described as a reliable diagnostic test [11].

Injury to the recurrent thenar motor branch has been reported as 0.01% [6]. Loss of thenar branch function leads to weakness of thumb abduction and apposition. Care should be taken to determine if the functional deficits are due to nerve injury or preexisting atrophy due to long-standing carpal tunnel syndrome [6]. Three variations of the course of the thenar branch have commonly been described and include the extraligamentous, subligamentous, and transligamentous course [20]. Extraligamentous type will arise distal to the transverse carpal ligament (TCL) and runs retrograde to reach the thenar musculature. Subligamentous type arises from within the carpal tunnel and runs deep to the TCL until it reaches the thenar muscles. The preligamentous type branches proximal to the carpal tunnel and runs superficial to the TCL into the thenars. A recent prospective clinical study showed the presence of hypertrophic muscle overlying the TCL in all cases of sub- and preligamentous course, noting that the motor branch ran within the hypertrophic muscle [21]. Hypertrophic muscle superficial to the TCL should be incised with care, staying along its ulnar border to avoid injury to the thenar motor branch. Surgeon awareness of these variable patterns can help decrease risk of injury. A cadaveric analysis found the average distance from the distal TCL to the thenar motor branch was 6.9 ± 0.4 mm [22].

Injury to the median nerve has been reported at 0.06% [19]. Complete transection following endoscopic and open release has been reported [23] (Fig. 14.6a–c). The nerve is the most superficial structure within the carpal tunnel, typically lying radially, and may be injured with CTR. The nerve is mixed motor and sensory; therefore, patients may have a variable exam depending on

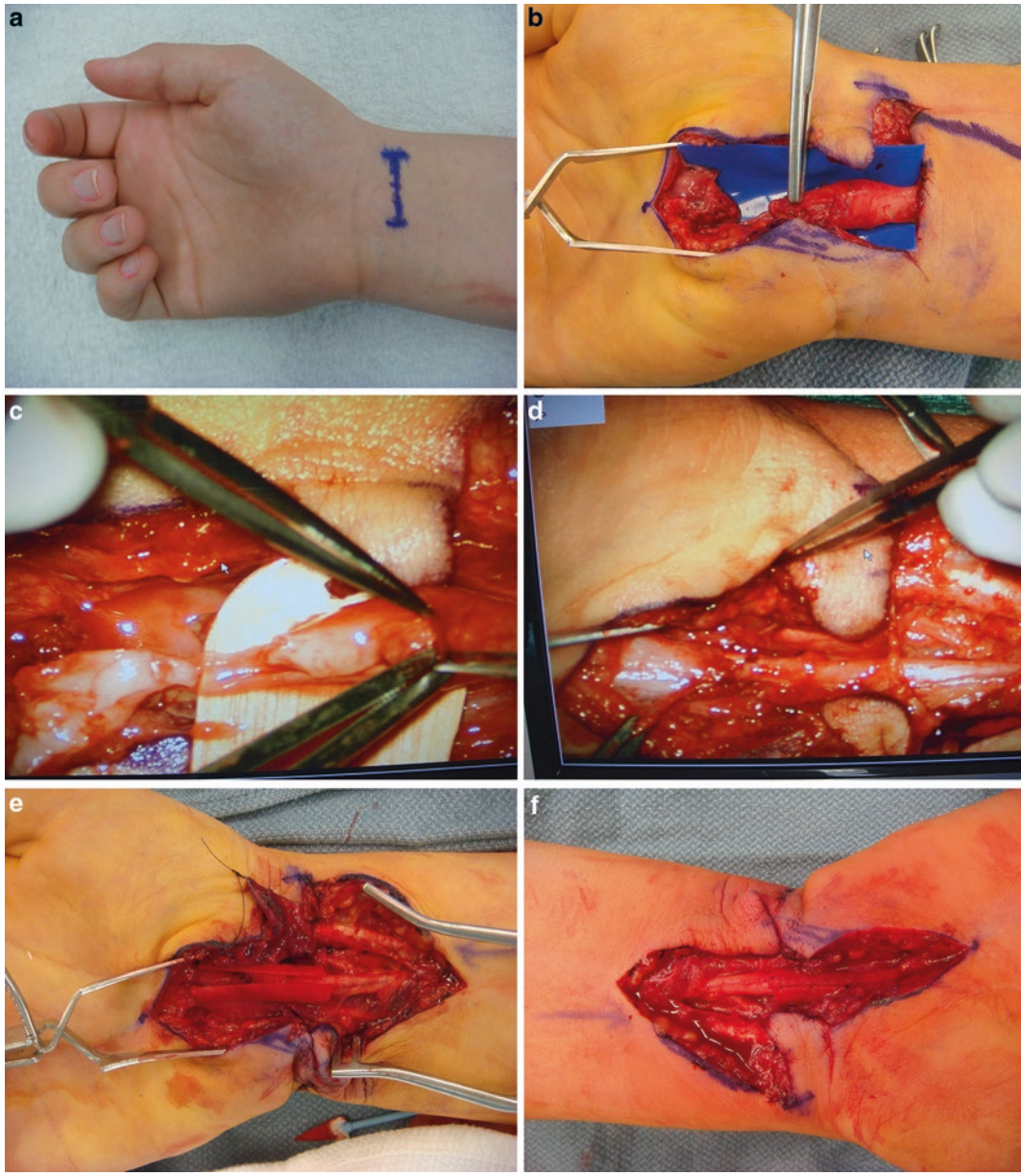

Fig. 14.6 This 22-year-old woman presented following prior endoscopic carpal tunnel release performed elsewhere with dense median nerve dysfunction, worse than prior to surgery. Repeat electrodiagnostic testing demonstrated absent median nerve function. Her prior endoscopic surgical incision site was a large transverse incision proximal to the wrist (**a**). The operative note described an endoscopic release. An extensile exposure revealed a transected median nerve with only a few fibers of scar tissue remaining and a proximal neuroma (**b**). The neuroma was resected (**c**) back to healthy-appearing fascicles proximally (**c**) and distally (**d**) and was repaired primarily in mild wrist flexion with a nerve tube wrap (**e**, **f**). Copyright Julie Adams MD

the extent of partial vs complete injury [6]. Injury to the ulnar nerve has been reported with an incidence in some series of 0.03% [19]. Causes of injury to the ulnar nerve include a neurapraxia from excessive traction from the carpal tunnel retractor, laceration, or even transection from the wrong tunnel released. The ulnar nerve lies superficial to the transverse carpal ligament within Guyon's canal, and misidentification of the carpal tunnel could lead to inadvertent ulnar nerve injury en route to the transverse ligament. Injury to the deep motor branch of the ulnar nerve leads to loss of intrinsic function including the ulnar two lumbricals, dorsal and palmar interossei, abductor digiti minimi, opponens digiti minimi, and flexor digit minimi [6]. Injury to the common digital nerve to the long and ring finger has been reported, especially following endoscopic release [9].

Vascular injury has been associated with CTR. The superficial palmar arch lies in close proximity to the transverse carpal ligament. Care must be taken to prevent injury to the arch. Although unlikely to lead to significant ischemia, arch injury causes substantial bleeding and may lead to hematoma formation, wound complications, and circulatory compromise to the hand [1, 6]. Arch injury likely does not warrant direct repair but rather can likely be addressed with coagulation. Recent cadaveric study has shown the average distance from the distal edge of the TCL to the superficial arch is 18.8 ± 0.6 mm [22]. Damage to the ulnar artery within Guyon's canal can also occur. Patients with an incomplete arch without collateral flow from the radial artery may rely solely on the ulnar artery, and injury could result in ulnar ischemia [6]. If injured, the artery should be explored and repaired if found to lead to significant hand ischemia.

For all the nerve injuries, intervention should proceed expeditiously. Intraoperative complications that are recognized should be treated as quickly as possible. Treatment options include operative exploration with neurolysis and the potential need for nerve primary repair or nerve grafting. Injury to the median nerve proper may lead to a neuroma in continuity and may need to be addressed with internal neurolysis [6], although internal neurolysis is controversial [9]. Injury to the palmar cutaneous branch can be treated with primary repair in the early stages or more likely with neuroma excision and neurolysis and burial of the nerve end within the flexor musculature if found late [6, 11]. Recurrent motor branch injury may be treated with direct nerve repair or nerve graft if possible but may require opposition transfer.

New Symptoms: Evaluation of Pain, Erythema, and Swelling Postoperatively or Wound Dehiscence, Drainage, and Infection

Following CTR, patients with increasing or persistent pain, erythema, swelling, and edema should be evaluated for infection. History should inquire for the presence of absence of fever or chills. Wound drainage or dehiscence should be noted. Vital signs may show fever or hemodynamic instability. Evaluation may reasonably include serologic studies for infectious markers (ESR, CRP, WBC). The differential diagnosis includes inflammatory arthritis flare (gout, pseudogout, rheumatoid arthritis) which is not uncommon in susceptible patients following CTR. A history of gout or pseudogout or other inflammatory arthritis should be sought from the patient although rarely postoperative flare may be the first recognized manifestation of otherwise minimally symptomatic disease. Advanced imaging such as ultrasound or MRI may rarely be indicated to search for abscess or fluid collection if infection is suspected, although generally in the setting of suggestive clinical findings, irrigation and debridement are often the most reasonable next step rather than imaging. Alternatively, specialized imaging to evaluate for gout crystals using dual-energy computerized tomography (CT) is an emerging technology available in some centers [24, 25]. Care must be taken to rule out infection, as patients may present with both infection and inflammatory arthritis.

The rate of infection after CTR in the literature ranges from 0 to 11% [26–31]. The highest published rate is from a study by Platt et al. in

1995 showing 11%; however, this is for all outpatient hand surgery and the specific rate among CTR is not clear [26]. The most recent studies (2010–2016) found infection rates ranging from 0.24 to 0.37% [27, 30, 31]. Hanssen et al. in 1989 published a large series of 3620 cases and found a deep infection rate of 0.47% [28]. Harness et al. evaluated 3003 CTR and found an infection rate of 0.37% (11/3003) noting no increased incidence among diabetics or patients who did not receive perioperative antibiotics [27]. Bykowski et al. studied all outpatient hand surgery procedures and risk of surgical site infection (SSI) and noted a rate of 0.24% among CTR [30]. When reviewing the entire cohort of outpatient hand surgery patients, in contrast to Harness et al.'s findings, there was an increased incidence of SSI among diabetics as well as among smokers and those with a longer duration of case. Their study also found no decreased incidence of SSI among patients receiving prophylactic antibiotics. The question of prophylactic antibiotic use in outpatient hand surgery continues to be debated, especially in relation to diabetics or immunocompromised hosts, and prophylactic antibiotic use should be left to the individual surgeon's discretion. Nevertheless, in the great majority of cases, prophylactic antibiotic administration prior to a CTR is not indicated.

Minor wound dehiscence or drainage may be initially treated with careful wound care. Oral antibiotics can be prescribed. However, if the wound or the drainage does not improve, a low threshold should be set for return to the operating room for irrigation, culture of wound, and revision closure as indicated.

Diagnosing infection after hand surgery can be difficult as some erythema and swelling can be normal postoperatively. A small wound separation can be colonized but not necessarily infected [32]. Patients may present with an edematous painful hand with erythema at the incision site, and this may be the so-called suture abscess; this superficial irritation typically resolves with suture removal with or without empiric oral antibiotics and is generally a reaction to the foreign body of the suture rather than a true infection [32]. If the superficial irritation does not improve with these measures or if there is presence of lymphangitis, fevers, or hemodynamic instability, the patient may be admitted for intravenous antibiotics and possible operative irrigation.

The surgeon should have a low threshold for operative irrigation and debridement. Biopsy of tissue is indicated to search for infectious (bacterial, atypical bacterial, or fungal) etiology. A trial of antimicrobials (oral or intravenous) may be considered before operative intervention; however, involving an orthopedic infectious disease specialist may be helpful. They can also assist with appropriate agent and course after microbiology data has been obtained. There are no established guidelines for duration of antibiotic therapy for surgical site infection (SSI) of the hand [32], but a recent study by Osterman et al. recommends a 7–10 day course of antibiotics for both superficial/suture abscess and deep infections [33]. If soft tissue defects remain after infection eradication, consideration should be given to local, regional, or free flap coverage given the proximity of the median nerve and the flexor tendons [6].

New Symptoms: Pain After CTR

Complex Regional Pain Syndrome

Patients with postoperative pain, erythema, swelling, and edema should first be thoroughly evaluated for infection. Once this has been ruled out, complex regional pain syndrome (CRPS) may be entertained as an etiology. This must be a diagnosis of exclusion as the surgeon must take care to avoid missing the diagnosis of infection, inflammatory arthropathy, or malignancy. Incidence of CRPS is felt to be uncommon in the orthopedic surgery literature with <2% prevalence [34]. Incidence among reports in CTR literature ranges from 0.6 to 11% [1, 4, 10].

When exhaustive search yields negative results, CRPS may be considered. CRPS can occur when the small fiber nerves regain function and begin transmitting pain signals. Previously termed reflex sympathetic dystrophy (RSD), CRPS comprises abnormal pain, swelling, vasomotor instability, contracture, and osteoporosis

[34]. CRPS is divided into type 1 where there is no causative nerve damage (RSD) and type 2 where there is (causalgia) [34].

In type 2 where injury to a nerve is causative, injured peripheral nerve fibers undergo cellular changes which allow even simple tactile inputs to stimulate the dorsal horn cells via input from low-threshold mechanoreceptors leading to the allodynia seen in CRPS [34]. Type 1 is likely related to an inciting trauma which releases cytokines and inflammatory mediators that sensitize nociceptors to respond in a similar way [34].

The role of surgery is limited in CRPS type 1. When there is a surgically correctable painful lesion (CRPS type 2), decompression of a compressed nerve is indicated [34]. Based on intraoperative findings, neurolysis and release of all sites of constriction or excision of a neuroma may be indicated. Relief of symptoms with injection of local anesthetic at the site of presumed injury can be a helpful diagnostic test [11].

There is no proven way to avoid CRPS, and the surgeon is advised to take time to counsel patients preoperatively of the risk of this complication. When symptoms do occur, CRPS should be treated early and vigorously [1, 13]. Treatment is no longer focused on manipulating the sympathetic nervous system but is rather geared toward functional rehabilitation of the affected extremity to break the cycle of pain and disuse [34]. Treatment includes a coordinated effort by the surgeon, the hand therapist, and a provider with training in the management of CRPS. Careful, focused, intensive physical therapy is a mainstay of treatment. A certified specialist in hand therapy can be extremely helpful in preventing contractures, avoiding abnormal limb posturing, retaining reasonable joint motion, providing protective splints, avoiding and improving edema, and preventing compensatory shoulder pain and stiffness [35]. Evaluation by a practitioner with advanced training in multimodal pain management and the use of neuropathic agents may be valuable to the patient.

Current modalities utilized for CRPS include centrally acting analgesics (amitriptyline, gabapentin, carbamazepine), regional anesthesia, membrane-stabilizing drugs (mexiletine), sympathetic blockade, peripheral nerve receptor desensitization with capsaicin, transcutaneous nerve stimulation, or implanted dorsal column stimulator [34]. Reports of peripheral median nerve stimulation in the treatment of type 2 CRPS show good pain relief and may be an option [36].

New Symptoms: Scar Sensitivity

Many patients will experience scar sensitivity after surgery including tenderness, tingling, burning pain, deep pain, dysesthesias, and hypesthesias around the scar with incidence reported in the literature from 19 to 61% [37]. Hypothesized causes of pain include inflammation or swelling of the subcutaneous tissue, specific suture materials, cutaneous nerve injury, operative technique, and sectioning of the TCL; however, evidence to support these theories is either weak or inconsistent [38].

Based on anatomical studies which showed the incidence and distribution of branches of the palmar cutaneous nerve in the palm, a modified open technique was studied to avoid the cutaneous nerves. One study showed significant improvement in scar pain with the modified technique compared to standard open; however, this study was not randomized or blinded [37]. A subsequent prospective randomized controlled trial found no difference in postoperative scar discomfort between the two techniques [39]. Endoscopic techniques should avoid the cutaneous nerves of the palm and may result in decreased scar sensitivity. A recent meta-analysis reviewing endoscopic and open CTR demonstrated a significant decrease in scar tenderness among the endoscopic patients ($p = 0.005$) [15].

A prospective analysis of scar pain after open CTR in 83 patients by Kim et al. found a significant correlation with depression score and postoperative symptoms in relation to scar pain intensity [38]. Multivariate regression analysis showed that depression, assessed using a validated survey, and postoperative symptoms, assessed by the Boston carpal tunnel questionnaire (BCTQ), predicted scar pain intensity and accounted for 38% of scar pain intensity variance. The study also found that scar pain did not correlate with patient satisfaction and other factors likely largely determine satisfaction after CTR [38].

New Symptoms: Pillar Pain

Patients may relatively frequently report persistent pain in the palm, termed "pillar pain." The etiology of pillar pain is not well understood. At one time, pillar pain was thought to be related to transection of microscopic cutaneous nerves of the palm. Endoscopic CTR was thought to avoid this complication and would lead to decreased pillar pain. However, recent meta-analysis comparing outcome studies of endoscopic and open CTR showed no significant difference in risk of pillar pain [15].

Although exact etiology is unknown, some authors postulate it may be due to the biomechanical consequences of release of the TCL [40]. Presumably the transverse carpal ligament has a biomechanical function (rather than just being God's gift to hand surgeons to earn our livelihood); studies have shown its release causes changes in carpal arch stability [41]. These changes may contribute to decreased grip strength and pillar pain seen following CTR [40].

Patients with complaints of scar sensitivity or pillar pain should be counseled in scar massage and desensitization and sensory reeducation. Surgeons can consider referral to a hand therapist for additional assistance to the patient. Fortunately, symptoms generally resolve by 9–12 months postoperatively, and patients can be counseled that they can reasonably expect resolution of pain with time.

New Symptoms: Subluxation of Flexor Tendons

Subluxation of the flexor tendons is a rare complication following CTR [1, 13, 35]. The TCL is believed by some to form an important "pulley" in the flexor system, and division may lead to increased flexor excursion during wrist flexion [40]. The potential for such bowstringing of the flexor tendons could potentially be a cause for postoperative wrist flexion weakness [40].

Patients may present with painful snapping sensation and paresthesias when flexing the wrist. Clinically, there may be a visible or palpable subluxation of the tendons with wrist flexion. Some authors say this is generally well tolerated and does not require intervention [35]. If symptomatic, treatment in the chronic setting may involve repeat exploration of the carpal canal and reconstruction of the transverse ligament, usually with the use of tendon allograft [1]. To avoid this complication, the ligament should be divided along the ulnar border of the canal [1, 13], and a cuff of tissue should be left behind on the hamate to help prevent bowstringing. Some advocate temporarily immobilizing the wrist in extension postoperatively to help prevent this complication, although this is theoretical rather than practical or evidence based [13]. If this complication does occur, first-line treatment is immobilization in moderate wrist extension for 4 weeks, particularly if the condition is diagnosed shortly after index carpal tunnel release. This complication is believed to be more common among those with abnormal collagen such as those with Ehlers-Danlos syndrome.

Summary

A study by Stutz et al. found that in a series of 200 cases of revision CTR, 83% of cases of persistent or recurring symptoms could have been prevented [8]. The authors conclude that this emphasizes that CTR is not a benign procedure and should be performed by a skilled surgeon with thorough operative technique based on exact knowledge of the anatomy of the region. Furthermore, despite its reputation for simplicity and efficiency, CTR does not invariably produce good results [8]. A thorough understanding of the risks inherent to the procedure and the ability to proficiently evaluate and manage them is an indispensable trademark of the capable hand surgeon. In addition, it is crucial to describe these risks to patients preoperatively. This author counsels patients preoperatively regarding the risks associated with carpal tunnel release and describes these risks as "including but not limited to risks of anesthesia, risk of incomplete relief, risk of recurrent or residual symptoms, risk of devastating and permanent nerve or vascular injury (fortunately rare), risk of infection (rare

<1%), risk of pillar pain (common—to be expected, almost 100%), and 100% chance of a scar which rarely may be bothersome."

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Recurrent Carpal Tunnel Syndrome

15

Scott G. Edwards and Joshua W. Hustedt

Introduction

Carpal tunnel syndrome is the most common peripheral nerve compression syndrome, occurring in approximately 7 per 10,000 persons [1]. Surgical release of the transverse carpal ligament ("carpal tunnel release") usually has excellent clinical outcomes with return to function and pain reduction [2]. However, complications and failures can occur, varying from 3% to 25% of cases reported in the medical literature [3–5].

Recurrent carpal tunnel symptoms are a challenging problem that is often clinically underestimated [3]. Revision surgery for persistent symptoms is needed in 3–12% of patients [3, 6]. Unfortunately, results following revision carpal tunnel release are disappointing, with 40% of patients reporting unfavorable results and 95% of patients with residual symptoms following revision surgery [4, 6]. Herein, we review the common etiologies of recurrent carpal tunnel syndrome and present treatment options for clinical practice.

S.G. Edwards (✉)
Department of Orthopedics, University of Arizona College of Medicine-Phoenix, 320 N. 10th St., Suite A, Phoenix, AZ, USA

Center for Orthopedic Research and Education, Phoenix, AZ, USA
e-mail: scott.edwards@thecoreinstitute.com

J.W. Hustedt
Department of Orthopedics, University of Arizona College of Medicine-Phoenix, 320 N. 10th St., Suite A, Phoenix, AZ, USA

Clinical Evaluation

Any evaluation of a patient that returns complaining of persistent or recurrent carpal tunnel symptoms must include a thorough evaluation of all possible etiologies. The most common etiologies of recurrent carpal tunnel symptoms include incomplete release of the transverse carpal ligament, median nerve fibrosis, and iatrogenic nerve injury. However, the clinician must be certain to also evaluate the patient for other causes of hand pain, including other upper extremity peripheral neuropathies.

The largest clinical clues when evaluating a patient with recurrent carpal tunnel syndrome come from the time course of the patient's symptoms. Each patient can be placed into one of three groups: patients who experience persistent symptoms, patients who experience recurrent symptoms, and patients with new onset symptoms following surgical release. Persistent symptoms refer to a specific complaint that was present prior to surgery and was never relieved. Recurrent symptoms differ in that the patient did experience relief after surgery; however, the same symptoms that were present prior to release have now

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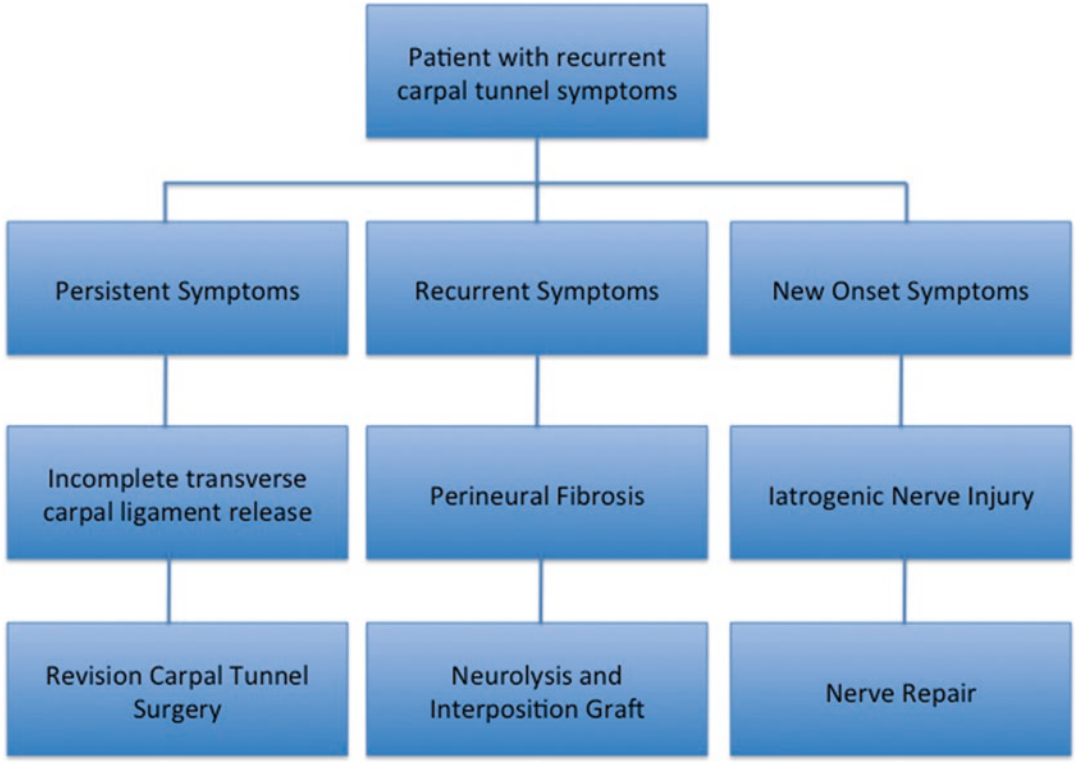

Fig. 15.1 Decision-making tree for diagnosis of recurrent carpal tunnel symptoms following carpal tunnel surgery

returned. Lastly, new symptoms refer to a unique complaint that was not present prior to surgery (Fig. 15.1) [7].

Persistent Symptoms

Persistent symptoms are most commonly caused by incomplete release of the transverse carpal ligament. A recent study analyzing 50 patients who required revision carpal tunnel release found that 58% of patients had persistent symptoms due to incomplete release. Compression occurred at the distal transverse carpal ligament in 56% of cases and at the proximal antebrachial fascia at the wrist crease in 44% of cases [3]. Endoscopic carpal tunnel release has often been cited as a risk factor for incomplete release of the transverse carpal ligament, particularly in early studies of endoscopic release [8]. However, meta-analysis data on endoscopic versus open releases find that endoscopic release is comparable to open release in regard to most complications, including the need for revision surgery and rate of persistent symptoms. The only difference is a slightly higher risk of catastrophic complications with endoscopic release, most commonly from complete transection of the median nerve [9].

Persistent symptoms may also be caused by chronic nerve injury. Relief of pain and numbness in a chronically compressed nerve may take many months to resolve even with complete surgical release. Often, exacerbating symptoms (such as nighttime pain) will be relieved with transverse carpal ligament release, but numbness will persist and gradually improve over time as the median nerve returns to full function [10]. Studies have shown that the best way to monitor gradual nerve function over time is with periodic clinical sensation assessment with Semmes-Weinstein monofilaments [11]. Careful clinical follow-up, therefore, is key in determining gradual improvement, particularly in patients with significant preoperative compression.

Persistent symptoms that fail to resolve should alert the clinician to examine other etiologies of hand and wrist pain. Even with careful history, thorough physical exam, and testing, the diagnosis of carpal tunnel syndrome in the patient with wrist and hand pain is not always straightforward. Hand pain can easily be confused with other common problems such as cervical radiculopathy, radial sensory neuritis, De Quervain's tenosynovitis, carpal-metacarpal thumb arthritis, ulnar neuropathy at the elbow, or trigger finger. Other metabolic causes for neuropathy must also be considered including diabetes, alcoholism, vitamin deficiencies, HIV, chemotherapy agents, and adverse reactions from medications. In combination with slightly abnormal but clinically inconsequential electrodiagnostic studies, these patients may be incorrectly indicated for carpal tunnel release and result in persistent symptoms after surgery.

Recurrent Symptoms

Recurrent symptoms are defined as a return of preoperative symptoms after a period of complete or partial relief following surgery. The most common cause of recurrent symptoms is the formation of excessive scar tissue surrounding the median nerve (perineural fibrosis) or postoperative edema (swelling) causing median nerve compression. The patient with recurrent symptoms will often complain of the exact same symptoms experienced preoperatively. It is, therefore, essential that clinicians document preoperative symptoms carefully, to aid in evaluation of postoperative recurrent carpal tunnel syndrome.

The time interval to recurrent symptoms can vary widely from patient to patient. In a retrospective review of recurrent carpal tunnel symptoms, the average time from the initial surgery to recurrence was 21 months but ranging from 14 days to 8 years [3]. In another study the average time to recurrence was 4.8 months, with the most common complaint consisting of numbness in the median nerve distribution [12]. While recurrent latency periods vary widely, the key to determining whether a patient has recurrent symptoms is some period of initial relief (which represents full transverse carpal ligament release), followed by return of preoperative symptoms.

New Onset Symptoms

Perhaps the most frustrating complaint following carpal tunnel release is the onset of a new symptom that was not present prior to surgical release. While the causes of new onset symptoms are numerous, the most common in the immediate onset is iatrogenic nerve injury. Patients may complain of new onset pain, trigger finger, and incisional "pillar" pain, which are largely separate issues from the original diagnosis. Worsening numbness or loss of two-point discrimination should alert the clinician to suspect iatrogenic nerve injury [13].

While rare, iatrogenic nerve injuries have been shown to occur. In revision surgeries iatrogenic nerve injury occurred in 3–6% of cases [3, 6]. Transection of the median nerve has also been documented, in one series occurring in 1 of 24 revision procedures and in another series in 2 of 200 revision procedures [6, 14]. Iatrogenic injuries can occur to the palmar cutaneous branch, recurrent motor branch, or median nerve as well as to digital nerves [10].

Diagnostic Studies

Clinical examination maneuvers, diagnostic studies, and diagnostic injections are all options in evaluating a patient with recurrent carpal tunnel syndrome. These studies are particularly valuable when preoperative studies are available for comparison. Provocative maneuvers, such as Phalen's and Durkan's tests and Tinel's sign, are useful in eliciting compression in the carpal tunnel, especially when compared to the contralateral side and to preoperative assessments. Studies have shown that up to 50% of patients with recurrent carpal tunnel syndrome will have positive Phalen's and Tinel's tests, as well as experience loss in grip strength and limitations in performing fine motor tasks [15, 16]. In addition to provocative exams, diagnostic steroid injections have been shown to be helpful isolating pathology to the carpal tunnel.

Table 15.1 Clinical recommendations based on electromyographic findings following carpal tunnel release

EMG findings after surgical release	Clinical recommendation
Improvement	Monitor clinically
Worsening	Iatrogenic nerve injury: surgical exploration
Same	Consider other etiologies/ confirm diagnosis with additional diagnostic studies

In one study examining patients with recurrent carpal tunnel syndrome, positive Durkan's and Phalen's tests in the presence of relief of symptoms from corticosteroid injection combined to provide a clinical diagnosis of median nerve compression with a sensitivity of 100% and a specificity of 80% [16].

Electrodiagnostic (EMG) studies can also be helpful in determining the etiology of recurrent symptoms, particularly when preoperative studies are available for comparison [3]. EMG studies are particularly helpful when showing either clinical improvement or worsening (Table 15.1). If EMG findings are improved after surgical release, clinicians may monitor for clinical improvement over time. If EMG findings are worsened after surgery, clinicians should suspect iatrogenic nerve injury or exuberant postoperative perineural fibrosis. Equivocal EMG findings are more difficult to interpret and should lead clinicians to examine for other sites of compression or attempt a diagnostic intra-carpal tunnel steroid injection. In addition, imaging studies, particularly MRI, may be helpful to rule out other causes of compression within the carpal tunnel such as overly abundant tenosynovitis, fibrosis, or any space-occupying mass. MRI does not, however, reliably exclude incomplete release of the transverse carpal ligament [17].

Revision Carpal Tunnel Surgery

Revision carpal tunnel surgery can be difficult due to excessive scar formation and perineural fibrosis distorting normal anatomy and surgical planes. Therefore, it has been recommended that the incision for revision surgery be made ulnar to the prior incision, as the median nerve may be adherent to the underside of the previous incision and is at risk during the initial dissection. In our experience, however, the median nerve usually resides away from the original incision and remains adherent underneath the radial leaflet of the incised transverse carpal ligament in close proximity to the tendon of the flexor pollicis longus. Certain authors also advocate for the extension of the incision, either proximal or distal, to access native tissue planes and identify the median nerve prior to surgical exploration in the prior surgical field [10]. This technique offers significant advantages in the setting of significant perineural fibrosis.

Revision for Persistent Symptoms

Patients who experience persistent carpal tunnel symptoms are often treated for incomplete release of the transverse carpal ligament. Revision surgery in this case is utilized to identify any existent transverse fibers, which are transected. The most common site of persistent transverse fibers is at the distal end of the carpal tunnel. We recommend proceeding distally with the dissection until the perivascular fat of the superficial arch is encountered. The second most common site of compression is proximal transverse fibers near the wrist crease or antebrachial fascia at the wrist [3, 6]. Additionally, proximal sites of compression can also occur including compression by the pronator teres and the flexor digitorum superficialis muscles. Both of these muscles may have a fibrous band or edge compressing the nerve [7].

Revision Carpal Tunnel Release for Recurrent Symptoms

Patients who experience recurrent carpal tunnel symptoms are often treated for perineural fibrosis of the median nerve. The treatment of perineural fibrosis consists of both removal of scar tissue (neurolysis) and interposition grafting with either autograft or allograft to prevent future postoperative scar formation. Some authors have advocated

an internal neurolysis for all recurrent carpal tunnel syndromes [7]. This involves opening the epineurium using microsurgical techniques until normal perineurium is exposed. Care must be taken to protect the perineurium to preserve the blood-nerve barrier. Although shown to be of no benefit in routine primary carpal tunnel surgery, it has yet to be studied thoroughly in the revision setting, but many authors advocate its benefits anecdotally [7]. Regardless of technique, the fibrosis surrounding the median nerve needs to be carefully dissected away from the epineurium to prevent future proliferation of fibrosis against the nerve and consequent recurrent compression.

Perineural fibrosis is inevitable after carpal tunnel surgery and little can be done to prevent its formation. The clinical consequences of this fibrosis, however, are variable and can be modulated [18]. Since we cannot stop perineural fibrosis from forming, the focus should be on protecting the nerve from its contractile effects if perineural fibrosis has proven to be a problem in the past. Interposition grafting has been recommended to "insulate" the nerve from inevitable scar tissue formation in the setting of revision surgery where perineural fibrosis has been proven to be an issue [19]. Both non-vascularized and vascularized flaps are available for interposition grafts. The choice of which surgical technique to use is largely dictated by the surrounding soft tissue bed and the appearance of the nerve. The treatment should be aimed at logically addressing the underlying pathology. When the nerve appears well perfused and fibrosis is the main culprit, then a vascularized flap may not be necessary. However, if there are dysvascular areas surrounding the nerve, then a vascularized flap may be preferred.

Autologous non-vascularized interposition grafts may include dermal fat grafts from the abdomen [20], hypothenar fat grafts (not to be confused with hypothenar fat flaps) [21], synovial grafts [22], and saphenous vein grafts [23]. Autograft saphenous vein wrapping of the median nerve has been shown to effectively prevent neural fibrosis while improving neovascularization [24, 25]. Clinical outcomes after autologous vein grafting have been good with patient satisfaction of 98%, two-point discrimination improvement in 80%, and signs of improvement on EMG testing [21]. Allograft saphenous or umbilical veins may be used, and in our experience, perform as well as autografts without the donor morbidity and prolonged operative time. Studies have shown, however, that allograft vein wraps do not promote the same epineural neovascularity as seen in autografts [26]. The clinical significance of this, however, remains unclear.

Similar to vein wrapping, bovine xenograft collagen conduit nerve wraps have also been shown to have similarly improved clinical outcomes [27]. The advantages of collagen wraps are that they appear to have all the mechanical barrier protection and physiologic incorporation of autograft veins, without the donor morbidity and prolonged operative time [28, 29]. The obvious disadvantage of these xenograft collagen wraps is their costs. Bovine collagen wraps are well established and most extensively studied, but porcine small intestine submucosa (SIS) recently has been modified for this purpose and reported to have advantages of added modulating factors to promote nerve health [30]. SIS has been criticized for inciting unacceptable inflammation for other indications such as in rotator cuff and cardiac surgery [31, 32]. But recent refinements in SIS processing may have solved this problem, but to date this claim has not been validated clinically [33].

Another option for interposition grafting is a vascularized graft. The proposed advantages of the vascularized flaps include promotion of neovascularization of the epineurium and reduction of resorption and host rejection. Several vascularized flaps have been described for the purposes of carpal tunnel revision surgery including the hypothenar fat flap [34], flexor synovium flap [35], abductor digiti minimi flap [36], palmaris brevis flap [37], lumbrical flap [38], flexor digitorum superficialis flap [21], pronator quadratus flap [39], and vascularized free flaps [27]. Perineural fibrosis causing compression distally may best be addressed with flaps from the abductor digiti minimi, palmaris brevis, or lumbrical muscles.

The most popular vascularized interposition graft is the hypothenar fat flap, largely due to the fact that the most common location for postoperative fibrosis occurs in the central portion of the carpal tunnel adjacent to this flap. The flap is based on an ulnar artery pedicle and is brought into final position between the median nerve and the radial remnant transverse carpal ligament. The flap is harvested through the same surgical incision as the index surgery, though slightly extended, is technically simple, and does not sacrifice any hand function (as opposed to the muscle-based flaps) [40]. Clinical outcomes of hypothenar fat flaps have been excellent, with 88–95% of patients reporting satisfaction with the procedure [34, 41]. If perineural fibrosis is most evident in the proximal portion of the carpal tunnel and the hypothenar fat flap may not have adequate coverage, a flap from the flexor superficialis or pronator quadratus muscle may be used. The flexor superficialis muscle is easy to identify since its belly extends distally on its tendon further than any other muscle from the forearm. After identifying the muscle belly that extends the furthest distally, elevate a 4 cm slip of the muscle belly from the proximal portion of the tendon, and rotate it distally based on its remaining intact myotendinous junction. It is important to identify the epitendinous perforating vessel supplying the flap. Sparing this vessel at the myotendinous junction limits the dissection distally. The muscle pedicle is draped over the nerve and secured radially and ulnarly with absorbable suture [21].

Iatrogenic Nerve Injury

When iatrogenic nerve injury is suspected, there is almost always an indication to return to the operating room for operative exploration. While short periods of observation may be warranted in certain situations, no improvement after 3 months, especially with worsening electromyography findings, is an indication for surgical exploration. Surgical exploration requires little additional morbidity, while offering significant benefits to long-term function [10]. When a nerve injury is encountered, treatment options include primary repair, artificial neural tube grafting, or interposition graft with autograft harvested from the medial antebrachial cutaneous nerve or sural nerve (utilized for larger grafts) [7, 42].

Outcomes

The results of revision carpal tunnel surgery vary widely, with some patients reporting improvement, but with 41–90% of patients reporting at least some residual symptoms [11]. Clinical decision-making for the hand surgeon is made difficult by the lack of good comparative outcomes data. Most data on recurrent carpal tunnel surgery involves small series of patients with poor or no controls and inconsistent outcomes metrics [43].

Authors have attempted to examine variables associated with outcomes of revision carpal tunnel surgery. Studies examining reasons for poorer outcomes have identified worker's compensation patients, higher preoperative pain scores, use of preoperative pain medication, and normal preoperative EMG results to portend a negative result after revision surgery [11, 44]. Studies examining variables that increase success have found initial surgical approaches with short or transverse incisions (leading to higher rates of incomplete transverse carpal ligament release), activity-related symptoms (only exacerbating symptoms present), positive Phalen's sign, and nocturnal symptoms are all signs of a good prognosis with revision surgery [11]. These guidelines, however, may be too narrow for our broad patient population, and systematic strategies, such as the ones previously described, may be more clinically relevant.

Ultimately, the expected benefit of revision surgery is based on the etiology of the underlying nerve compression. Patients with persistent carpal tunnel symptoms due to incomplete transverse carpal ligament release should expect to have similar successful results as patients undergoing primary carpal tunnel release. Patients, however, that have recurrent carpal tunnel syndrome due to perineural fibrosis may have worse outcomes. While there has yet to be a prospective study to identify the most effective treatment for

recurrent carpal tunnel symptoms, there is a preference in the literature for revision surgery with hypothenar fat pad interposition grafting [4, 6].

Summary

The patient with recurrent carpal tunnel symptoms provides a difficult clinical scenario for the hand surgeon. It is crucial that a proper diagnosis be obtained to determine the underlying etiology of the recurrent symptoms. The timing of the presentation of the symptoms is often the most valuable clue in the diagnostic process. Patients with new onset symptoms should lead to a suspicion of iatrogenic nerve injury. Patients with persistent symptoms should be evaluated for incomplete transverse carpal ligament release and other causes for upper extremity neuropathy. Finally, patients with recurrent symptoms should be evaluated and treated for perineural fibrosis. Ultimately, the etiology of the recurrent symptoms needs to be correctly identified and then proper surgical management can be undertaken.

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Revision Carpal Tunnel Surgery Options

16

Yaron Sela, Loukia K. Papatheodorou, Lindsay Hess, Dean G. Sotereanos, and Mark E. Baratz

Key Points

- In evaluating a patient for revision carpal tunnel surgery, it is important to document whether the symptoms are persistent, recurrent, or acutely worse after the CTR.
- If numbness is worse, two-point discrimination and Semmes-Weinstein testing can help define the distribution and severity of sensory dysfunction.
- Persistent carpal tunnel syndrome may result from an incomplete release but is more commonly the result of chronic compression in compromised host, e.g., diabetic, elderly, and heavy smoker.
- Recurrent CTS is rare but is characterized by a symptom-free interval.

Y. Sela • L. Hess • M.E. Baratz (✉)
Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, 2000 Oxford Drive, Bethel Park, 15102, Suite 510, Pittsburgh, PA 15102, USA
e-mail: mebaratz@gmail.com

L.K. Papatheodorou • D.G. Sotereanos
Department of Orthopaedic Surgery, University of Pittsburgh School of Medicine, Orthopaedic Specialists - UPMC, 9104 Babcock Blvd, 5th Floor, Pittsburgh, PA 15237, USA
e-mail: papatheodoroulk@upmc.edu; dsoterea@hotmail.com

Introduction

Carpal tunnel syndrome (CTS) is the most frequent compressive neuropathy in the upper extremity, with an incidence of 1–3 cases per 1000 patients per year [1]. The prevalence is 2.7% based on symptoms, clinical signs, and neurophysiology [2]. Carpal tunnel release (CTR) is the most common surgical procedure performed on the hand, and, fortunately, adverse sequelae are uncommon [3]. Decompression can be performed via open, mini-open, or endoscopic techniques with excellent success rates. Although most patients are satisfied with their result and have complete resolution of their symptoms, there are a certain percentage of individuals who have either recurrent or persistent symptoms. Traditionally, persistent symptoms have been attributed to an incompletely released transverse carpal ligament (TCL). It is our experience that persistent symptoms are more commonly the result of chronic compression in compromised host (e.g., diabetic, elderly, obese with thyroid gland disorders) [4]. Other causes for recurrent CTS are incorrect diagnosis, neuroma of a superficial nerve in the area (palmar cutaneous nerve), fibrous proliferation, recurrent tenosynovitis, and permanent nerve injury prior to surgery [5–8].

Recurrent CTS occurs in up to 19% of patients following CTR, with 12% requiring re-exploration [5]. Recurrence of symptoms is thought to be the

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result of progressive scar formation around the median nerve [9, 10]. Incomplete release of the TCL is cited as a cause of recurrence [3, 11, 12]; however, in our experience, the ligament quickly reconstitutes itself, and it is difficult to define "incomplete release." There are reports of a higher recurrence rates and poorer outcomes in patients with occupation-related CTS [5] and in patients who are involved in workers' compensation claims [9, 13].

Revision median nerve decompression alone or with neurolysis does not always result in sufficient relief of symptoms [14, 15]. Therefore, many different surgical techniques for coverage or wrapping of the median nerve have been proposed and reported in the literature for this recalcitrant condition. The goal of revision surgery for recurrent CTS is to decompress the nerve, prevent recurrent scar formation, and promote nerve recovery.

Various flaps have been used to cover the nerve including free omentum [16], subcutaneous tissue [14], hypothenar fat pad, synovial flap, abductor digiti minimi flap [14], pronator quadratus flap [17], pedicled reverse radial forearm flap [18], and vein wrapping [19, 20]. Some are technically demanding and use tissue that may be too small or poorly positioned to adequately cover the median nerve. Most published series are small, making it difficult to draw conclusions about the best technique.

Evaluation

Clinical Indicators for Failed CTR

Failed CTR manifests with either persistent symptoms or worsening symptoms. Persistent symptoms are common in the elderly and in patients with medical comorbidities, such as diabetes. Increased numbness after CTR should be cause for concern because it may reflect nerve injury. During revision surgery of the median nerve, iatrogenic injury was noted to have occurred in 3–6% of cases [3, 10]. These injuries can be due to lacerations of the palmar cutaneous branch, the median nerve proper, the recurrent motor branch, or one of the common digital nerves. Treatment is guided by the history and exam to a greater extent than imaging and nerve studies [21].

Clinical Indicators for Recurrent Symptoms

Initial improvement of preoperative symptoms suggests complete release of the TCL. In a retrospective review of 18 wrists in 17 patients with recurrent CTS, the average time between initial relief after the procedure and the presentation of recurrent symptoms was 21 months, with a range of 7 months to 8 years [3]. Table 16.1 summarizes the evaluation of recurrent CTS versus failed CTS with persistent or worsened symptoms.

The patient returning to the clinic after CTR complaining of symptoms consistent with median nerve compression can be difficult to assess. The patient's perception of symptoms preoperatively and postoperatively can be vague and inconsistent. A thorough history must be taken to evaluate for any new or undiagnosed disorders, such as hyperthyroidism, hypertension, or diabetes [22]. In a retrospective review of 2357 patients treated with CTR, 48 patients required secondary surgery for recurrent symptoms, and among these patients, hypertension and diabetes were found to be significantly associated with carpal tunnel recurrence [23]. It is important to delineate what the patient's symptoms were before the primary CTR. The most common presenting symptom in primary CTS is intermittent impaired sensation in the median nerve distribution. Pains in the hand and wrist are the next most common symptoms, with nighttime paresthesias and weakness as other common complaints [24].

In those cases in which patients return for their first postoperative visit and report that they are "not any better," specific questioning as to which symptoms persist is crucial to identifying the cause and treatment for these persistent symptoms. Many will report that they still have numbness, but their night pain and dysesthesias have resolved. This suggests complete release of the ligament and no immediate intervention is

Table 16.1 Evaluation of recurrent versus failed (persistent or worsened) CTS

	Symptoms	Examination	Etiology	Treatment options
Recurrent CTS	Numbness completely resolved then recurs	Findings range from normal to (+) Tinel's, Phalen's, carpal compression test, or expanded two-point discrimination	Most common: no obvious abnormality other that adjacent, compressive scar. Other reasons: tenosynovitis, masses, incomplete release	• Revision CTR • Neurolysis • Interposition graft • Synovial flap • Muscle flap • Hypothenar • Fat pad flap • Vein wrap
Failed (persistent) CTS	Symptoms persist	Key finding: normal or unchanged two-point discrimination	Advanced age, diabetes, intrinsic nerve disease, concurrent compression, e.g., cervical, radiculopathy, incomplete release of TCL	• Observation if symptoms reoccurred to advanced age patients or medical comorbidities • Revision CTR for incomplete release of TCL
Failed (worsened) CTS	Noticed by the patient in the immediate postoperative period	Tinel's over incision. Expanded or absent two-point discrimination	Suspected nerve injury	• Neurolysis • Nerve repair • Interposition • Graft

CTR carpal tunnel release, *TCL* transverse carpal ligament

necessary. With observation, this numbness will continue to improve in most patients. It is helpful to perform Semmes-Weinstein or two-point discrimination testing at this point as this can be a sensitive method to monitor progressive nerve recovery [25].

It is important to distinguish persistent or recurrent pain from persistent or recurrent numbness. There are many reasons for these symptoms, including arthritis in adjacent joints and scar-related pain. An increase in numbness suggests nerve compromise. It is helpful to ask the patient whether the main complaint before the operation was numbness or pain. Nerve decompression for numbness is predictable, decompression for pain is not. Preoperative nerve studies and the operative report can help define the original problem and the extent of the surgical release. The incision should be inspected and a Tinel's sign test performed proximal to, along, and distal to the scar from the release. Worsened or absent Semmes-Weinstein monofilament or two-point discrimination as compared to preoperative measurement is consistent with intraoperative nerve injury. Objective measures, such as grip strength or sensory testing, should be used when possible to quantify deficits in the affected hand. Provocative maneuvers, such as Phalen's test, and carpal tunnel compression test can be performed and compared with the contralateral side and with any preoperative findings.

The use of cortisone injections has been advocated in the diagnosis of recurrent CTS. In a retrospective series of 28 wrists in 23 patients, Beck et al. [26] studied whether the result of cortisone injection predicted the outcome of revision CTR. Of the 23 wrists that had relief from injection, 20 had symptom improvement with surgery. The sensitivity and positive predictive value for injection alone predicted outcome of revision CTR in 87%. The results of injection as a predictor of successful revision CTR showed a positive trend, although they did not achieve statistical significance. The authors concluded that relief from injection as a diagnostic test for predicting successful revision CTR was found to have both a high sensitivity and a positive predictive value. Coupled with the components of the physical examination, injection seems to provide a good screening test to establish surgical success with revision CTR. The specificity of the test was lower, at 40%.

Even with careful preoperative evaluation and precise surgical release, revision CTR remains less successful than primary CTR [5]. Consequently, the treating surgeon must combine a thorough history, diligent examination, and information from adjunct tests to estimate the likelihood of success with revision CTR.

The Role of Diagnostic Tools

Supportive accessory studies take a secondary role in the management of failed or recurrent CTS. Nerve conduction studies (NCS) with electromyography (EMG) can help support a diagnosis though should not be relied on to determine the diagnosis. Electrodiagnostic studies are not always helpful in diagnosing recurrent CTS because electrical changes can persist even after successful releases [27, 28]. The use of these studies in the context of recurrent CTS can be useful if the patient had preoperative studies done. If the repeated NCS are worse or show signs of denervation of the thenar muscles, surgery may be indicated [3]. Unfortunately, worsened electrical studies don't predict the success of revision surgery [24].

Magnetic resonance imaging (MRI) can reveal extrinsic compression from a mass or bony excrescence. Stutz and colleagues [10] reported on 4 cases, out of 200 revision CTR surgeries, where a mass was found in the carpal tunnel (2 ganglions, 1 lipoma, and 1 fibroma). In our opinion, MRI is not accurate enough for diagnosis of recurrent compression or nerve injury. The AAOS guidelines recommend against the use of MRI in the routine evaluation of patients with CTS.

In a retrospective study of 34 patients who presented with CTS and underwent CTR, Karabay et al. [29] assessed the usefulness of ultrasonography for determining the potential causes of ongoing symptoms following CTR. An abnormal finding was detected by ultrasonography in 25 (74.5%) patients. The most common pathological findings were median nerve swelling (70.6%), incomplete transection of the TCL (23.5%), and perineural fibrosis (17.6%). The authors concluded that in the majority of the patients, the pathology related to the ongoing symptoms was detected by ultrasonography, suggesting that ultrasonography could be used as a complementary imaging method for identifying the causes of failure following CTR.

In a prospective study of 36 patients, Karabay et al. [30] sonographically evaluated the anatomy of the TCL after open CTR, in order to establish new ultrasonographic criteria for the completeness of TCL release. Patients were evaluated with physical examination and ultrasonography before and after the operation. All patients' symptoms resolved after surgery. TCL was found to be diffusely thickened and to have lost its smooth form after surgery. Postoperative TCL thickness showed a statistically significant increase when compared with preoperative values ($p < 0.05$). The authors concluded that sonography is a capable imaging method for assessment of the TCL after open CTR. In addition, ultrasound may be considered as a complementary tool to exclude diagnosis of incomplete transection of TCL in patients with persistent symptoms.

High-definition ultrasound has improved in its ability to delineate peripheral nerves and the surrounding tissues. It has been increasingly used to localize the anatomical causes of nerve compression in patients with persistent or recurrent CTS [31].

Nonoperative Care

In most cases of recurrent CTS, conservative measures will not provide adequate relief [32]. Scar modification, splinting, and other exercises to promote nerve and tendon glide can be instituted. Nonoperative treatment of recurrent CTS may provide symptomatic relief for a small number of patients but fail to benefit most patients in the long term, as reported by Strickland et al. [33]. Given our limited ability to control scar formation, revision decompression and neurolysis of the median nerve for treatment of perineural fibrosis are frequently disappointing [14, 15]. Wadstroem et al. evaluated the causes of unsatisfactory results after surgery for carpal tunnel syndrome in a retrospective analysis of 40

patients. Their most common pathological finding was fibrosis and adhesions in the carpal canal. In 30% of patients, other neuropathies were present, and bilateral operations had been performed in 55%. We offer revision surgery to patients with worsening numbness immediately after their first operation, patients with recurrent numbness after a previously successful operation, and a select subgroup of patients with persistent numbness after surgery.

Re-operative Strategies

Principles of Revision Nerve Surgery

We use nerve autograft for complete or partial nerve lacerations that cannot be sutured together without tension. Our choice of nerve graft includes medial antebrachial cutaneous (MABC) nerve and sural nerve. Before surgery, be sure to obtain consent to harvest nerve graft or to use a nerve conduit. Loupe magnification or a dissecting microscope is advocated.

The incision is planned so that it extends into normal tissue at least 2 cm on either end. The median nerve is recognized in the distal forearm straight beneath the palmaris longus tendon. The nerve is traced toward the carpal canal working on the anterior, ulnar margin of the nerve. As the scarred region comes nearer, care is taken to recognize the plane between the nerve and the scar. The existence of perineural fat forms a natural plane except in those occasions when the nerve has been lacerated. If you lose the plane between nerve and scar, proceed with the dissection distal to the carpal tunnel starting in normal tissue. Start on the anterior margin of the third common digital nerve and trace that nerve to the anterior, ulnar margin of the median nerve proper. When there is no clear plane between the nerve and scar, you can infer the line of dissection from the distal and proximal anterior, ulnar margins of the nerve. Dissect just ulnar to this line keeping a cuff of synovial tissue on the nerve. Once the nerve is released from scar, check the nerve for signs of injury such as disruption of fascicles or proximal neuroma (Fig. 16.3a). Identify the motor branch and common digital nerve. Adequate exposure of the median nerve and carpal tunnel is required. The revision CTR begins by extending the previous incision into normal tissue to allow proximal or distal identification of the median nerve to first facilitate exploration.

Dissection of the median nerve from proximal to distal should be performed along the ulnar border of the nerve to avoid damage to the motor branch. If dense scar is encountered during the proximal to distal dissection, stop and find the nerve in normal tissue distal to the densely scarred area. Alternate the exposure from proximal to distal and then distal to proximal until the nerve has been safely mobilized.

Repeat Simple Decompression

Unfortunately, given our limited ability to control scar formation, revision decompression and neurolysis of the median nerve for treatment of perineural fibrosis frequently yield unsatisfactory results [14, 15].

In patients with a significant interval between primary CTR and recurrent symptoms, Mosier et al. [22] treated recurrence of symptoms with simple repeat CTR. They define a “significant interval” as more than 1 year with resolution of carpal tunnel symptoms during this time. Beck et al. [26] demonstrated good relief with repeat decompression at many time intervals.

Revision Decompression with Interposition of Local or Remote Flaps

Interposition of a biologic barrier between the nerve and surrounding tissues may discourage scarring and provide a nutrient bed for axonal regeneration [34]. The advantage of local flaps like the ADQ, pronator quadratus, hypothenar fat flap [35], and palmaris brevis muscle flap [36, 37] is the ease with which they can be used. Unfortunately, length limitations may restrict their utility. Our preference is to use a hypothenar fat flap when possible (Fig. 16.1). After simpler techniques have

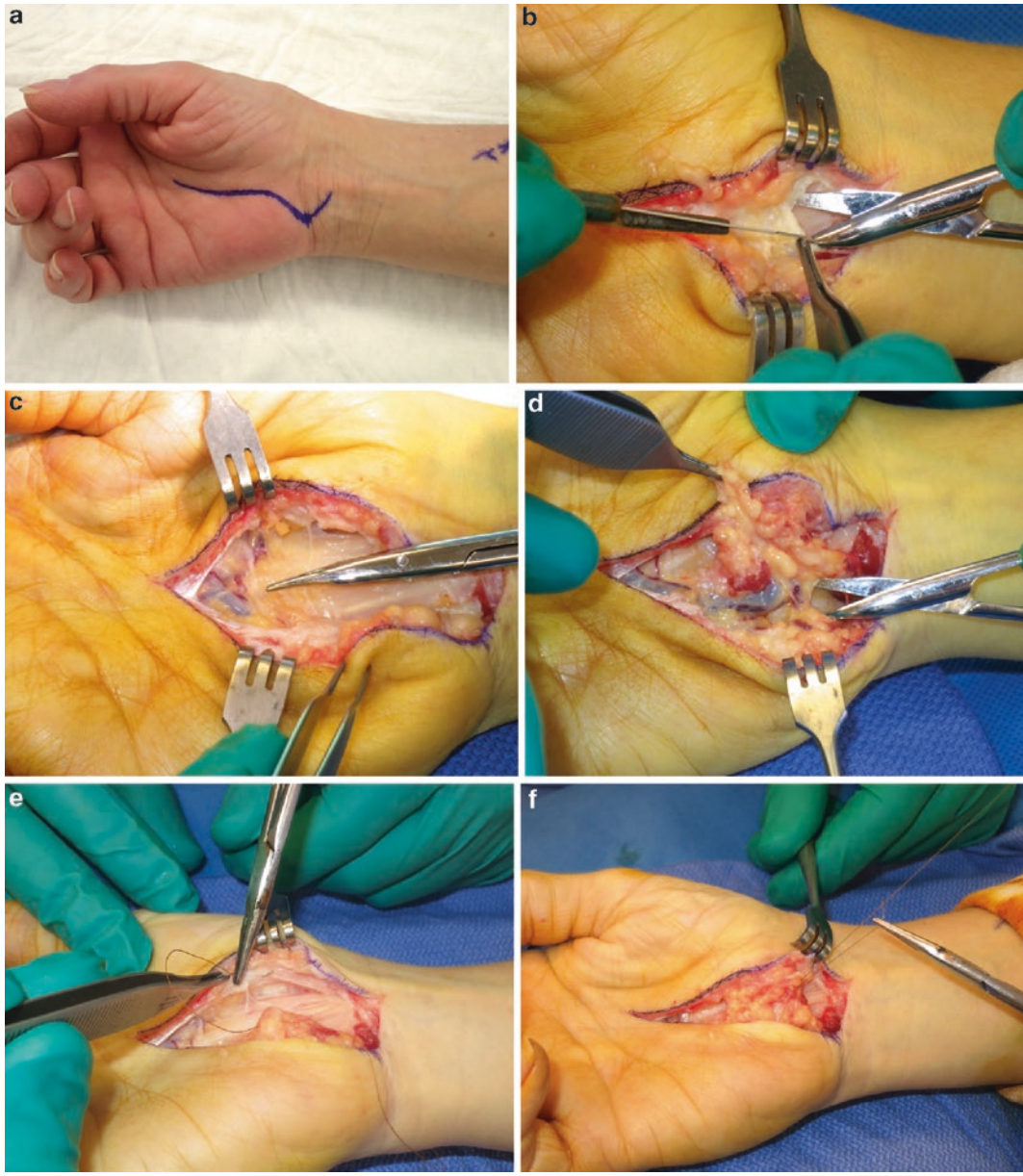

Fig. 16.1 Hypothenar fat pad flap. This patient had failed CTR and presented with a very sensitive median nerve. The hypothenar fat was mobilized to cover the scarred median nerve. (**a**) Extended approach. (**b**) Nerve exposure along the ulnar margin of the median nerve. (**c**) Identification of the superficial palmar arch. (**d**) Mobilization of fat flap. (**e**) Secure flap underneath TCL and suturing it to the radial leaflet of TCL. (**f**) Inset flap

been ruled out as options, it may be necessary to employ more complex free tissue transfers [12].

When the surgeon feels that the local tissue environment is fibrotic and/or avascular, several procedures may be performed to help protect the nerve from recurrent scarring, including autologous and synthetic nerve wraps and vascularized soft tissue coverage. Other factors to consider are also ease by which the tissue can be obtained and the comorbidities associated with its harvest. There are generally two categories of these procedures, as explained by Abzug et al. [38]:

1. Flaps that provide neovascularization, such as hypothenar fat pad flaps and synovial flaps, can help to improve nerve regeneration and gliding
2. Interposition materials, such as vein grafts and synthetic implants, help prevent scar formation by providing a mechanical barrier

Vascularized Flaps

Hypothenar Fat Pad Flap

The hypothenar fat pad flap interposes adipose tissue from the hypothenar eminence between the median nerve, the remnant of the TCL and surrounding scar. First described by Cramer [35] and refined by Strickland et al. [33], the hypothenar eminence includes a generous layer of adipose tissue of sufficient width and thickness to provide coverage for the median nerve within the carpal canal. Dissections of the hypothenar fat pad have demonstrated arterial branches to the fat pad arising from the medial side of the ulnar artery in Guyon's canal and more distally from branches of the ulnar artery to the small finger and fourth web space. These transverse and somewhat tortuous branches occurr approximately every 1 cm beginning at the distal wrist flexion crease. Additional arterial branches to the fat pad arise from arterial branches to the hypothenar muscles and palmaris brevis muscles [33].

Once sufficient mobilization of the fat pad has been accomplished, it is transposed over the median nerve and sutured to the undersurface of the radial leaflet of the TCL [33] (see Fig. 16.1).

In a retrospective series of 58 patients with 62 hands, Strickland et al. [33] showed excellent results in relieving recurrent symptoms with use of the hypothenar fat pad flap at an average follow-up of 33 months, with 37 of the 43 patients returning to their pre-surgery employment. Subjectively, the vast majority of patients had improvement of proximally referred pain, hypersensitivity, and nocturnal symptoms. There was also significant improvement in the Phalen's and Tinel's signs, and relief of dysesthesia and paresthesia was seen in 89% of patients. This relief was not immediate and in some cases took as long as 2.5 years to achieve. Two-point discrimination remained normal in 35 patients, improved from an expanded range to normal (<6 mm) in 21 patients, and remained expanded in 5 patients.

In a retrospective study of 28 patients, Craft et al. [34] showed significant improvement in the average two-point discrimination tests, the grip tests, and in the number of cases with positive Tinel's sign. Pain resolved in 83% of patients and numbness resolved in 42% of patients. The subjective complaint of "tingling" disappeared in 50% of patients.

Fusetti et al. reported on 20 patients who were treated with a hypothenar fat pad flap. Sixteen patients had adherence of the median nerve to the radial leaf of the divided TCL. The remaining four patients had an unidentifiable plane between the epineurium and the remains of the TCL. Subjectively, 18 of the 20 patients had complete resolution of their hyperesthesia and allodynia by 6 months after surgery. One patient had no improvement and would not recommend the procedure, while the remaining 19 patients stated that they would recommend the procedure. Seventeen of the 20 patients had resolution of provocative signs, including Phalen's, Durkan's, and Tinel's. Seven of the nine workers' compensation patients returned to work [39].

Wichelhaus et al. [40] conducted a retrospective study of 18 patients with recurrent CTS due to fibrotic adhesions of the median nerve, with scar formation of 3 to 5 cm in length. The hypothenar fat pad flap was used in all the cases, as it covered the entire length of the scarred nerve. Pain disappeared after the surgery in 14 patients, and the Tinel's sign disappeared in 16 patients. Hand function, grip strength, and pinch strength improved in all patients, as well as two-point discrimination recorded from the fingertips. Fifteen of the 18 patients would elect to have the operation done again if necessary. None of the patients reported hypothenar pain, none deteriorated after surgery, and all of the patients reported complete resolution of nighttime symptoms.

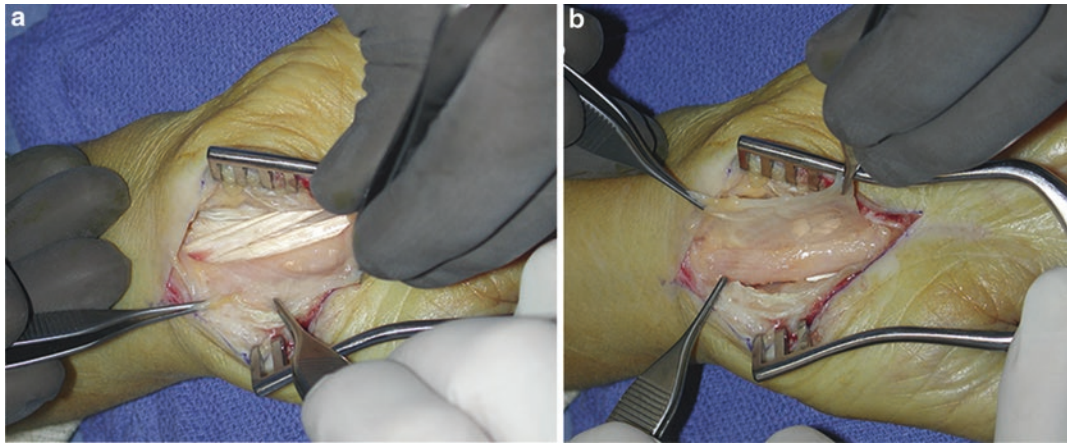

Fig. 16.2 (**a**) Synovial flap being elevated off of the FDS tendons. (**b**) Synovial flap before interposition placement on the median nerve

Synovial Flap

A vascularized synovial flap can be used to supply interposition and neovascularization to a scarred median nerve. This technique has the advantage of being able to be performed over the same incision without the requirement for expanded additional dissection. The synovial flap, raised off of the superficial flexor tendons deep to the median nerve, is a barrier to scar formation. The surgical technique is described in Figs. 16.2 and 16.3.

To make a synovial flap, raise a flap of synovium from the superficial flexors starting on the ulnar aspect of the carpal canal (Fig. 16.3b). Continue raising the flap from the level of the superficial arch to the wrist crease. At the proximal and distal margins of the flap, cut transversely to allow the flap to be mobilized. Continue to raise the flap to the margin of the median nerve (Fig. 16.3c). The flap is then draped over the nerve and sewn to the inner surface of the radial remnant of the TCL (Fig. 16.3d). The wrist is immobilized for 10 to 14 days post-surgery. If there is an associated nerve injury that was repaired or grafted during the procedure, the wrist is immobilized for 4 weeks. Splints and casts are kept low in the palm to permit full and prompt finger motion. Scars are treated with massage and elastomer.

In a retrospective series of 36 hands in 20 patients, Gannon et al. [21] demonstrated good results in relieving recurrent symptoms with use of the synovial flap. During the course of 6 years, eight patients had complete relief of their symptoms, ten had partial relief, and two had no improvement in symptoms. The average age of patients who had full relief was 53.5 years, in comparison with 61.8 years for patients with partial relief and an average age of 61.5 years for patients with no improvement.

Stutz et al. [28] compared clinical outcomes and electrophysiologic results of the hypothenar fat pad flap to the synovial flap, and the hypothenar flap appeared to produce superior clinical results, although statistical significance was not achieved.

Vascularized Fascial Flap

Indications for this procedure include recurrent CTS with soft tissue deficiency. The physical exam should include Allen's test and, if needed, an arteriogram test. Another important preoperative test is the NCS/EMG.

The operating room setup includes upper extremity nerve block, or other suitable anesthesia, hand table, tourniquet, and loupe or microscope magnification. The incision planning includes identification of the course of radial artery by landmarks or handheld Doppler. It is important to template the expected fascial flap

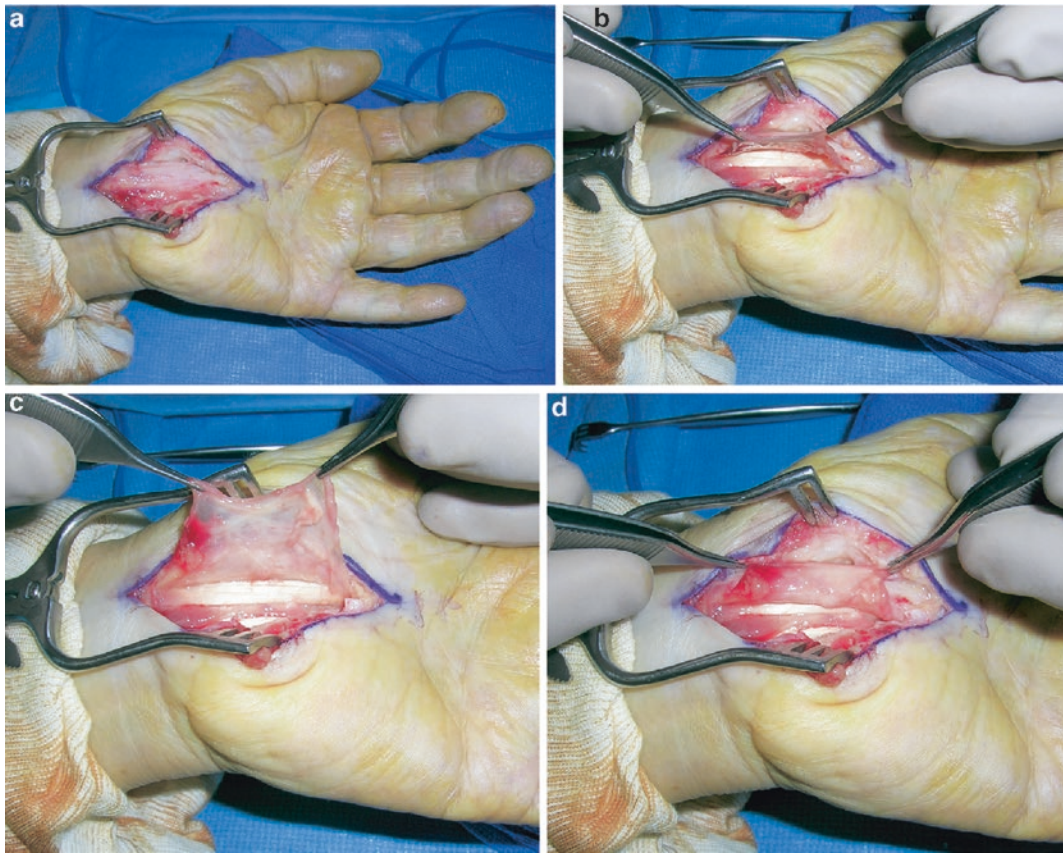

Fig. 16.3 Synovial flap technique. (**a**) Median nerve re-released. The dissection was extended approximately 2 cm on either end of the original incision into normal tissue. (**b**) The synovial flap raised from ulnar to radial side off the superficial flexors. (**c**) The synovial flap raised to the level of the median nerve. The distal border is at the level of the superficial arch. The proximal border is at the level of the wrist crease. (**d**) The synovial flap wrapped loosely about the median nerve

length in order to transpose it over the course of the radial artery. It is beneficial to overestimate pedicle length with an expected pivot point at the radial styloid. Diagram the planned incision as an extended open CTR with a Brunner-type incision across the wrist crease with proximal extension over the radial artery. A skin flap of subcutaneous tissue is raised as a single layer. Mark the underlying fascia with the outline of the previously designed template with surgical marking pen. The neurolysis involves exposing the median nerve at the carpal tunnel with neurolysis of the scarred nerve. The fascial flap is elevated by incising the fascia at the proximal and distal margins of fascia, identifying the radial artery at both margins, and confirming location deep to flap. Incise the remaining fascial flap along the margins of the underlying muscle.

Reverse Radial Artery Fascial Flap (Distally Based Radial Forearm Flap)

Tham et al. [41] defined making use of a reverse radial artery fascial flap to cover the whole length of scarred median nerve. It is critical to perform an Allen's test to guarantee patency of the ulnar artery. Following median nerve neurolysis, the incision is lengthened to the proximal third of the forearm using a point that is 4 cm proximal to the radial styloid as the expected pivot point. This incision will allow a

fascial flap measuring 4 cm wide and 5 cm long to be harvested. Dissection is carried down just superficial to the antebrachial fascia. The fascia is then incised at its periphery and elevated superficial to the epimysium of the forearm muscles while protecting the vascular connections to the radial vessels. The radial artery and its vena comitans are divided proximally to allow sufficient mobilization of the fascial flap. The fascial flap is then turned distally, passed deep to the flexor carpi radialis, and wrapped around the median nerve with the gliding surface of the flap in contact with the nerve. It is important to have a tension-free flap transposition. Suture is utilized to tack the flap in place [41].

Tham et al. reported on this procedure in six patients with an average of 2-year follow-up. All patients had previously sustained two or more decompressions. Operative findings reported evidence of chronic scarring of the median nerve with flattening and perineural fibrosis. All patients had improvement of their symptoms. Two patients had full resolution of pain and paresthesias, and the remaining four had only mild infrequent pain or paresthesia [41].

Distally Based Radial Forearm Perforator Flap

The lateral portion of fascial flap is reflected to expose the radial artery. Perforating vessels are identified as they branch perpendicular to the main axis of the radial artery. The flap is elevated in the subfascial plane from proximal to distal until adequate flap length is obtained leaving one or two dominant distal perforators.

In a study by Mahmoud et al. [42], the perforator-based radial forearm fascial flap was performed when patients had either already undergone a revision carpal tunnel surgery or if fibrosis around the median nerve extended proximally into the distal forearm. Out of eight patients, none reported dissatisfaction or worsening of symptoms after the surgery. Tinel's sign was fully resolved in four patients and greatly improved in the other four. The Phalen's sign disappeared in all patients. Two-point discrimination, grip strength, and pinch strength improved overall.

Dahlin et al. [43] noted that 3 out of 14 patients considered themselves cured or almost cured after this type of surgery, 7 patients improved, 1 patient was unchanged, and 3 patients were worse. Overall, pain and sensitivity at the wrist decreased significantly, and no patient experienced worse tingling or impaired sensation in the hand and fingers. However, ten of the patients reported problems from the donor site.

Interposition Materials

The ideal wrapping material should protect the nerve from compression by scar tissue, inhibit tissue adhesions to the nerve, improve gliding of the nerve during motion of the extremity, and decrease the scarring within the nerve trunk [34].

Autologous Vein Wrapping

Experimental studies in a rat model have shown that the autologous vein wrap can improve the functional recovery of the nerve and prevent scar formation around the previously scarred segment of the nerve [44–46]. Even though the mechanism still remains uncertain, human histopathologic analysis from re-exploration of autologous vein-grafted nerves further confirmed the inhibition of adhesions between the vein and the nerve. These biopsies also revealed neovascularization of the autologous vein graft and structural transformation of the vein endothelium [47, 48].

The autologous vein wrapping procedure is indicated for recurrent CTS in patients with at least two previous failed operations. The technique is also indicated in patients with severe nerve scarring or neuroma formation. However, it is not recommended in patients with chronic lower extremity venous insufficiency.

General anesthesia is used for this procedure because two operating fields are required, one for the median nerve re-exploration and one for the greater saphenous vein harvesting. The revision

surgery with the autologous vein wrapping technique involves revision decompression of the median nerve with neurolysis, greater saphenous vein harvesting from the lower extremity, and wrapping the vein graft around the previous compressed median nerve segment.

The median nerve in the wrist is exposed and released from the surrounding scar tissue. It is important to measure the length of the median nerve that needs to be covered. The length of the greater saphenous vein graft must be four to five times the scarred length of the nerve. The vein length harvested is usually 25–30 cm. A vein stripper can be used to harvest the greater saphenous vein graft minimizing the length of the incision in the lower extremity. After the saphenous vein graft is harvested, it is incised and opened longitudinally. The vein is circumferentially wrapped around the scarred segment of the median nerve from distal to proximal with the intima of the vein against the nerve. The two ends of the graft are tacked distal and proximal to the scarred segment of the median nerve on an immobile tissue. Each loop of the vein is stabilized with the adjacent loop using a loose 7-0 nonabsorbable, monofilament stitch. It is important to ensure that the intima of the vein graft is opposed to the nerve after each loop. Wrapping should not be too snug. The entire segment of the scarred nerve must be completely covered with the vein graft to prevent recurrence (Fig. 16.4). The wrist is immobilized in slight extension for 2 weeks postoperatively. Active and passive range of motion exercises are started after the splint is removed.

Several clinical studies have shown that the autologous vein wrapping technique is an effective treatment method for recurrent CTS [20, 49, 50]. After autologous vein wrapping, significant improvement of pain and grip strength has been noticed in the majority of patients. Most patients also showed improved two-point discrimination postoperatively. Nerve conduction studies revealed improvement of findings postoperatively in several patients, although they did not return to normal values. No complications due to the saphenous vein graft harvesting were noted other than transient swelling at the donor site that resolved in approximately 6 months.

Synthetic Wraps

In a similar fashion, synthetic devices can be utilized to supply interposition around the scarred nerve and inhibit scar reformation. Currently, there are available synthetic devices from bovine collagen (NeuraWrap, Integra LifeSciences, Plainsboro, NJ) and porcine extracellular matrix (Axoguard, Axogen Inc., Alachua, FL). Synthetic devices, such as Neuragen (Integra) and Axoguard (Stryker), are composed of an absorbable semipermeable collagen that is absorbed by the body over time through normal metabolic pathways [38]. During this process, no scar tissue forms nor does an inflammatory reaction arise, as

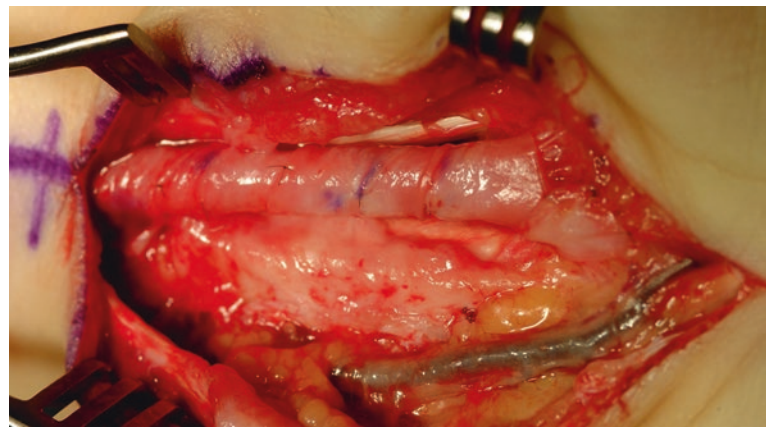

Fig. 16.4 Vein wrap technique. Wrapping the median nerve with autologous saphenous vein graft with its intima against the nerve. Each loop of the wrapped vein is stabilized to the adjacent loops with a 7-0 nonabsorbable, monofilament stitch. The entire scarred portion of the median nerve is covered with the vein graft

the device is composed of a semipermeable membrane which blocks fibroblasts and in this manner lessens perineural fibrosis [51, 52].

Synthetic nerve wraps used for revision carpal tunnel surgery have the advantages of decreased operative time and donor site morbidity. However, the cost of allograft nerve wrap may be considered a relative contraindication at some facilities. Currently, there is not sufficient data to demonstrate that these synthetic wraps are better than autologous vein wraps [38].

The surgical procedure involves revision median nerve decompression through a typical open carpal tunnel approach with proximal extension across the wrist flexion crease. The median nerve is recognized and freed of surrounding scar tissue. Once the nerve is sufficiently free, the synthetic nerve wrap is placed around the decompressed segment of the median nerve. The entire segment of scarred nerve must be completely covered to prevent recurrence. The synthetic nerve wrap is secured around the nerve with sutures. Care is taken to avoid suturing the synthetic nerve wrap to the nerve.

Clinical Outcomes

The results of revision CTR are variable, and many patients will experience some improvement, but 41% to 90% of patients will report persistent symptoms [25]. There is little evidence to help the physician know what clinical features or diagnostic studies are helpful in predicting a good outcome after surgery. There are many variables, such as physiologic and anatomic factors, as well as psychosocial contexts, that can preclude a favorable outcome.

Zieske et al. [13] evaluated intraoperative findings and outcomes of revision CTR in order to identify predictors of pain outcomes. In their retrospective study of 97 hands in 87 patients who presented with persistent, recurrent, or new symptoms, the recurrent group demonstrated a higher incidence of diabetes and a longer interval from primary CTR. This group was also less likely to present with pain. Incomplete release of the flexor retinaculum and scarring of the median nerve were common intraoperative findings. Nerve injury was more common in the "new symptoms" group. Higher levels of preoperative pain, use of pain medication, and workers' compensation were significant predictors of greater postoperative pain. They concluded that number of prior CTRs, baseline pain, pain medications, and workers' compensation status are important predictors of outcomes in this population.

Stutz et al. [10] described a number of causes for recurrent or unresolved CTS. Of the 200 patients included in their study, 108 (54%) experienced persistent or recurrent symptoms as a result of incomplete transection of the flexor retinaculum. In 65 cases, the distal edge of the retinaculum was intact, in 27 the proximal edge was intact, and in 5 the entire ligament was felt to be intact. Twelve patients experienced iatrogenic nerve lacerations from their initial procedure: four patients had incomplete lacerations, one had complete laceration of the motor branch, two had complete lacerations of the median nerve, two patients had lacerated motor branches, and three had lacerated palmar branches. The incomplete release and iatrogenic groups were thought to compose the patients with persistent CTS (120 patients). In the remaining 80 cases, the authors felt that symptoms were recurrent. In 46 patients, symptoms were caused by the constriction of the nerve as the result of scar tissue (23%). A mass within or adjacent to the carpal canal was responsible for symptoms in four patients (2%). The remaining 13 patients (7%) had no identifiable reason for recurrence.

Similarly, in a retrospective review of the surgical findings and outcomes of 50 consecutive patients who had undergone 55 revision CTRs, Jones and colleagues [3] reported incomplete release of the flexor retinaculum in 32 patients (58%) as the most common finding. Complete relief of symptoms following revision surgery was similar after open (57%) or endoscopic (56%) techniques. Ten patients (20%) showed no improvement and five patients required a third operation. This study also demonstrated that the precise location of the incomplete release did not correlate with the original technique (endoscopic or open).

Intraoperative findings that have been shown to have poorer outcomes are severe circumferential fibrosis around the median nerve, proliferative tenosynovitis, and amyloidosis [3]. The outcome ultimately lies with the pathology causing mechanical compression. Patients with an incompletely released TCL can expect to have outcomes similar to primary CTR. Outcomes are less predictable in more severe cases with circumferential fibrosis causing decreased vascularity or traction injury to the median nerve.

Based on the literature, it seems that median nerve re-decompression coupled with placement of a flap is an adequate treatment for recurrent CTS. Pedicled flaps seem to be preferable to free flaps, but there is no evidence in the articles arguing for the specific donor. Although there are no prospective data differentiating which treatment algorithm is the best for recurrent CTS, there is a trend in the literature favoring vascularized coverage with flaps, with the hypothenar fat pad flap appearing to have equal or better results than the others in clinical results and electrophysiologic testing [28, 53]. Unfortunately, we are not aware of any prospective study that examines the value of decompression alone versus decompression with placement of a flap.

Soltani et al. [54] compared two general treatment groups: decompression with flap interposition and repeated open decompression in a systematic review of the literature on the outcomes of treatment for recurrent and persistent CTS. They presented higher success rate with decompression and vascular flap coverage over simple repeated decompression (86% vs. 75% success rate, respectively). The difference in success rate between flap and nonflap was highly significant ($p = 0.001$). Our approach has evolved to the following algorithm:

1. Re-release, hypothenar fat flap
a. Recurrent carpal tunnel
b. Nerve injury
c. Atrophic subcutaneous tissue over carpal canal

2. Re-release, pedicle flap
a. Above with atrophic skin and subcutaneous tissues

3. Re-release, nerve wrap
a. Autologous vein wrap: recurrent symptoms, excessive scar, and/or two or more previous surgeries

Summary

Recurrent and persistent CTS can be a debilitating and difficult disease process with imperfect surgical results. The clinical examination and workup after primary CTR can be confusing and fraught with a number of confounding variables. In patients with persistent or recurrent symptoms, exploration with repeat TCL release and median nerve neurolysis may be performed. If severe scarring is noted, the use of an interposition material or flap is warranted. If the patient presents with new or worsening symptoms of numbness or weakness after CTR, then the physician must be concerned for iatrogenic nerve injury and exploration with repair should be considered.

Although patients may not obtain complete relief of symptoms as readily as after primary CTR, the literature supports repeat surgery, as improvement often occurs. However, one should keep in mind that the optimal treatment for this condition is not clear and there is not an established superior surgical option.

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Neuroma in Continuity

17

J. Megan M. Patterson, Andrew Yee, and Susan E. Mackinnon

Introduction

Carpal tunnel syndrome is the most common peripheral compressive neuropathy in the upper extremity, and surgical release is usually successful with recurrence rates ranging from 3 to 20% [1–4]. Symptoms after carpal tunnel release (CTR) have been classified into three different types – persistent, recurrent, and new [1]. Persistent symptoms are those that do not show any improvement after CTR, often due to inadequate release of the transverse carpal ligament, proximal compression, or incorrect diagnosis. Recurrent symptoms are those that initially improve after CTR only to recur at a later date and may be due to scar formation around the median nerve with subsequent traction neuritis, or proximal median nerve compression. Finally, new symptoms are symptoms that occur after CTR that are different than those that the patient initially presented with. These new symptoms are typically due to iatrogenic injury and will be the focus of this chapter.

Iatrogenic injuries that occur during carpal tunnel release may involve injuries to the vasculature, median or ulnar nerves or their branches, or to the surrounding flexor tendons [1, 5–7]. Injury to the median nerve during CTR commonly involves the nerve to the third webspace, the recurrent motor branch, or the palmar cutaneous branch (seen with more radially placed incisions) [5, 7, 8]. Complete transection of the median nerve has also been reported [6].

It is useful to review the classification of nerve injury when discussing iatrogenic median nerve injury following CTR (Fig. 17.1). Sunderland described I–V degree injuries with IV and V degree injuries being neurotmetic injury with no opportunity for recovery [9]. A IV degree injury is an in-continuity nonrecoverable injury. A V degree injury implies a physical separation between the proximal and distal physical components of the injured nerve with a neuroma proximally and a glioma distally. Typically, true IV degree injuries following carpal tunnel release would imply a complete or near-complete transection that had "healed" with dense scar tissue.

J.M.M. Patterson (✉)
Department of Orthopaedic Surgery, University of North Carolina, Chapel Hill, 3135 Bioinformatics Building, Campus Box 7055, Chapel Hill, NC 27599, USA
e-mail: mpatters@med.unc.edu

A. Yee • S.E. Mackinnon
Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, 660 South Euclid Avenue, Suite 1150, Northwest Tower, Campus Box 8238, St. Louis, MO 63110, USA
e-mail: yeea@wudosis.wustl.edu; mackinnon@wudosis.wustl.edu

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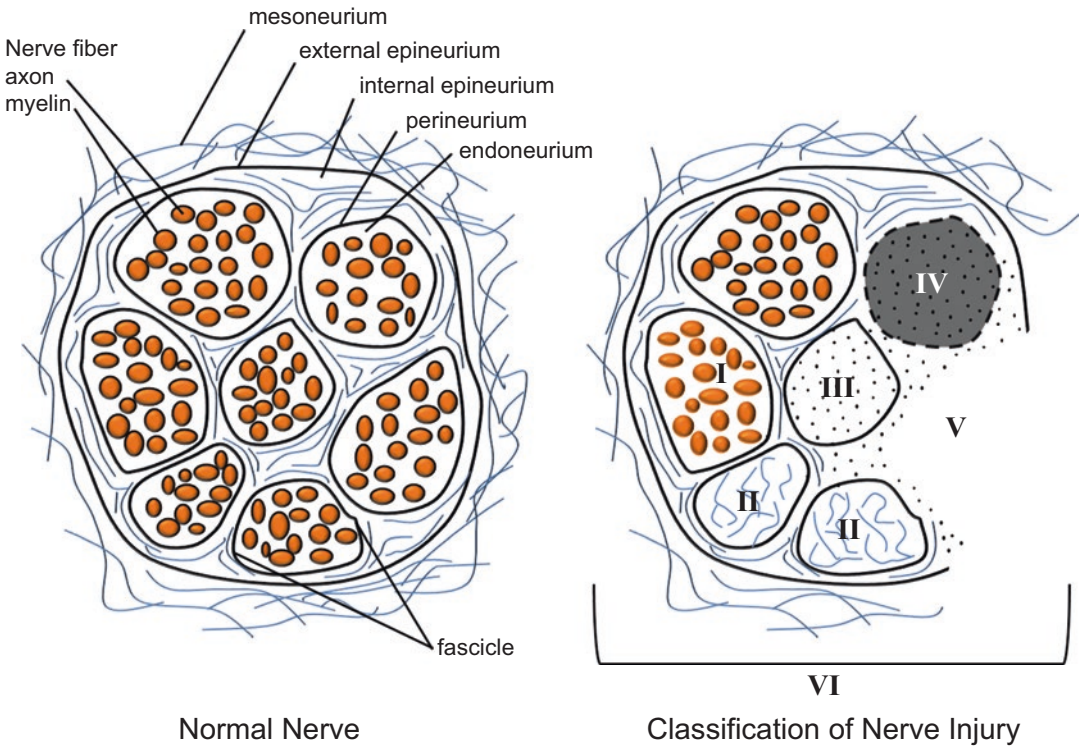

Fig. 17.1 (**a**) Schematic representation of the cross-section of a normal peripheral nerve showing the connective tissue and nerve tissue components. (**b**) The cross-section of the peripheral nerve demonstrates a mixed, or sixth degree, injury pattern. This fascicle at the top left is normal. Moving in the counter clockwise direction, fascicle I is a first degree injury (neurapraxia) with segmental demyelination. Fascicle II is a second degree injury (axonotmesis). The second degree involves both the axon and the myelin. The endoneurial tissue is not damaged. Fascicle III demonstrates a third degree injury, with injury to the axon, myelin, and endoneurium. The perineurium is intact and normal. Fascicle IV demonstrates a fourth degree injury, with injury to the axon, myelin, endoneurium, and perineurium. The fascicle is marked by scarring across the nerve, with only the epineurium being intact. Fascicle V is a fifth degree injury in which the nerve is not in continuity and is transected. The surgeon will separate the fourth and fifth degree injury patterns, which will require reconstruction from the normal fascicles and the fascicles demonstrating first, second, and third degree injury patterns. These latter patterns of injury require, at most, neurolysis. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

Those would be treated with nerve grafting. The management of the IV degree, or true neuroma in continuity, is therefore fairly straightforward. By contrast, it is the combination injury or, as Mackinnon has emphasized, a VI degree injury that is the major challenge for reconstructive nerve surgeons [10]. In these injuries, some of the fascicles may be normal or have the potential for complete recovery. Other fascicles with neurotmetic injuries will need reconstruction. It is these more challenging VI degree injuries that we emphasize in this chapter.

Diagnosis

The evaluation of these patients starts with a detailed history and physical exam. Focus is placed upon the pre- and postoperative symptoms. Patients with an iatrogenic injury to the median nerve resulting in a neuroma in continuity will complain of new neurological symptoms after their CTR, in the form of numbness, weakness, or pain, and these symptoms are often severe (Fig. 17.2). Physical examination can help to identify the area of injury. Careful sen-

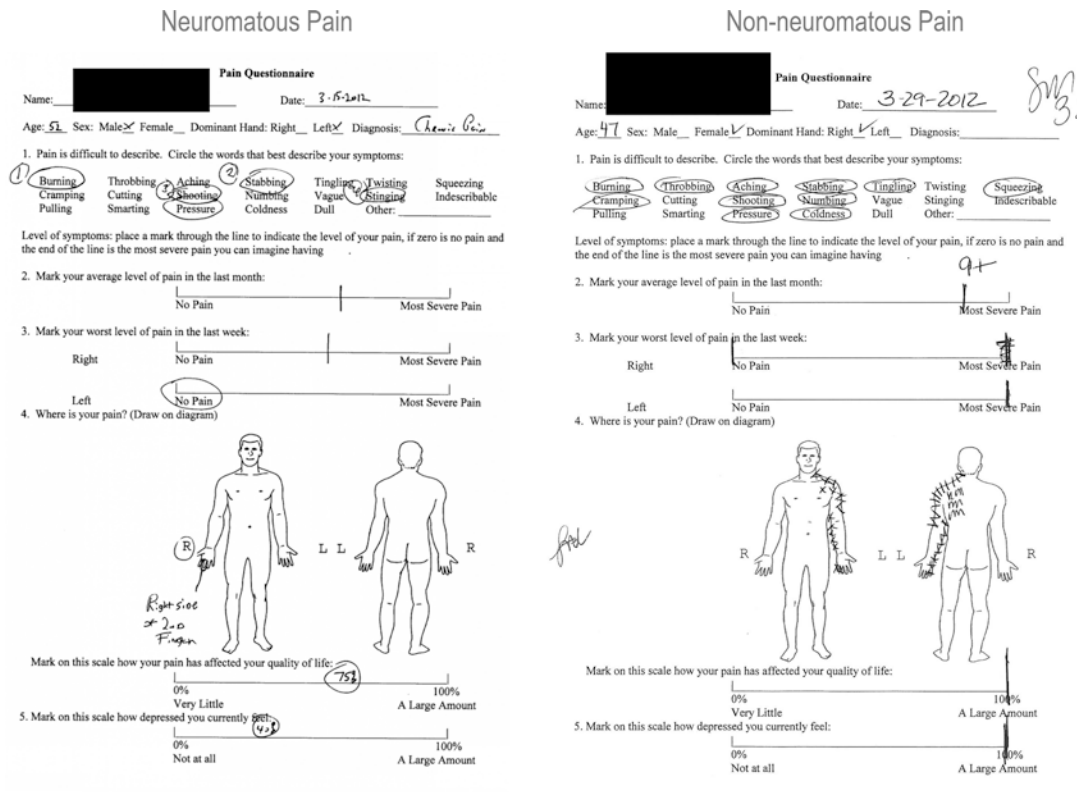

Fig. 17.2 Pain descriptions for neuromatous pain and non-neuromatous pain. The pain evaluation is an important tool for distinguishing types of pain and helping with the diagnosis. Neuromatous pain includes description of focal, brief, intermittent, sharp, often intense, and localizes to a specific nerve territory. Non-neuromatous pain includes description of diffuse and of varying quality and duration. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

sory testing including two-point discrimination, Semmes-Weinstein monofilament testing, and the ten test of both the median innervated digital nerves and the palmar cutaneous branch can determine if all or a portion of the nerve has been injured which will help guide surgical management. Each digital nerve should be separately evaluated in the autonomous area (the volar lateral side of the middle phalanx). We have found the ten test to be very useful in the evaluation of these patients. Patients are given a scale of 1–10 with 10, normal; 5, half; and 0, no sensation. The normal hand is used as the control for 10, and then the injured finger(s) is touched in the same autonomous zone simultaneously with the contralateral side, and the patient reports a number between 0 and 10 [11]. We also use the scratch collapse test ethylene chloride hierarchy to evaluate for persistent and recurrent secondary carpal tunnel, evaluation of the median nerve in the forearm as well as iatrogenic median nerve injury [12]. A Tinel sign can help to localize the area of injury and should be performed proximal to the carpal tunnel as percussion over the carpal tunnel at the level of the injury will often result in severe and intolerable pain for the patient. We call this a "proximal" Tinel and specifically ask the patient to describe the precise distribution of the Tinel. Weakness or atrophy of the abductor pollicis brevis indicates an injury to the recurrent motor branch of the median nerve.

Nerve conduction studies should be performed during the evaluation of any patient presenting with symptoms of a failed carpal tunnel release, and the results should be compared to preoperative studies. Evidence of worsening median nerve function when compared to previous studies often

implies injury to the median nerve or one of its branches and helps guide the decision for surgery. Recording to each median nerve, innervated digital nerve may be necessary to evaluate the VI degree injury pattern. For example, an injury to the third webspace fascicular group may not be noted if the electrodiagnostic reading is from the index finger.

Treatment

General Principles

Surgical treatment of a neuroma in continuity after carpal tunnel release requires careful attention to technique. The original incision site should be ignored in favor of a larger ulnarly placed incision that crosses the proximal wrist crease and carries on distal to the original incision to allow adequate exposure. The median nerve is first identified both proximal to the zone of injury in order to minimize the risk of further iatrogenic injury. Guyon's canal is then released and the flexor retinaculum divided on the ulnar border. The flexor retinaculum is then retracted, and the injured median nerve will be visualized adherent to the overlying scar from original incision.

Identification and Resection of the Zone of Injury

Internal neurolysis of the internal and external epineurium is performed using microsurgical instrumentation until normal fascicles and bands of Fontana are encountered (Fig. 17.3). The extent of

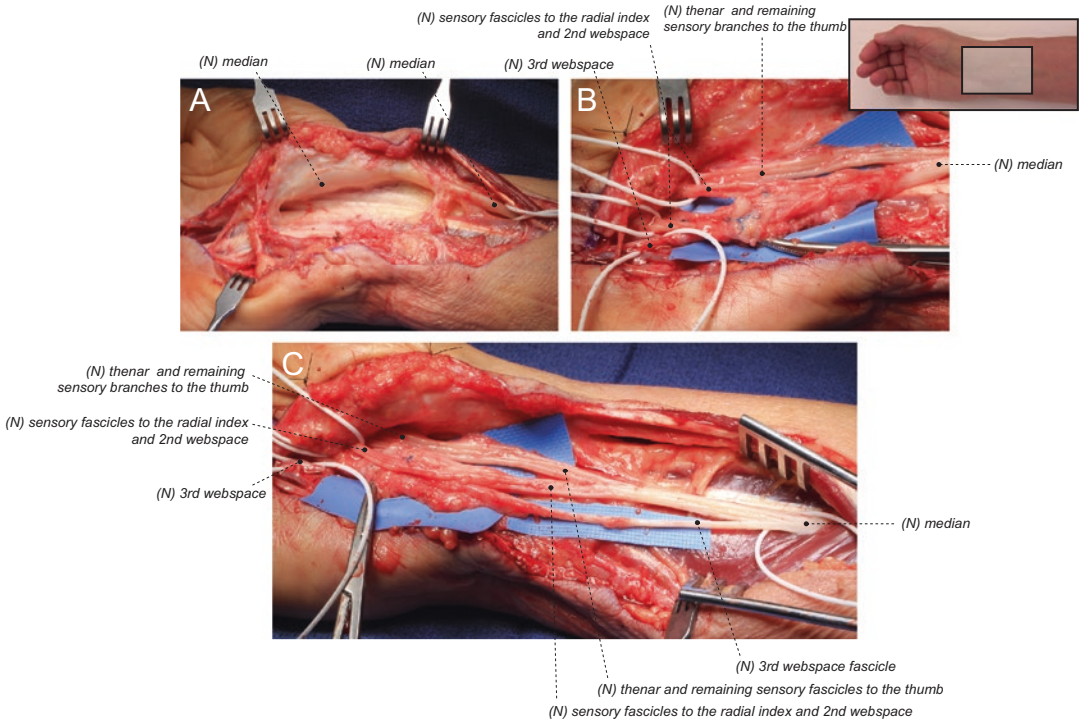

Fig. 17.3 Exposure of median nerve and intraneurolysis. (**a**) The median nerve was identified proximal and distal to the zone of injury. It was found to have a course within dense scar tissue. (**b**) The median nerve was isolated from the scar tissue, and distal neurolysis revealed the sensory branches of the median nerve. The intact thenar motor branch and sensory fascicles to the thumb were protected. Suture material was found within the remainder of the injured median nerve. (**c**) Proximal neurolysis revealed the fascicular anatomy of the median nerve. The third webspace is neurolyzed proximally so that it can be used as graft material. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

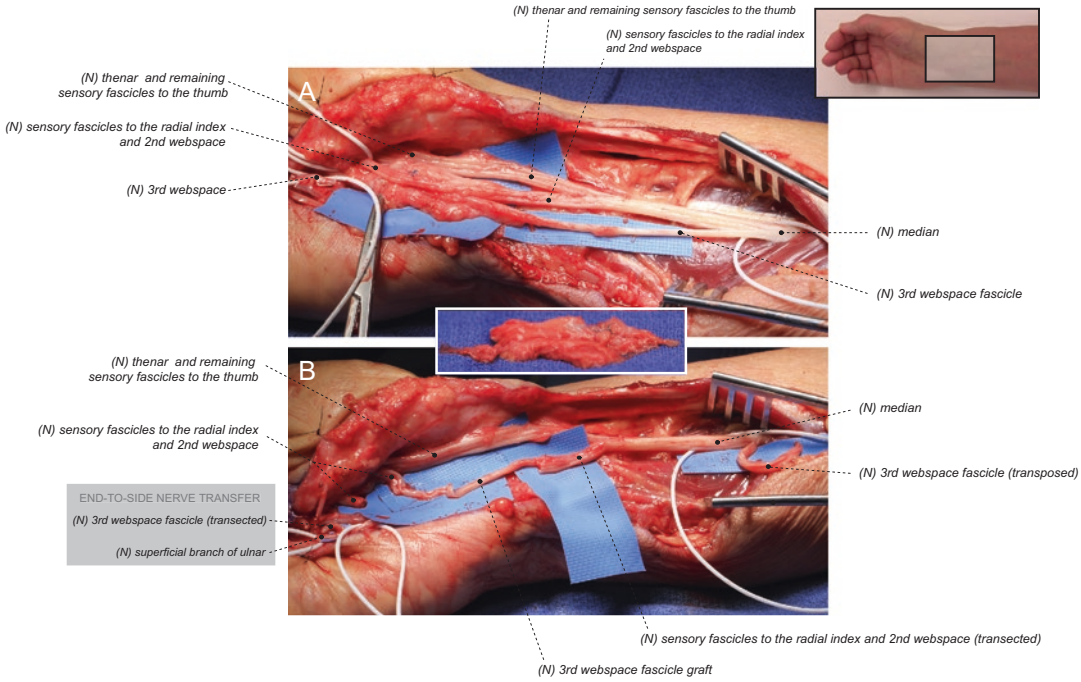

Fig. 17.4 Neuroma resection and first webspace grafted with a third webspace graft. (**a**) The zone of injury was identified, and the neuroma was resected with proximal and distal median nerve components identified. The third webspace was further neurolyzed proximally to mobilize graft material. (**b**) The proximal end of the third webspace fascicle was transected and used as a nerve graft to repair a portion of the median nerve. The proximal remainder of the third webspace was transposed proximally to prevent a painful neuroma. The distal third webspace was end-to-side transferred to the sensory component of the ulnar nerve to provide rudimentary sensation for donor deficit. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

neurolysis required will vary by case and should continue until normal fascicles are encountered. We start the neurolysis proximally above the area of suspected injury and carefully proceed distally. Normal fascicles are first neurolysed to protect their function. All injured fascicles are identified and resected taking care to protect the uninjured, healthy portions of the nerve (Fig. 17. 4).

Selection of Nerve Graft

We recommend the use of autogenous nerve grafts to reconstruct injuries involving critical portions of the median nerve and the use of allografts to reconstruct noncritical sensory injuries. Typically an allograft will not be necessary.

It is our preference to obtain a nerve graft from the operative extremity. The anterior branch of medial antebrachial cutaneous (MABC) nerve is our graft of choice when a long graft is needed (Figs. 17.5 and 17.6). It is located in the medial upper arm next to the basilic vein along the medial border of the biceps and supplies sensation to the ulnar volar forearm. If a shorter segment of graft is needed, the anterior interosseous nerve to the pronator quadratus muscle in the distal forearm is an excellent donor which is in the operative field and results in no sensory deficit. Alternatively, the lateral antebrachial cutaneous nerve may be used.

The branch of the median nerve to the third webspace may also be used as a donor (Fig. 17. 7). Proximal mobilization of the third webspace branch results in an appropriately sized graft which may be used to reconstruct more critical median nerve function. We will then transfer the distal aspect of the third webspace branch end-to-side to the sensory component of the ulnar nerve to provide restoration of rudimentary sensation to the third webspace. The proximal end of the third

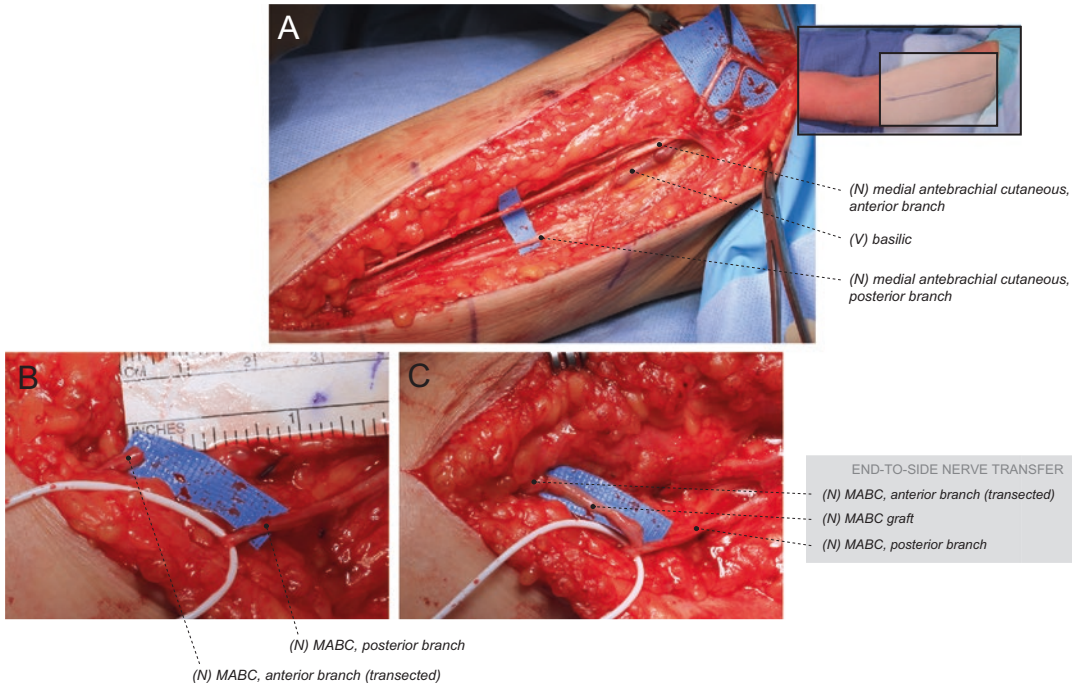

Fig. 17.5 Anterior branch of medial antebrachial cutaneous nerve graft harvest. (**a**) The anterior branch of the medial antebrachial cutaneous nerve (MABC) was exposed superior to the basilic vein and isolated in the medial aspect of the arm. The posterior branch of the MABC nerve was also identified inferior to the basilic vein. (**b**) The anterior branch of the MABC nerve was harvested. (**c**) To restore rudimentary sensation in the MABC anterior branch distribution, the distal end of the MABC anterior branch was transferred to the MABC posterior branch in an end-to-side fashion. Following the prioritized ulnar nerve reconstruction with the harvested MABC graft, the unused MABC graft material was used to bridge the end-to-side nerve transfer for a tension-free repair. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

webspace branch should be transposed proximally and buried between the superficial and deep flexor muscles to prevent a painful neuroma. We do a proximal "crush" of the third webspace fascicle to make a II degree injury and move the axonal regeneration front proximally. We also use a long (5 cm) nerve allograft to repair to the distal end of the third webspace nerve to "dwindle" nerve regeneration and prevent neuroma formation.

Outcomes

There have been a number of studies looking at the outcomes of patients requiring revision carpal tunnel surgery, though most of these cases involve patients presenting with recurrent or persistent symptoms with little data available on the long-term outcomes of those patients treated for a neuroma in continuity. Zieske et al. reviewed the results of revision carpal tunnel surgery in 97 extremities [7]. Revision surgery was performed for new symptoms in 36 of these 97 extremities, and of these 36 patients with new symptoms, 19 were noted to have an iatrogenic nerve injury. At an average postoperative follow-up of 4.7 ± 3.3 months, these patients showed an improvement in pinch and grip strength and an improvement in pain scores (Fig. 17.8). Detailed outcomes regarding improvement in sensation and function were not possible given the duration of follow-up reported. Jones et al. reported on 55 revision

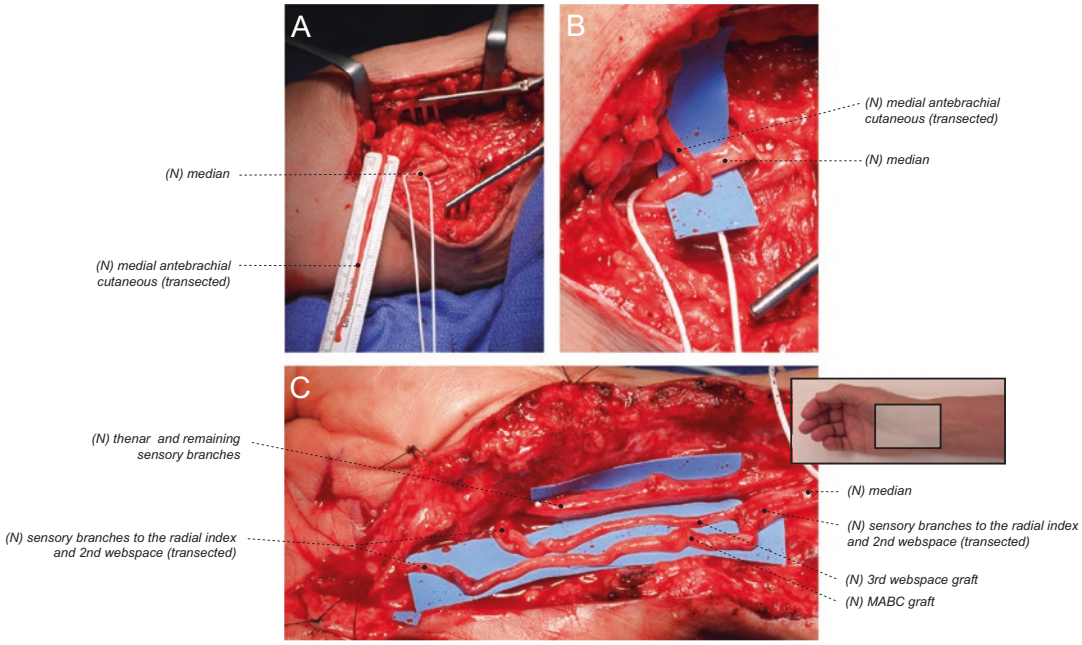

Fig 17.6 Second webspace grafted with a medial antebrachial cutaneous nerve graft. (**a**) The medial antebrachial cutaneous nerve (MABC) was isolated within the arm for donor material. (**b**) The MABC was than transected with the distal end transferred to the sensory component of the median nerve through and end-to-side epineural window fashion. The sensory component of the median nerve is located on the superior aspect of the median nerve. Note that in this image, the median nerve has been rotated so that it appears to be on the inferior portion. (**c**) The MABC graft was used to repair the remaining portion of the median nerve. The thenar branch and remaining sensory branches to the thumb were protected and were found to be not injured. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

carpal tunnel surgeries, only 2 of which involved patients presenting with new symptoms related to iatrogenic nerve injury [8]. Improvement in thenar strength was seen in 48% of patients, and pain, numbness, and paresthesias improved or resolved in 80% of patients. They did not report specifically on the outcomes of those patients with iatrogenic nerve injuries.

Iatatrogenic nerve injury after carpal tunnel release resulting in neuroma in continuity is a devastating complication. Careful diagnosis and meticulous surgical reconstruction will often improve patient's symptoms, but further study is needed to better define the long-term outcomes of this challenging patient population.

Conclusion

There is universal agreement that *prevention* of median nerve injuries during carpal tunnel surgery is imperative. Points we emphasize with primary carpal tunnel release include the following:

- Our incision is made 6 mm ulnar to the thenar crease to avoid direct healing over the median nerve which can result in scar traction neuritis and recurrent carpal tunnel syndrome and to place it in the watershed between the palmar cutaneous median and ulnar nerves.
- The incision is "as long as needed." If necessary, a Bruner incision is used to cross the

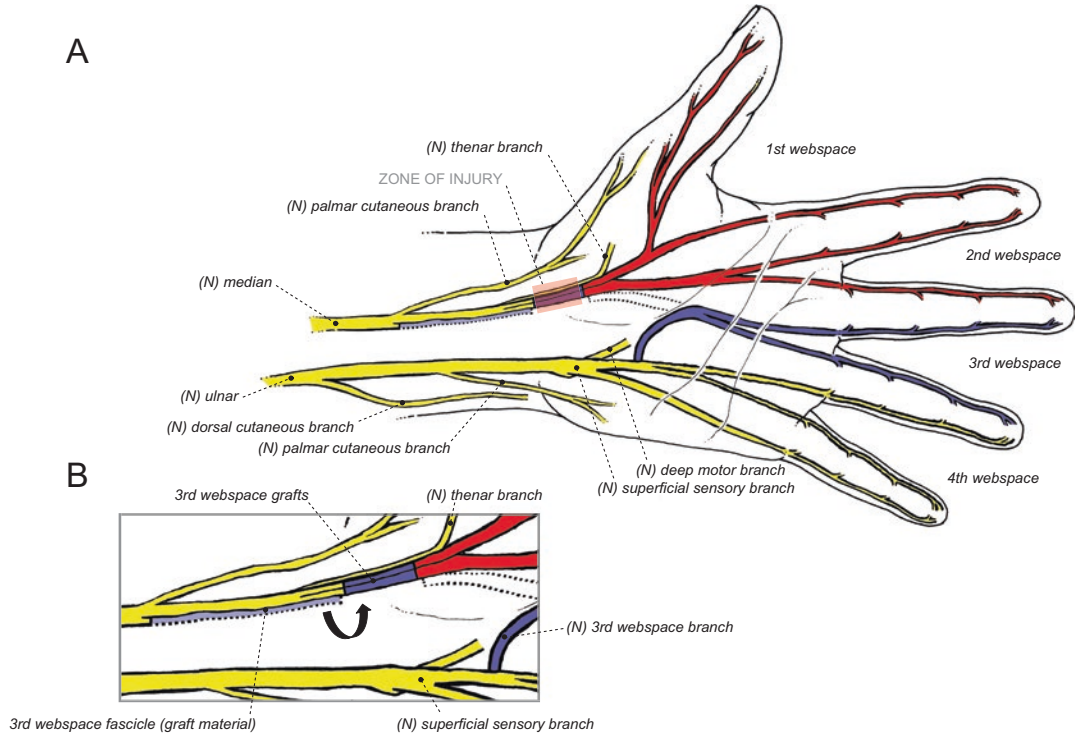

Fig. 17.7 Noncritical nerve graft material from proximal to nerve injury. Noncritical nerve material proximal to a nerve injury is an available option for grafting. (**a**) The third webspace is an excellent donor nerve for grafting in a case of distal median injuries. Injury to the median nerve at the wrist allows for the harvest of the proximal noncritical third webspace nerve fascicle. The harvest of the third webspace fascicle occurs on the medial aspect of the median nerve. (**b**) The third webspace fascicle can be used as graft material for reconstructing critical components of a distal median nerve injury. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

wrist to get safe and complete release of the distal antebrachial fascia.

- In obese patients, a forearm tourniquet is utilized to prevent the development of a venous tourniquet.
- The ligament is released on the ulnar side so as to not have healing of the median nerve to the cut edge of the ligament which can result in scar traction and recurrent carpal tunnel syndrome.
- At the proximal and distal ends of the release, the surgery is "slowed" to ensure no iatrogenic injury to the median nerve and that there is a complete release [13]. The third webspace component of the median nerve branches from the main median nerve in the distal aspect of the release, and this is an area where "slowing down" is critical.
- The proximal release is never "blind." We will move to the end of the operating table to be able to release the proximal portion of the carpal ligament and the distal antebrachial fascia under direct vision. If visualization of the median nerve is not complete, then the incision is extended.
- The wrist is immobilized in a neutral position for 2 days after which the dressing is removed and patients are encouraged to "move, but not use" their hand for 2 weeks.

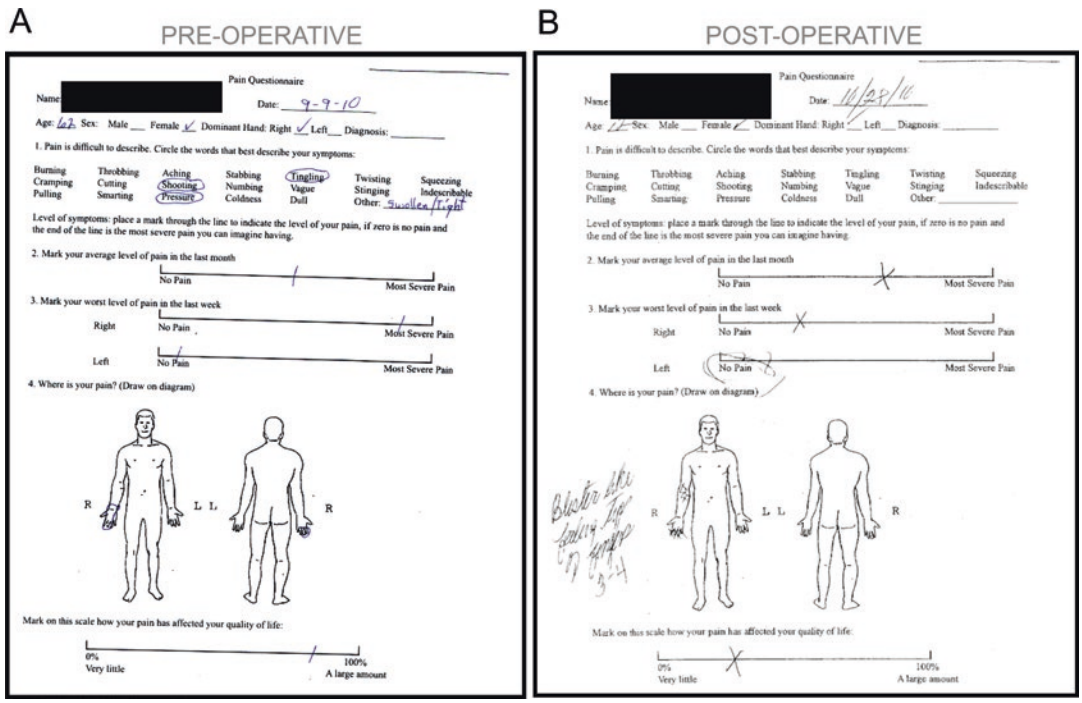

Fig. 17.8 Preoperative and postoperative pain diagram. (**a**) Preoperative pain diagram demonstrates pain upon presentation 2 years after a right-hand endoscopic carpal tunnel release, failed primary median nerve repair, and stem cell injection into the wrist. (**b**) Postoperatively following the revision reconstruction by our institution, pain was reduced significantly. (Permission to reprint from Thieme in Nerve Surgery by Mackinnon)

While CTR is a relatively easy and straightforward procedure, the potential for catastrophic nerve injury exists. We believe that attention to these critical points minimizes the risk of nerve injury during CTR.

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Treatment of Median Nerve Transection

18

Julie Balch Samora and Philip E. Blazar

Introduction

Upper limb peripheral nerve injury can have devastating effects on functional ability [1]. Etiologies of peripheral nerve injury can include penetrating laceration, crush, traction, ischemia, thermal necrosis, electric shock, radiation, and vibration [2, 3]. The first description of median nerve lesions was by Stopford in 1918 [4]. Upon evaluation of 1111 peripheral nerve injuries of the upper limb, there were 211 (19%) median nerve injuries [5]. Lacerations account for 30% of peripheral nerve injuries [2]. Nerve repair was reported as early as the seventh century, when Paul Aegina approximated cut nerve ends [6]. This chapter will discuss the neuropathology of median nerve injury, clinical examination, indications for surgery, surgical treatment options, rehabilitation, and outcomes after median nerve transection.

J.B. Samora
Nationwide Children's Hospital,
700 Children's Drive, Columbus, OH 43205, USA
e-mail: julie.samora@nationwidechildrens.org

P.E. Blazar (✉)
Brigham and Women's Hospital,
75 Francis Street, Boston, MA 02115, USA
e-mail: pblazar@partners.org

Neuropathology

In order to best treat peripheral nerve injuries, having an understanding of the basic anatomy is important. The individual myelinated axons and unmyelinated groups of axons are surrounded by endoneurium. Fascicles are collections of axons which are surrounded by perineurium. The internal epineurium lies between fascicles, and the external epineurium surrounds the nerve trunk. Whereas the endoneurium is longitudinally oriented, the epineurium and perineurium are circumferential [7] (see Fig. 18.1). The Seddon classification (1943) [8] includes neurapraxia, axonotmesis, and neurotmesis. This chapter will focus on the latter two. The axon is damaged or destroyed in axonotmesis, but the connective tissue is maintained. In neurotmesis, the nerve trunk is completely disrupted with no continuity and disrupted connective tissue.

Wallerian degeneration occurs with disruption of the axon [9], and repair and regeneration occur following nerve injury. With lesions involving fewer than 20–30% of the axons, recovery is mostly by collateral sprouting from surviving axons and occurs over 2–6 months [2]. When more than 90% of axons are injured, the primary mechanism of repair is regeneration from the injury site and depends largely on the age of the patient; distance from the injury site, but is also affected by the level of injury; and local biologic

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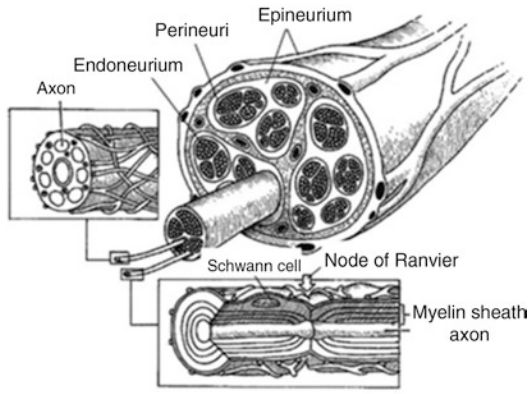

Fig. 18.1 Cross-sectional appearance of peripheral nerve. Obtained from: Biazar E, Khorasani MT, Montazeri N et al. Types of neural guides and using nanotechnology for peripheral nerve reconstruction. Int J Nanomedicine. 2010; 5: 839–852

factors. The neuron's capability to sustain regenerative attempts persists for at least 12 months after injury. Poor functional recovery occurs if the growth cone fails to reinnervate the motor end plate by 12 months due to secondary end-organ degeneration [10] leading to time dependence after injury for those injuries involving motor components.

Clinical Examination

Patients with median nerve injuries can present acutely or in delayed fashion. Generally, they are open injuries with sensory deficits involving the thumb, index, long, and radial half of the ring fingers. Partial injuries are more common than complete injuries, and lacerations at the wrist are more common than at the elbow. Depending on the level of injury, motor deficits can involve the pronator teres, flexor carpi radialis, palmaris longus, flexor pollicis longus, and flexor digitorum profundus muscles to the index and long fingers. If the entire nerve has been injured proximally, thenar muscle weakness will be observed [11]. A Tinel's sign at the site of nerve injury will develop, and distal propagation of the Tinel's is a good marker for axon regeneration after repair.

Indications for Surgery

When nerve continuity is uncertain, one can take an observatory approach to determine if there is either clinical or EMG evidence of reinnervation. The mechanism of injury (e.g., sharp vs. blunt) will help guide treatment. Axon regrowth from the proximal stump optimally occurs at 1 mm/day after about a 1-month delay [2]. Irreversible muscle atrophy occurs anywhere from 12 to 18 months. Schwann cells and endoneurial tubes remain viable for 18–24 months after injury. An advancing Tinel's sign can help clarify if reinnervation is occurring. If deficits persist past 3 months or if there is no evidence for reinnervation clinically, authors agree that there has typically been axonal damage [12]. Any patients without evidence of clinical recovery should undergo surgical exploration by 6 months, and some surgeons advocate for even earlier intervention for more proximal injuries [2].

Electrodiagnostic studies may provide information to help guide when to proceed with surgical exploration. The optimal timing is still debated. Although loss of amplitude of compound muscle action potential and nerve action potential is complete by 11 days after injury [2], electrical studies performed before 3 weeks after injury can be unreliable. Within the first week, electrodiagnostic tests can be useful for localization and determining complete from incomplete injuries. At 1–2 weeks, they can help distinguish axonotmesis or neurotmesis from neurapraxia. At 3–4 weeks, after fibrillation potentials have had a chance to develop, this provides the most information from a single study. At 3–4 months, they may provide information regarding reinnervation [2].

Partial Nerve Lacerations

There are times when the nerve is not entirely transected and there is no universal agreement on management of these lesions. Options include conservative management, nerve grafting, and repair of the lacerated fascicular groups only. Depending on the severity of the lesion, the

deficit, and the aforementioned factors affecting recovery, treatment is individualized. Early end-to-end microsurgical repair of lacerated fascicular groups has been shown to result in good motor and sensory outcomes (BMRC 4 and 3.81, respectively) [13].

Surgical Options

The principal surgical options for complete lacerations include neurolysis, primary end-to-end repair, nerve grafting, and nerve transfer [14]. Primary nerve repair involves direct end-to-end suture of separated nerve ends [15] and has the best prognosis [16] (see Fig. 18.2). The indications for primary repair include the ability to directly approximate nerve ends without undue tension in a nerve that has not sustained either a crush injury or mechanical disruption. If there is tension on the repair, ischemia will occur, leading to dysfunction. If nerves are stretched by 8–10%, blood flow is reduced by half [17]. A basic clinical tenet is that if one cannot coapt two nerve ends with a single 9-0 nylon suture, there is too much tension [18]. However, there is little clinical literature supporting this assertion.

Tissue approximation and alignment will be easier with earlier repair [19], with most surgeons preferring to operate before 2 weeks. Furthermore, with earlier repair, there is improved neuron survival [20] and decreased fibrosis of the distal stump [21] (see Fig. 18.3). The definition of secondary repair is end-to-end suture 2–3 weeks after injury. If a tension-free repair cannot be achieved, primary repair should be abandoned for another method.

Neurorrhaphy can be performed with sutures, fibrin glue, or nerve tubes. One must dissect to scar-free, healthy appearing tissue. The injured portion of the nerve must be removed to expose healthy nerve with a visible fascicular pattern. It is of paramount importance to align the proximal and distal stumps. One must utilize both surface landmarks and other indicators to properly align the nerve fascicles. Recommendations for alignment include visualizing fascicular patterns, using surface vessels as markers and any obliquity of the injury. Some authors have reported on using histologic acetylcholinesterase staining to identify motor axons and carbonic anhydrase staining to identify sensory fibers [22], but this adds a great deal of time to the operative procedure. Others have advocated "awake" electrical nerve stimulation to identify motor fibers [23]. Neither of these methods has resulted in significantly improved results.

Ends should be lined up such that the fascicular groups are gently touching. One may place sutures in the epineurium, which is less traumatic but may not adequately approximate the deep fascicles. A fascicular repair involves dissecting the epineurium and suturing the perineurium of each fascicle. Grouped fascicular repair minimizes nerve trauma and allows for improved alignment. There

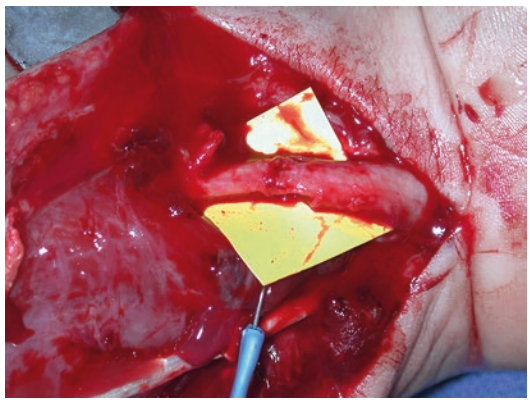

Fig. 18.2 Epineural repair of median nerve in the setting of a spaghetti wrist

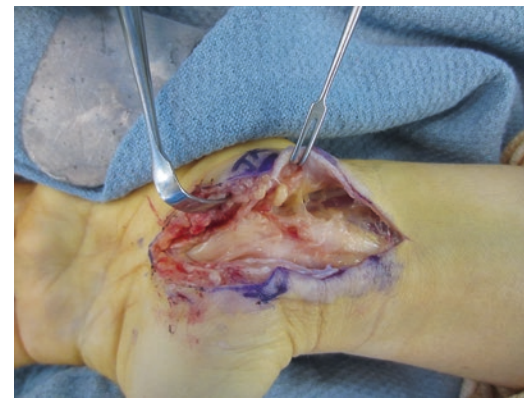

Fig. 18.3 This patient had a median nerve laceration and was taken to surgery at 2 weeks post-injury. Scar has already formed

have been no studies documenting superiority of one technique over another [24].

Fibrin-based tissue glue is becoming more popular for coaptation of the nerve ends. Its advantages include efficiency, simplicity, minimal trauma, and creation of a barrier to invading scar tissue [25]. Furthermore, there is animal data suggesting fibrin glue can promote angiogenesis, stimulate chemotaxis and leukocytosis, enhance macrophage proliferation, and provide hemostasis [6, 26, 27]. Fibrin glue does not appear to be a barrier to regeneration [28], but may have inferior holding strength [29, 30].

In secondary reconstruction with retraction of nerve endings and a large gap, end-to-end neurorrhaphy is no longer an option. Nerve diameter, gap size, and quality of the injured nerves influence the decision-making process. When a tension-free neurorrhaphy is not feasible, nerve grafting is typically the first option. Nerve graft can be autogenous (e.g., sural) or allograft (e.g., cadaver). The gold standard for a long gap is autograft. A variety of options exist, although the most commonly utilized donor is the sural nerve. Advantages of using sural nerve include a lack of motor deficit, a fairly superficial dissection to harvest, and a relatively lengthy course of the nerve with limited branches. Disadvantages of using autograft include limited availability, sensory donor nerves instead of mixed nerves as options, the obligate loss of nerve function, scarring, and painful neuroma formation [31].

Dissection, scar removal, neuroma resection, and management of median nerve injuries with a gap rest on the knowledge of interfascicular relationships and nerve architecture. It is important to align the median nerve and place the autograft accordingly in as near anatomic position as possible. Authors have previously identified the internal topography of the median nerve [32, 33]. In the upper two thirds of the forearm, the motor branches to the extrinsic muscles lie about the periphery, on the radial and ulnar aspect [32]. The sensory branches to the hand, the thenar motor branches, and the palmar cutaneous branch are in the central and dorsal quadrant. In the distal third, the thenar motor, lumbrical and sensory components are segregated and can be isolated.

Processed nerve allografts provide decellularized and predegenerated human nerve tissues which maintain the microarchitecture including the epineurium, fascicles, endoneurial tubes, and microvasculature [34, 35]. Processed nerve allograft may provide a viable option for mixed nerves and has the advantage of avoiding donor morbidity and decreasing surgical time [34]. The thickness and length of the processed autograft are also variable, and they are available in a range of sizes. Furthermore, they can be easily obtained. It is unclear, however, if there is a limit in the efficacy based on the length of the gap.

Nerve substitutes can include vein grafts, synthetic nerve conduits, and Schwann cell-lined nerve conduits [35, 36]. Nerve conduits are also an option for small gaps or partial lacerations. Lundborg and Hansson originally presented the concept of nerve entubulation in 1980 [37]. Conduits available include those made of collagen, polyglycolic acid (PGA), and polycaprolactone. In 1997, Lundborg et al. [38] performed a prospective, randomized clinical study comparing conventional microsurgical repair of median and ulnar nerves to using silicone tubes, with gaps measuring 3–4 mm between nerve ends. They found no difference in sensory or motor function between the two groups. Lundborg et al. [39] demonstrated that the median nerve can regenerate across 5 mm gaps equivalently to direct repair. However, a recent report was published describing four cases of failed conduit-based major nerve reconstructions [40].

A combination approach can also be made. For example, there is one case report describing reconstruction of a 4 cm median nerve graft with a piece of autogenous median nerve placed in a bioabsorbable conduit [41]. At 2 years after surgery, the patient had 7 mm moving and static two-point discrimination to the thumb and had recovered palmar abduction and EMG evidence of reinnervation of the abductor pollicis brevis.

It is beyond the scope of this chapter, but branches of the radial or ulnar nerve have been transferred to median nerve branches in the forearm, hand, or even digits [42–44]. Nerve transfers utilize intact motor nerves with a minor function to reinnervate critical muscles. One can

join the distal end of the cut normal nerve with the distal stump of the injured nerve. Another option is to perform neurorrhaphy of selected fascicles from a normal nerve to an injured nerve. End to side involves taking the end of a healthy donor nerve to the side of a target nerve distal to the site of injury [45].

Rehabilitation

There is a lack of consensus on postoperative immobilization and rehabilitation after median nerve repair or grafting. The rehabilitation decision is generally patient and surgeon dependent. Tactile gnosis is generally not regained in adult patients after injury to a major nerve trunk [24, 46]. Sensory reeducation has been proposed and combines techniques to help patients with sensory impairment to learn to interpret the altered neural impulses by attempting to reprogram the brain [46, 47]. In 40 patients with low median nerve complete transection and repair, 20 were rehabilitated with a sensory reeducation program, and 20 had no further treatment than the initial therapy. In the first group, locognosia (ability to localize touch) was significantly improved compared to group B, but static and moving two-point discrimination was not different [48]. In a systematic review evaluating the effects of sensory reeducation programs on functional hand sensibility after median and ulnar nerve repair, there was limited evidence to support the use of early or late sensory reeducation programs [49].

Outcomes

The best-known scale for sensibility and motor grading is the British Medical Research Council (MRC) scale, which is the most widely accepted classification system to score outcome of peripheral nerve injuries [50–52]. Functional outcomes have been assessed successfully using the DASH including the functional symptom score, with strong relation found with motor and sensory recovery [53]. DASH score, Rosen score, and Highet score were found to correlate significantly when evaluating outcomes of median and ulnar nerve injuries [54]. Studies have not universally utilized the same outcome assessments, making comparisons difficult.

There are multiple factors that influence recovery, such as cooperative and motivation of the patient, hand therapy, cognitive capacity, psychological stress due to the trauma, and comorbidities such as diabetes and alcoholism [55]. Age, gap length, and delay to surgery greatly influence outcome after repair of median and ulnar nerve transection injuries [55, 56]. Time of improvement can be variable as well, with one study indicating that grip and tip-pinch strength improve over a period of 3 years following median or ulnar nerve lesions [57]. Return to work after isolated median nerve injuries is influenced by level of education, type of job, and compliance with hand therapy, with 80% of workers returning to work within 1 year [58].

Primary repair produces superior results compared to those of delayed repair [59, 60]. In a series of 2181 acute nerve injuries, a primary repair was achieved in 87% of the cases with end-to-end approximation [18]. In median nerve injuries at the wrist, protective sensation in the fingertips can be reliably restored by direct suture or nerve grafting [55]. However, more proximal injuries have had less sensory recovery due to the long distance between the site of injury and the target cutaneous receptors in the fingertips.

In a long-term outcome study, 71 median and ulnar lesions were assessed 8 years after microsurgical repair and were classified according to the DASH, the Rosen's hand protocol, and the Highet scale. Patients regained approximately 70% of their original hand function [54]. Satisfactory motor (M4/M5) and sensory (S3+/4) recovery occurred in more than 50% of patients if the delay in repair was less than 3 months and the gap was less than 6 cm [56]. In 28 patients undergoing primary repair of a sharp transection of the median nerve at the wrist, S4 was elicited in 36%, S3+ in 29%, and S3 in 14%. This study demonstrated a significant correlation between age and functional sensibility [61].

Birch and Raji [59] reported on repair of 108 median and ulnar nerves after a clean laceration in the forearm with 48 undergoing primary repairs. None of these repairs failed, which they defined as motor grade of 3 or less, trophic changes, lack of sweating, no sensation or the presence of severe cold sensitivity, and general hypersensitivity. On the other hand, Mailander et al. [62] reported on ten median nerve repairs at the wrist with only 40% achieving S4, whereas 90% achieved at least an M4. Puckett and Meyer [63] reported on a series of 38 volar wrist lacerations involving either or both of the median and ulnar nerves (age range 1–61 years). Only 19 of 37 (51%) patients regained moving two-point discrimination better than 12 mm.

Hudson and de Jager [64] reported on 15 patients with spaghetti wrist who underwent primary repair of median and ulnar nerves at the wrist and found better functional results for median repairs compared to ulnar nerve repairs. Two children recovered 2PD of less than 10 mm with another two patients achieving 2PD between 10 and 15 mm. Hudson et al. [65] evaluated 18 children who underwent primary epineurial repair of median nerve lacerations and found mean static 2PD was 5 mm and motor strength of opponens pollicis was 4.5 on the MRC scale. Distal injuries fared better than proximal injuries.

In autograft repair of median nerve injuries, meaningful recovery was observed in 67% of patients [66]. In a functional outcome study following nerve repair using processed nerve allograft, there were no adverse events, and overall meaningful recovery was found in 75% of median nerve repairs [34].

In a study using tube conduits for mixed nerve injuries, functional recovery in gaps between 2 and 25 mm was only obtained in 1 of the 12 patients [67]. In contrast, Ruijs et al. [55] reported a 52% success rate in motor outcomes from mixed nerve repairs using conduits. Dienstknecht et al. [68] found purified type 1 bovine collagen conduits to be a good option for median nerve injury in the distal forearm in nerve gaps ranging from 1 to 2 cm. They found static two-point discrimination to be less than 6 mm in three patients, between 6 and 10 mm in four patients, and over 10 mm in two patients.

A prospective multicenter registry of peripheral nerve injuries associated with orthopedic trauma has been established and may lead to prospective studies to better evaluate outcomes following repair and reconstruction [69].

Conclusions

Median nerve injuries can lead to devastating consequences, and unfortunately the results frequently lead to some loss of function despite surgical repair. Early diagnosis and treatment is of paramount importance. Primary repair of median nerve injury consistently leads to best outcomes. Alternative treatments include autograft, allograft, and nerve conduits, particularly when a primary repair would require undue tension. In select injuries, nerve transfers are viable options.

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Diagnosis of True Recurrent Carpal Tunnel Syndrome

19

Bilal Mahmood and Warren C. Hammert

Recurrence of carpal tunnel syndrome is a challenging condition, often requiring additional surgery and in some cases, prolonged treatment for pain management. Carpal tunnel syndrome (CTS) is the most common compressive neuropathy in the upper extremity and clinical practice guidelines for diagnosis exist through the American Academy of Orthopaedic Surgeons [1]. These are currently being updated, with anticipated publication of new guidelines in 2016. Most of the time, treatment is successful with carpal tunnel release and patients experience permanent relief of symptoms. Occasionally, a patient will have a recurrence of symptoms, but this is not common and there are no evidence-based guidelines for diagnosis or treatment of recurrent carpal tunnel syndrome. Studies suggest that complications and failures of carpal tunnel release occur in 3% to 25% of cases and reoperation is performed in less than 5% of cases [2–5].

It is important to differentiate recurrence from persistent symptoms. Specifically, recurrence occurs following a symptom-free period of time following surgical decompression [6]. This is often defined as a 6-month interval, but there is no definitive evidence to set this time point. For the purposes of this discussion, we exclude recurrence of symptoms that may occur following nonoperative treatment, even if there is a symptom-free interval. In these cases, initial decompression surgery is the next step.

The pathophysiology of recurrent carpal tunnel syndrome is challenging to confirm. Postoperative perineural fibrosis is thought to contribute to recurrence, causing traction at specific points along the course of the median nerve or direct compression due to circumferential fibrosis [7–11]. The incidence of constriction of the median nerve during revision surgery is reported as 23–100% [2, 10]. If recurrence occurs several years following the index procedure, the cause is attributed to increased pressure in the carpal tunnel, which may be due to degenerative conditions leading to changes in the shape of the wrist. The challenge in the above explanations of recurrent carpal tunnel syndrome remains that there are no prospective studies to define the normal appearance of a completely released

B. Mahmood
Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, 601 Elmwood Ave., Box 665, Rochester, NY 14612, USA

W.C. Hammert (✉)
Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, 601 Elmwood Ave., Box 665, Rochester, NY 14612, USA

Division of Hand Surgery, Department of Orthopaedics and Rehabilitation, University of Rochester Medical Center, Rochester, NY, USA
e-mail: Warren_Hammert@URMC.Rochester.edu

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Table 19.1 History and physical exam findings with persistent, recurrent, and new symptoms following carpal tunnel release

History	Exam	Symptoms	Potential causes
Paresthesias in the median nerve distribution unchanged following surgery	+ Provocative tests unchanged following surgery, ± thenar atrophy	Persistent	Incomplete release of the transverse carpal ligament
Paresthesias in the median nerve distribution improved following surgery prior to returning	+ Provocative tests returning following symptom-free interval following surgery, ± thenar atrophy	Recurrent	Perineural fibrosis or reconstitution of the transverse carpal ligament
Paresthesias not present prior to surgery, increased intensity of pain following surgery, new onset weakness	Tinel sign at new injury site, ± provocative tests	New	Iatrogenic nerve injury, complex regional pain syndrome

Adapted from Mosier and Hughes [11]

transverse carpal ligament or what a normal amount of fibrosis may be [6]. Such studies are difficult to perform given most patients have good relief of symptoms following surgery and do not need additional studies [6].

Persistence of symptoms may occur following an incomplete release or an error in diagnosis resulting in the incorrect surgery. In these cases the patient does not experience any relief after surgery [11]. New symptoms may also develop that are different than preoperative symptoms. Even with a symptom-free interval, a variety of possibilities exist that can cause symptoms that are grouped into a diagnosis of recurrent carpal tunnel syndrome. Table 19.1, adapted from Mosier and Hughes [11], summarizes persistent, recurrent, and new symptoms. In this chapter, we introduce an appropriate workup to diagnose true recurrent carpal tunnel syndrome.

Clinical Presentation

The diagnosis of recurrent carpal tunnel syndrome begins with a thorough history, attempting to document symptoms prior to primary carpal tunnel decompression, including details such as nighttime awakening, daytime numbness, whether the numbness was intermittent or constant, and whether the initial symptoms were confined to the median nerve distribution [12, 13]. Pain should be differentiated from numbness, as many patients perceive all wrist or hand pain to be synonymous with carpal tunnel syndrome. In addition, any preoperative electrodiagnostic studies should be obtained. In summary, the anatomic distribution of symptoms, specific symptoms, and exacerbating and alleviating factors if any are all important aspects of the history that will help in diagnosing recurrence.

Following the establishment of the clinical picture prior to the initial diagnosis of carpal tunnel syndrome, one must elicit the patient's description of events surrounding decompression and the return of symptoms. It is important to determine if any symptoms improved or resolved, if any symptoms worsened, and the timing of these. The goal is to determine whether the patient has persistent, recurrent, or new symptoms [11]. An improvement in position-specific symptoms, improvement in paresthesias, or improvement in intermittent pain all point toward a complete release of the transverse carpal ligament. If the same symptoms return after a symptom-free interval, true recurrence is likely. Persistent numbness may be due to chronic compression and does not always improve following complete release of the ligament. One may consider baseline Semmes-Weinstein testing to observe improvement over time [14]. If intermittent symptoms worsen or new symptoms develop immediately following surgery, one has to consider iatrogenic nerve injury. No change in intermittent symptoms may cause one to consider an incomplete release. Of note, at least one study in the literature has found hypertension and

diabetes to be associated with recurrence of carpal tunnel syndrome [15]. Thus, one should still take a full history, including a complete past medical history, family, and social history. Amyloidosis and inflammatory disorders can also cause proliferative tenosynovitis and contribute to symptoms for which a patient is seeking revision carpal tunnel surgery [2].

Another important reason for a detailed history is to determine whether the initial diagnosis of carpal tunnel syndrome was correct. It is possible that a patient presenting with a wide variety of hand and wrist complaints is diagnosed with carpal tunnel syndrome. Conditions such as ulnar neuropathy, basal joint arthritis, or compression of the median nerve proximal to the carpal tunnel are all conditions that may coexist or be mistakenly diagnosed as carpal tunnel syndrome. In addition, the patient may have electrical studies that indicate median nerve compression at the carpal tunnel, but clinical symptoms that are not typical for CTS and do not respond to carpal tunnel release.

Physical Examination

The physical examination should be thorough and include the entire upper extremity, evaluating for other common conditions that may coexist with CTS. In addition, other areas of nerve compression must be ruled out, including compression proximally such as with pronator syndrome and even cervical spine pathology. The exam begins with inspection and comparison to the contralateral limb, beginning at the hand and working proximally. Skin color and any warmth or erythema is noted. Thenar strength is evaluated, noting any atrophy that may be present. The prior incision is also inspected and then palpated. Tenderness anywhere along the incision site is noted as well as tapping on the nerve to illicit a Tinel sign.

The sensory exam is of particular importance. This consists of light touch and two-point discrimination. Decreased two-point discrimination can be a late finding in median nerve compression and may still be present following a complete carpal tunnel release. Similarly, a change in threshold with Semmes-Weinstein monofilament may be present in chronic nerve compression even after complete release. However, this information is useful in comparing the bilateral upper extremities as well as having a comparison to the exam prior to initial release if these data were obtained. When checking two-point discrimination, it is important to be oriented in a longitudinal direction to prevent measurement of the adjacent digital nerve [16].

Motor function of the intrinsic muscles is important in the physical examination for carpal tunnel syndrome. Opposition of the thumb to the little finger is used to test thenar muscle function and median nerve innervation. When testing opposition and strength, one should note that the deep head of the flexor pollicis brevis (innervated by the ulnar nerve) and the flexor pollicis longus can flex the thumb across the palm to the little finger [16].

Specific provocative maneuvers for median nerve compression should be performed in a complete examination of the hand. In cases of compression elsewhere, such as with pronator syndrome, a Tinel sign will be absent over the transverse carpal ligament but present in the proximal anterior forearm. In the event there is compression of the nerve in the distal forearm, possibly from incomplete release of the antebrachial fascia, the patient may have symptoms when tapping on the nerve in this region. If an iatrogenic injury to a branch of the median nerve is being considered, percussion five to eight centimeters proximal to the incision site may lead to the patient localizing paresthesias along the course of the injured nerve [17]. When done over the site of injury, the pain may be too much for the patient to localize. Provocative maneuvers for median nerve compression include the carpal tunnel compression test (Durkan's test), performed by applying manual compression over the transverse carpal ligament for 30 s. Tinel sign and the carpal tunnel compression test are both positive when paresthesias are elicited along median nerve innervation. Phalen and reverse Phalen are performed by maximal flexion (Phalen), and extension (reverse Phalen), held for 60 s to illicit numbness in the median nerve distribution [16].

A thorough physical examination as described above is performed not only for current symptoms but as a comparison for prior symptoms. It further guides the clinician toward recurrent, persistent, or new symptoms and adds to information obtained in the history. For example, thenar atrophy confirms the likelihood of chronic compression of the median nerve. A lack of change in symptoms combined without improvement symptoms post-surgery points toward an incomplete release of the transverse carpal ligament causes persistent symptoms. Pain along the third web space with percussion proximal to the incision site may indicate entrapment or iatrogenic injury of the superficial branch coming off the median nerve to the third web space [17]. Most importantly, comparison of physical exams prior to and post initial carpal tunnel release may provide notable information with regard to the presences of a symptom-free interval or an iatrogenic injury.

Diagnostic Studies

A thorough history and physical exam can lead to the correct diagnosis when considering recurrent CTS and also rule out persistent symptoms, new iatrogenic nerve injury, or an error in initial diagnosis. When recurrent carpal tunnel syndrome is strongly suspected, further studies can be confirmatory, and when the clinical picture is still vague, further studies can provide valuable information in leading one to the correct diagnosis.

Electrodiagnostic studies are often a part of a carpal tunnel syndrome workup. The AAOS guidelines state that they are a good practice in workup and, although they may not be necessary to establish the diagnosis, should be ordered for patients undergoing surgery. For the diagnosis of carpal tunnel syndrome, a distal motor latency greater than 4.5 ms or distal sensory latency greater than 3.5 ms is often considered abnormal [13]. Chronic cases may show electromyography changes with increased insertional activity, fasciculations, and fibrillations of the abductor pollicis brevis. Utilization of electrodiagnostic studies is less clear in the workup for recurrent carpal tunnel syndrome. In cases where no preoperative studies were performed prior to initial carpal tunnel release, new studies may not be helpful. Studies have shown post carpal tunnel release nerve conduction velocities to be increased and not necessarily correlated with outcomes [12, 18]. In addition, there is no evidence to suggest electrical studies return to normal following carpal tunnel release, especially in more severe cases, so abnormal studies following carpal tunnel release can be difficult to interpret. However, in a patient already seeking treatment for continued symptoms, potentially with recurrent carpal tunnel syndrome or initial misdiagnosis, electrodiagnostic studies are valuable to obtain for future comparison even if they do not help with current diagnosis. When preoperative studies were performed, obtaining new studies are helpful. Improvement in electrodiagnostic studies, particularly nerve conduction velocities, indicates successful surgery and complete transverse carpal ligament release [11]. This may lead one away from a diagnosis of recurrent carpal tunnel syndrome when combined with other information from the history and physical examination. The literature varies with regard to worsening nerve conduction studies. Although Jones et al. in 2012 [2] recommended surgery when repeat nerve conduction studies are worse and there are signs of denervation of the thenar muscles, studies by Unglaub et al. [12] and Stutz et al. [18] from 2008 show post carpal tunnel release nerve conduction velocities to be increased for up to 24 months following carpal tunnel release. Thus, electrodiagnostic studies are a good adjunct when combined with a complete history and physical exam, but they need to be interpreted on a case-by-case basis in developing an accurate diagnosis of recurrent carpal tunnel syndrome.

A corticosteroid injection is often a useful nonsurgical management option in both primary and recurrent carpal tunnel syndrome. In primary carpal tunnel syndrome, it is known as a predictor of surgical success. Edgell et al. in 2003 [19] reported a surgical success rate of 87% in patients who had relief with a corticosteroid injection,

compared to 54% in patients who did not. Beck et al. [20] looked at predictive value of corticosteroid injection for recurrent carpal tunnel syndrome. The authors discovered similar rates when looking at surgical success rate in patients who had relief with a corticosteroid injection (87%) compared to those who did not (60%). However, this positive trend did not reach clinical significance. Using their data, the authors did note relief from injection as a diagnostic test for successful revision carpal tunnel release to have an 87% sensitivity, 87% positive predictive value, and 40% specificity.

Imaging

Radiographs are often a part of the initial visit in the office setting for any patient with wrist pathology. In the initial workup for carpal tunnel syndrome, radiographs are not required, and it is uncertain whether there is any merit to obtaining them due to the low likelihood of influencing the workup for a typical case of carpal tunnel syndrome [13]. Similarly, in the case of recurrent carpal tunnel syndrome, there are no data to suggest that wrist radiographs are necessary. In cases where a history of trauma produces the symptoms for which a patient is seeking medical attention, they may be obtained as per standard workup.

AAOS guidelines recommend against the use of MRI in the routine evaluation of patients with carpal tunnel syndrome. Similarly, no data exist to provide a framework for the use of MRI in working up recurrent carpal tunnel syndrome. However, it once again falls to a case-by-case basis, and it can be certainly helpful in defining pathologic anatomy that may or may not have been considered in a workup [11]. In 2006, Stutz et al. [10] reported on 200 revision carpal tunnel surgeries with intraoperative finding noting two ganglions, one lipoma, and one fibroma. This small group of findings could have been diagnosed via MRI prior to revision surgery and given the surgeon a definitive cause, but likely would not have changed treatment. A challenge in the interpretation of an MRI post carpal tunnel release is the lack of knowledge regarding the appearance of a released transverse carpal ligament and the normal amount and appearance of synovium [6]. Prospective studies to determine this would be expensive and difficult to perform without an agreed upon reference. However, obtaining an MRI remains an option to the clinician working up recurrent carpal tunnel syndrome if he or she has a specific question in mind that it can address.

Conclusion

Diagnosis of recurrent carpal tunnel syndrome is complex. One cannot take one piece of the history or an individual provocative maneuver during the physical exam as being predictive in terms of a correct diagnosis. However, used in combination, a thorough history, detailed physical examination, and appropriate diagnostic tests and imaging can be combined to give an accurate diagnosis. In 2012, Jones et al. [2] determined a positive Phalen test, weak abductor pollicis brevis compared to the contralateral side, and subjective splitting of ring finger sensation as the most important parts of the physical exam during the evaluation for recurrent carpal tunnel syndrome. Also in 2012, Beck et al. [20] used multivariate logistic regression analysis to determine numbness or weakness in the median nerve distribution, combined with a positive carpal tunnel compression test, positive Phalen test, and relief with corticosteroid injection provided a sensitivity of 100% and specificity of 80%.

Thus, a complete history and physical examination remain the foundation for the workup of recurrent carpal tunnel syndrome. Further tests are indicated based on information obtained by the clinician with a detailed history and appropriate examination. Electrodiagnostic studies should be pursued even when they are unlikely to help with the current workup, as they may be useful in the future. Radiographs or an MRI is used when specifically looking for pathology that one can diagnose based on images, although as normal post carpal tunnel release imaging is better defined, an MRI could be useful in evalu-

ating the amount of scar formation and volume in the carpal tunnel. Confidence in an accurate diagnosis is necessary as it dictates the appropriate treatment and optimizes the patients' chances for a successful outcome following revision treatment.

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Use of Reverse Radial Forearm Fascial Flap for Median Nerve Coverage

20

Regina M. Meis and Scott F.M. Duncan

Indications (Complications of CTR that May Necessitate Flap Coverage)

The goal of open surgery for carpal tunnel syndrome is to achieve sufficient exposure to fully decompress the median nerve by sectioning the transverse carpal ligament. Key structures at risk in this procedure include the superficial palmar arch and the median nerve itself. These and any anatomical anomalies present add to the complexity of an otherwise straightforward approach to the carpal tunnel. Of course, as with every surgery, appropriate postoperative healing is essential in obtaining a successful result. Thus, suboptimal outcomes in carpal tunnel release may be due to a number of factors.

In 2001, MacKinnon et al. classified failed carpal tunnel releases into three categories based on the temporal and qualitative nature of the symptoms: persistent, recurrent, and new [1]. Assuming carpal tunnel syndrome secondary to median nerve compression at the level of the wrist was the correct preoperative diagnosis, persistent symptoms are most frequently a result of incomplete release. It is usually the distal portion of the transverse carpal ligament that evades transection, although in posttraumatic carpal tunnel syndrome, scarring of the antebrachial fascia can lead to residual compression proximally. Inadequate exposure is the most likely reason for these cases, which argues against the use of limited incision or endoscopic surgery.

The etiologies of recurrent symptoms, where the patient experienced temporary relief for a short period but returns with the same preoperative complaints, are more nebulous. Postsurgical scarring occurring in such a manner as to reform the transverse carpal ligament or adhere to the nerve will recreate a compressive or traction environment. Appropriate healing of the transverse carpal ligament should ideally result in an increase in volume within the carpal canal, where the tendons and median nerve maintain their configuration and can still glide freely.

Altogether new postoperative symptomatology is usually either iatrogenic or an undesired consequence of the inflammatory process. The most common structure at risk for iatrogenic injury in carpal tunnel surgery is the palmar

R.M. Meis (✉)
Department of Orthopaedic Surgery,
Boston University Medical Center, Boston, MA, USA
e-mail: reginameis@gmail.com

S.F.M. Duncan
Department of Orthopedic Surgery, Boston University/Boston Medical Center,
Boston, MA, USA

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cutaneous branch of the median nerve, where subsequent neuroma formation can be quite painful to patients. A common vascular structure injured is the superficial palmar arch. A hematoma in the palm can potentially lead to necrosis of the overlying skin. Suboptimal healing conditions can lead to complications such as perinervous fibrosis or a flexor tendon hypertrophic synovitis. Anterior displacement of the median nerve within the two edges of the cut flexor retinaculum can trap the median nerve and/or its recurrent motor branch within the scar tissue [2].

Revision surgery will often reveal the issue, whether it be incomplete release of the transverse carpal ligament at the index surgery, fibrosis surrounding the newly released median nerve, or damage to some other structure. A number of treatment options exist for many of these complications. One method relies on soft tissue coverage for those complications in which the goal is to create an environment of smooth gliding where the nerve is insulated from tissue that will tether it and possibly constrict it. This chapter focuses on the reverse radial forearm flap as a potential solution.

The reverse radial forearm flap can be a very useful tool in the reconstructive armamentarium. It is based on the vascular territory supplied by the radial artery and relies on the redundant blood supply to the hand, such that the radial artery can be harvested. The flap can be elevated with skin for a fasciocutaneous flap and even with the bone for an osteocutaneous flap. However, sacrificing the radial artery has the associated disadvantages of donor-site morbidity and potentially inferior aesthetics. Where only soft tissue coverage is needed, a convenient fasciosubcutaneous alternative is available that spares both the artery and overlying skin. For the purposes of insulating the median nerve in failed carpal tunnel release, this last option is fitting.

Contraindications

The success of the flap relies on the ability to maintain perfusion. As such, patients at risk for microvascular disease may not be suitable candidates. Risk factors include smoking, diabetes, vasculitides, coagulopathies, and venous insufficiency. A history of trauma to the forearm may indicate the native anatomy is no longer intact. While preoperative imaging (angiography, ultrasound) is of little benefit for elucidating the pertinent microvasculature [3], it is warranted for determining the candidacy of the patient.

Anatomy

The vascular anatomy of the forearm is founded on the bifurcation of the brachial artery at the antecubital fossa into the ulnar and radial arteries. These two come together in the palm to form the superficial and deep palmar arches. An Allen test is performed to confirm the patency of these two arteries. If both are patent, then the radial artery is available to be sacrificed for the graft. However, it may be the case that the arches are incomplete or that disparate filling times suggest one artery is dominant. This would require reconstruction of the radial artery with a vein graft. Preservation of the radial artery is possible by taking advantage of its perifascial vascular network.

The radial perforator fascial flap can be characterized as an axial flap based on its longitudinally oriented vasculature [4]. As the radial artery courses through the forearm, small perforating branches supply the surrounding muscle, fascia, and skin. Vascular mapping of these vessels in the forearm [5] shows two main clusters of perforating arteries, one in the proximal third of the forearm and one in the distal fifth. Notably, the major perforator in the distal fifth was consistently found within 2 cm of the radial styloid. The study showed linking vessels connecting these perforators, with retrograde flow from the distal perforator cluster and antegrade flow in the proximal grouping. Tao et al. described four types of arteries in the forearm fasciocutaneous flap: direct cutaneous, musculocutaneous, intermuscular space cutaneous, and intermuscular septal cutaneous [6]. These authors determined that the intermuscular space cutaneous artery is the main contributor of blood supply to the flap. Anastomoses between

the intermuscular space and septal cutaneous arteries are organized into rows and oriented longitudinally along the axis of the forearm [7]. This property allows for the tissue to be elevated and transposed without losing its blood supply. Successful harvesting of these flaps requires an awareness of the anatomy so as not to disrupt these vascular territories.

Postoperative venous congestion can also threaten flap survival. Venous drainage needs to be a consideration during surgical planning. The forearm has two main venous systems: the superficial system (the cephalic and basilic veins) and the deep system (the venae comitantes). Studies looking into the venous drainage of these flaps have shown an intricate network exists between the superficial and deep veins with collateral branches and communicating branches functioning to bypass valves that may prevent drainage. Initial engorgement of the veins after transposition was followed by resolution of the edema and improved perfusion, suggesting valve "deactivation" once a certain intravenous pressure is reached [8–10]. The theory of valve incompetence [11] as the mechanism for reverse venous flow is still under debate. According to Chang et al., superficial venous valves do not become incompetent and suggested that the cephalic vein may need to be ligated to avoid deleterious venous congestion [12]. Still, though there remains much to be elucidated with regard to mechanisms of drainage in these flaps, it appears that the venous plexus that exists eventually feeds into the venae comitantes, and congestion does not appear to be a major problem clinically.

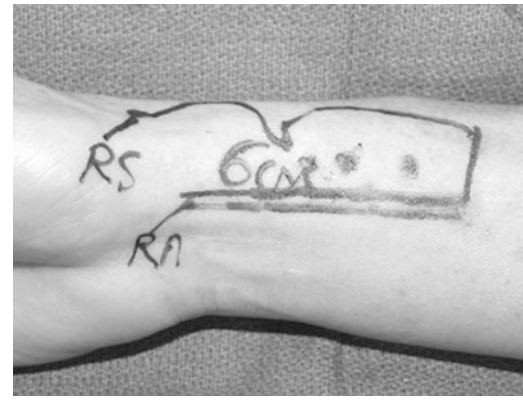

Fig. 20.1 Outline of radial artery and the perforators as identified by ultrasound

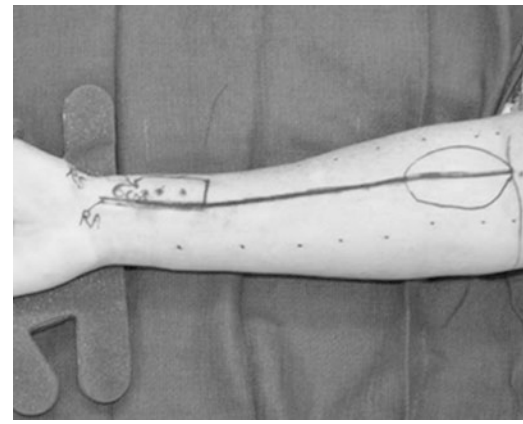

Fig. 20.2 The forearm marked out with the incision and dissection margin

Reverse Radial Forearm Flap

Surgical Technique

The patient is positioned supine with an arm table. The procedure should be performed with magnification available. Although the radial artery is not harvested here, an Allen's test should be performed at the beginning of the case in the event the radial artery is injured during the operation (Fig. 20.1). A tourniquet is placed. After appropriate prepping and draping in the usual sterile manner, the extremity is exsanguinated and the tourniquet inflated to 50 mmHg above the patient's systolic blood pressure.

For revision carpal tunnel cases, the incision will begin at the site of the previous scar. Perform a carpal tunnel release, ensuring the median nerve is circumferentially freed from any tethering or compressive structures. Debride scar tissue as necessary, taking care not to injure any important adjacent structures. To proceed with the flap, the incision is then extended, directed radially past the wrist crease to the level of the mid-forearm, where it then proceeds longitudinally along the axis of the forearm to within a few centimeters of the elbow crease (Fig. 20.2). Elevate the skin with care not to denude the

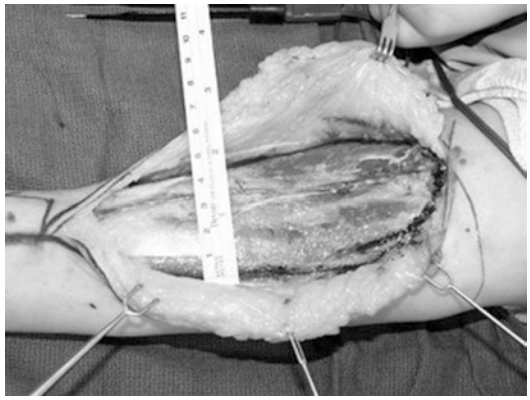

Fig. 20.3 Skin flaps elevated and fascial flap measured and outlined with a marker

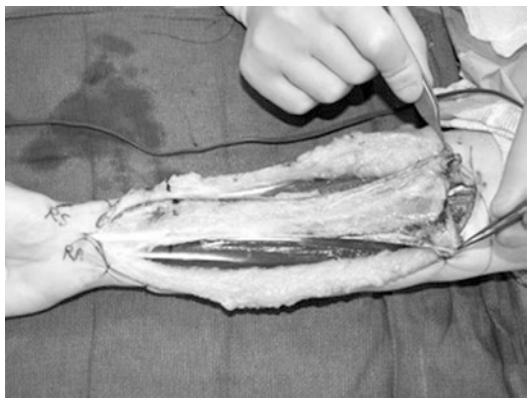

Fig. 20.4 Fascial flap elevated with radial perforators preserved

undersurface completely of fat (Fig. 20.3). Next, develop the flap by elevating the fat and deep fascia overlying the forearm flexors. Make two longitudinal incisions, centered over the intermuscular interval of the FCR and brachioradialis. That is, 2 cm on either side making the flap approximately 4 cm in width. Keep the fat and fascia together to preserve the small perforating vessels (Fig. 20.4). Recall that most of these will be clustered at the proximal third and distal fifth of the forearm [5]. Proximal perforators should be ligated as necessary to ensure flap can be rotated; the distal perforators will maintain the vascularity of the flap. Preserve the lateral antebrachial cutaneous nerve proximally when transecting the flap which will be approximately

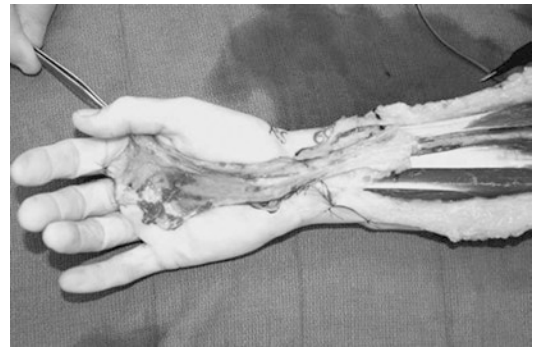

Fig. 20.5 Rotation of the fascial flap into the carpal canal to cover the median nerve

5 cm in length. Form the rectangular flap by transecting it proximally so that it remains attached distally. Once the flap is elevated, this distal end is turned 180 degrees toward the median nerve (Fig. 20.5). Ensure that the pivot point is proximal enough so as not to cause any kinks in the flap; this will be at least 4 cm from the radial styloid [13]. The flap should also be twisted such that the fascia is now superficial and the fat is in direct contact with the nerve. Envelop the nerve within the fascia for the full length afforded by the flap, extending both proximally and distally into the palm. Range the wrist to ensure sufficient laxity prior to suturing. The nerve should move freely within the newly created gliding interface. The flap should be sutured in place with fine absorbable sutures. The tourniquet is released at this point to confirm viability of the flap. The incision is then sutured over the flap with a standard skin closure.

- Whether ligation of the cephalic vein is necessary or not remains in question. One may ligate it at the beginning or choose to wait until the tourniquet is down to observe the degree of congestion if any [3].
- Remember to preserve both the lateral antebrachial cutaneous nerve proximally and the superficial radial nerve distally.
- Both the lateral antebrachial cutaneous nerve and the radial sensory nerve may have small branches transected during the procedure. Every effort should be made to be aware of these and

bury them within the adjacent muscles to prevent neuromas and skin sensitivity [14].
- Obese patients may have larger amounts of fat. In these cases, leave a larger layer of subcutaneous fat attached to the dermis as the skin flaps are elevated. If the final flap is too bulky, trimming should occur on the fat side since the perforators are running along the fascia [13].
- A drain may be placed at the surgeon's discretion.
- Postoperative splinting with bulky dressings is recommended for wound protection.

Clinical Results

The need for soft tissue coverage in treating persistent or recurrent median nerve symptoms depends largely on the intraoperative findings at the second operation. If the pathology is found to be due to incomplete release of the transverse carpal ligament distally or the antebrachial fascia proximally, or palmar subluxation of the median nerve, then it is not clear that soft tissue coverage would be beneficial. Interposition of a biological barrier between the median nerve and its surroundings is indicated in those situations where the postsurgical environment is the problem, namely, excessive scar tissue. Compression or tethering of the nerve by this fibrosis and adhesions around the nerve could potentially be avoided by wrapping the nerve in vascularized tissue that will provide a smooth gliding environment for the nerve [15].

Other procedures have been developed and employed for soft tissue envelopment of the median nerve. Two examples that have been successfully applied include the hypothenar fat pad flap [16, 17], the abductor digiti minimi flap [18]. A retrospective study looking at 28 patients undergoing microneurolysis and hypothenar fat pad flap coverage for recurrent carpal tunnel syndrome demonstrated positive outcomes with improved postoperative grip strength and decreased pain levels [15]. However, re-exploration of the carpal canal in these patients will often show fibrosis extending proximally up to the antebrachial fascia. In these cases, more tissue than what is generally available with a hypothenar fat pad would be required to completely isolate the median nerve. Some of the disadvantages of these methods include limited arc of rotation, size limitations in terms of shaping the bulk and area of the flap. Some of these studies also mention the technical challenges with these procedures.

With regard to the radial forearm flap, the perforator-based flap was developed in an attempt to spare the radial artery and create an easily customized adipofascial flap in terms of size and shape. This perforator-based flap has been successfully applied to tendons in recurrent De Quervain's syndrome [19] where fibrosis within the first dorsal compartment rendered simple surgical decompressions futile. Whether harvested on its own or with the overlying cutaneous tissue, a number of case reports and case series have demonstrated its utility in obtaining soft tissue coverage of both palmar and dorsal defects in the hand [10, 14, 20–23]. It has shown success with nerve coverage as well.

In 1996, Tham et al. published a series of six patients with recurrent carpal tunnel syndrome, all of whom had at least one revision carpal tunnel release [11]. These patients underwent a re-exploration of the nerve and elevation of an adipofascial flap to wrap around the medial nerve. All patients had good to excellent results. Similarly, in a study of eight patients with recurrent carpal tunnel syndrome where all patients had undergone surgical decompression and three had undergone at least one revision carpal tunnel release, Mahmoud et al. showed improvement and/or complete resolution of both motor and sensory symptoms in all patients [24]. Both of these studies included parameters such as two-point discrimination, presence or absence of Phalen's and Tinel's signs, residual paresthesias, and patient-reported satisfaction as outcome measures. No patients in these series required a reoperation for persistence, recurrence, or complications at a mean of 25 and 20 months, respectively.

The radial artery-based perforator adipofascial flap for coverage of the median nerve in recurrent carpal tunnel syndrome has been very useful in providing a vascularized smooth gliding environment to protect the nerve from post-

surgical fibrosis. Advantages of this flap include sparing of the radial artery and a larger area of tissue from which to harvest an appropriately sized flap. Disadvantages will include a larger scar extending up the forearm, but this has not been shown to be of concern to patients in the available studies, likely because in most of these cases, primary skin closure is not a problem. Knowledge of the vascular pedicles of the forearm is of the upmost importance, and mapping out the perforators and an ample pivot point are crucial to the success of the flap. Recurrent carpal tunnel is rare, and as such, there are limited studies with small numbers of patients available, but what is available shows good outcomes with this flap. Grip strength, two-point discrimination, and return to work statistics have all shown improvement. There are no reports of patients having reoperation for recurrence or persistence after this procedure.

Summary

The use of a reverse radial forearm fascial flap for coverage of the median nerve is a viable option in providing coverage for the scarred or injured median nerve. This technique can also be useful in situations where the palmar skin cannot be completely closed; as after a period of time, granulation tissue will form on the fascial flap, allowing skin grafting if needed.

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Vein Wrapping for Recurrent Carpal Tunnel Syndrome

21

Loukia K. Papatheodorou and Dean G. Sotereanos

Introduction

Carpal tunnel syndrome, compression of the median nerve at the wrist, is the most common entrapment neuropathy in the upper extremity [1]. Although carpal tunnel surgical release is generally considered efficacious, recurrence of symptoms of carpal tunnel syndrome can occur in up to 30% postoperatively [2–4]. The persistence of symptoms of carpal tunnel syndrome is commonly associated with incomplete initial release of the transverse carpal ligament, whereas recurrence of symptoms, after a distinct symptom-free period, is usually secondary to scarring or cicatrix around the median nerve at the site of the initial decompression [4, 5].

The treatment of recurrent carpal tunnel syndrome is much more difficult than treatment for the primary disease. Simple revision median nerve decompression or accompanied with neurolysis, external or internal, does not always lead to sufficient relief of symptoms. Repeated nerve decompression can enhance scar formation of the median nerve with the surrounding tissue, developing further compression of the nerve, resulting in traction or adhesive neuritis [5]. The optimal treatment may involve a combination of procedures.

Many investigators agree that after revision neurolysis of the median nerve, it is essential to cover the segment of scarred nerve with a soft tissue barrier to prevent scar tissue reformation from contacting the epineurium. In light of this, several surgical techniques have been attempted, ranging from nerve wraps to free flaps. The hypothenar fat pad flap can provide good results and is uncomplicated in most cases [6–8]. Pedicle or free flaps, including the groin flap and posterior interosseous flap, provide excellent protection of the median nerve, but the technique is complex and the results are not always satisfactory [9, 10]. Small local flaps, such as the abductor digiti minimi muscle flap, the pronator quadratus muscle flap, the palmaris brevis turnover flap, and lumbrical flap, have also been used. However, many of these flaps require technically demanding dissection, nerve coverage is sometimes insufficient, and problems may occur in skin closure [11, 12].

Several materials, such as allograft or autograft vein grafts, and synthetic devices have been used as adhesion barriers for recurrent carpal tunnel syndrome. The first clinical report of vein wrapping of a scarred peripheral nerve is attributed to Masear et al. [13]. Subsequent reports discussed the clinical applications of both autograft

L.K. Papatheodorou • D.G. Sotereanos (✉)
Department of Orthopaedic Surgery, University of Pittsburgh School of Medicine, Orthopaedic Specialists - UPMC, 9104 Babcock Blvd, 5th Floor, Pittsburgh, PA 15237, USA
e-mail: papatheodoroulk@upmc.edu; dsoterea@hotmail.com

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and allograft vein wrapping for recalcitrant carpal tunnel syndrome, and the experimental confirmation of these clinical observations followed [14–23]. The ideal nerve wrapping material should prevent adhesions and inhibit scar reformation around the previously scarred segment of the nerve, protecting the nerve from further compression and improving median nerve gliding during wrist motion.

Basic Science

The efficacy of autologous vein wrapping of scarred nerve was studied by our group in a rat model [16, 17]. Initially, the sciatic nerve in 30 rats was wrapped with autologous vein to study the safety of the procedure. No adverse effects on the nerve were recorded and no demyelinization, nerve degeneration, or adhesion formation. Then, an experimental chronic nerve compression model was created in 100 rats. The sciatic nerve of rats was constricted with a silicone tube, and nerve deficits were confirmed at 8 months. Animals were then randomly allocated in a vein-wrapping or a control group. The sciatic nerves in the vein-wrapping group showed greater functional improvement than those in the control group. In electrophysiologic testing the latency was significantly shorter in the vein-wrapping group. Histologic evaluation showed no scar tissue formation between the vein intima and the nerve in the vein-wrapping group but marked nerve degeneration and scar tissue formation around the nerve in the control group. These studies showed that the autologous vein graft could prevent adhesion around the nerve and improve the functional recovery of the nerve.

Human histopathologic analysis from re-exploration of autologous vein-grafted nerves further confirmed the inhibition of scar formation around the nerve [18]. These biopsies also revealed a structural transformation of the vein endothelium with neovascularization of the vein graft [19].

Allograft vein wrapping with the use of allograft umbilical veins was used clinically before autogenous vein wrapping with good results [13]. However, the autologous vein graft has been found to create fewer adhesions between the vein and the nerve compared with vein allografts. Ruch et al. [14] compared the femoral vein autografts with glutaraldehyde-preserved allografts in an animal rat model and found a significant increase in inflammatory cells and scar tissue associated with the allograft. If the allograft vein adheres to the nerve, the gliding between the nerve and the vein might be impaired, which may have a negative effect on recovery.

Autologous vein wrapping appears to prevent scar formation, extrinsic and intrinsic. Even though the mechanism still remains uncertain, histopathologic analysis and clinical observations from re-explored nerves have shown that prevention of epineurial adhesions, preservation or restoration of intrinsic epineurial vascularity, and formation of a gliding surface between the nerve and the surrounding tissues contribute to the good clinical results [19]. These findings suggested that locally produced molecules from either the nerve, the vein graft, or both may be responsible for the neovascularization and structural transformation of the endothelium of the vein graft.

A recent experimental study in a rat animal model for chronic nerve constriction injury further confirmed this hypothesis [20]. Concentrations of vascular endothelial growth factor (VEGF) and hepatocyte growth factor (HGF) in the ligated sciatic nerves were significantly higher in the vein-wrapping group suggesting that these neurotrophic factors may play a mechanistic role in the neovascularization and structural changes observed in vein graft. Additionally, immunohistochemistry analysis revealed prevention of upregulation of markers of inflammatory and nerve damage in the vein-wrapping group indicating that vein wrapping decreased pain-associated behavior and nerve damage caused by chronic constriction injury.

Indications

The primary indication for vein wrapping is significant epineurial scarring. Careful preoperative evaluation can guide patient selection for this

technique, but intraoperative confirmation of nerve scarring is essential. This technique is indicated for recalcitrant carpal tunnel syndrome in patients with at least two previous operations which failed to resolve the symptoms and in patients with significant nerve scarring or neuroma formation. The technique is not recommended in patients with chronic lower extremity venous insufficiency.

Patients usually present with recurrent symptoms after an adequate surgical decompression. It must be noted that there is a distinct period of improvement after the previous surgery or a subsequent neurolysis before symptoms recurred. The absence of even transient symptomatic relief after the initial surgery could signify inadequate decompression. The chief complaint of patients is severe pain which worsens with activities and paresthesias. Numbness is also an important patient concern. Most patients have abnormal two-point discrimination and positive Tinel's sign. Muscular atrophies are relatively uncommon, and when present, they are indicative of more severe intrinsic scarring of the median nerve. Electrodiagnostic testing often shows decreased electrical amplitude and sensory conduction after stimulation of the nerve; muscle denervation is seen less often.

Before revision surgery, a consultation by a vascular surgeon is recommended in patients with peripheral vascular disease or deep venous thrombosis history. The saphenous vein is a major source of vein grafts in reconstructive and cardiac surgery, and this should be taken into consideration in patients with coronary heart disease.

Operative Technique

The autologous vein wrapping procedure is performed under general anesthesia because of the need to have two operating fields, one for the median nerve re-exploration in the upper extremity and another for the harvesting of the saphenous vein in the lower extremity. This procedure involves median nerve repeated decompression with neurolysis, harvesting the greater saphenous vein of the lower extremity, preparing the vein properly, and then wrapping the vein around the compressed nerve segment.

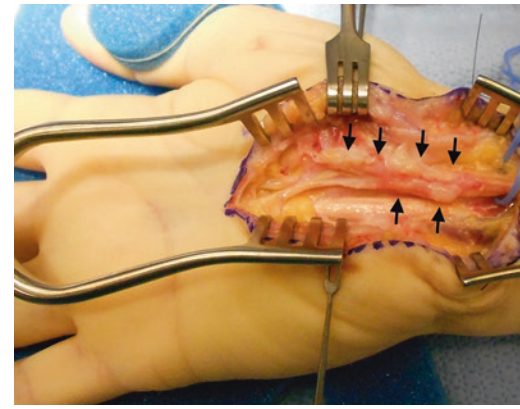

Fig. 21.1 The median nerve has been exposed at the wrist. Note the excessive cicatrix (*black arrows*) around the median nerve

The affected median nerve is surgically explored first at the wrist, and the vein harvesting is initiated only after the affected nerve is dissected and is found to be severely scarred (Fig. 21.1). Previous incisions for carpal tunnel release are used for the revision surgery and extended both proximally and distally to identify the compressed median nerve in an unscarred environment. The dissection should always begin in virgin tissues and traced distally. If excessive scarring of median nerve is noted, an internal neurolysis is performed under the microscope. Care is taken to measure the length of the segment of the median nerve that has to be vein wrapped. The required length of the vein graft is four to five times the scarred length of the nerve. A vein graft length of 25–30 cm is usually needed.

The greater saphenous vein graft is harvested from the ipsilateral or contralateral lower extremity. The vein graft can be harvested with a vein stripper to minimize the length of the incision and the morbidity of the donor site (Fig. 21.2a, b). A longitudinal incision (approximately 2 cm long) is made 1 cm anterior to the medial malleolus, and the greater saphenous vein is identified. Care is taken to avoid injury to the associated saphenous nerve. The saphenous vein is ligated distally, and a small longitudinal phlebotomy is made. The vein stripper is introduced through the phlebotomy and is advanced proximally within the vein. The vein stripper guide can be palpated through the skin, as it is advanced to the predeter-

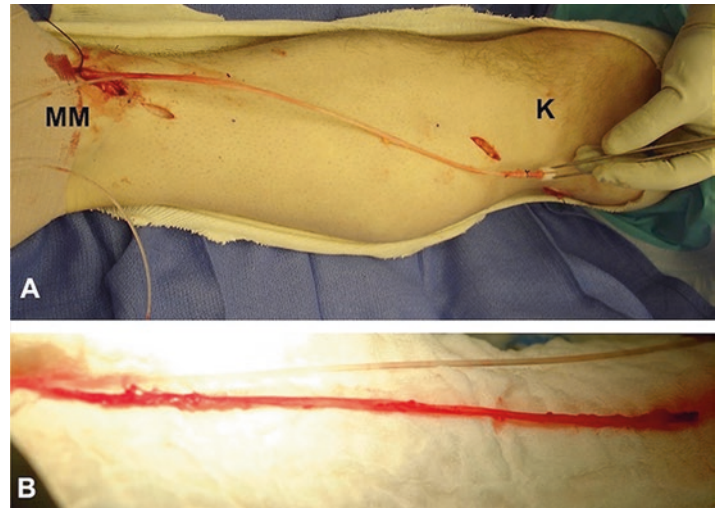

Fig. 21.2 (**a**) Harvesting of greater saphenous vein graft in the lower extremity using a vein stripper (*K* knee, *MM* medial malleolus). (**b**) Greater saphenous vein graft

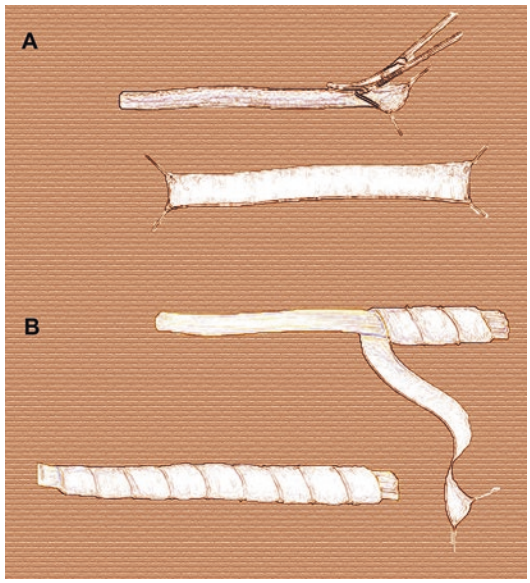

Fig. 21.3 Schematic of vein wrapping technique. (**a**) The saphenous vein graft is split longitudinally and is open to create a rectangle. (**b**) The saphenous vein graft is then wrapped around the scarred segment of the nerve with its intima against the nerve

mined length. At that point, a second incision is made over the stripper proximally, and the vein is ligated proximally. The vein stripper guide is advanced out of the vein through a second longitudinal phlebotomy. The vein graft is retrieved by slowly pulling out the stripper. The skin is closed and the leg tourniquet is deflated. Alternatively, the vein can be harvested through a continuous incision or interrupted incisions and dissection without the use of a vein stripper.

The vein graft is incised and opened longitudinally (Fig. 21.3a). With the intima of the vein graft against the nerve, the vein graft is wrapped carefully around the scarred segment of the median nerve (Fig. 21.3b). One of the ends of the graft is tacked distal to the scarred segment of the nerve on an immobile tissue. The vein graft is circumferentially wrapped around the exposed median nerve from distal to proximal. Each loop of the vein is loosely tacked to adjacent loop using a 7–0 Prolene stitch (Fig. 21.4). Wrapping should not be too snug. The other end of the vein graft is tacked proximal to the scarred segment of the nerve on unscarred tissue. During the wrapping procedure, care is taken to avoid nerve traction or suture of the vein to the median nerve. It is important for the entire segment of the scarred median nerve to be completely covered with the vein graft to prevent recurrence of the scarring (Fig. 21.5). The tourniquet is deflated, meticulous hemostasis is obtained, and routine closure is performed.

Postoperatively, the wrist is immobilized in slight extension for 2 weeks, and active and passive range of motion exercises are followed. Additionally, scar massage, desensitization, and strengthening exercises can also be initiated, if required. Heavy lifting is to be avoided for 6 weeks after surgery.

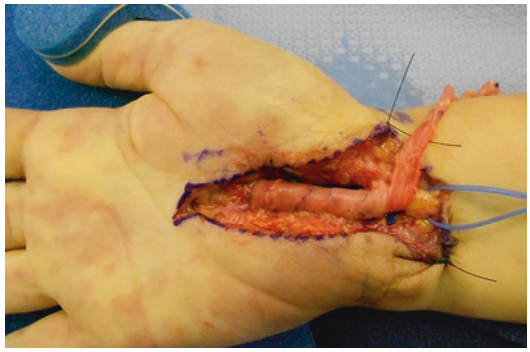

Fig. 21.4 The autologous vein graft is wrapped around the scarred segment of the median nerve in a distal to proximal direction with its intima against the nerve. Each ring of the wrapped vein is tacked to the adjacent rings with a 7–0 Prolene stitch

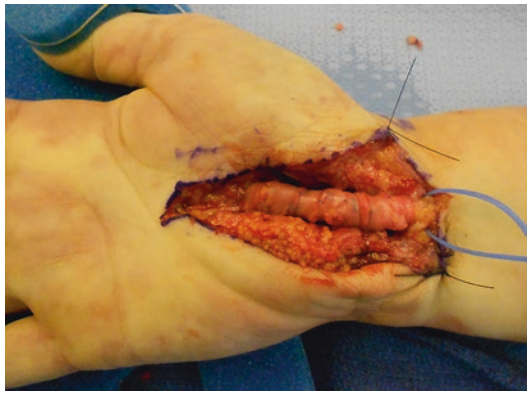

Fig. 21.5 The autologous vein graft is covering the entire scarred segment of the median nerve

Clinical Data

The use of the autologous vein wrapping as a supplementary technique to treat recurrent carpal tunnel syndrome secondary to cicatrix of the median nerve has been showed to be an effective treatment method in several clinical studies [16, 21–23]. Improvement of the pain and sensation were significantly noted in the majority of patients with recalcitrant carpal tunnel syndrome after autologous vein wrapping of the previously scarred median nerve. The grip strength and two-point discrimination were also improved postoperatively. Follow-up electrodiagnostic studies in several patients revealed improvement in motor and sensory nerve conduction velocities, although they did not return to normal values. The procedure was well tolerated in most individuals, and no complications due to the saphenous vein graft harvesting were noted except transient leg swelling at the donor site that resolved in approximately 6 months.

Since the original clinical series, consistently good results with the autologous vein wrapping technique have been noted in more than 100 patients with recurrent carpal tunnel syndrome and severe median nerve scarring in the senior author's (D.G.S.) personal series.

Based on the senior author's (D.G.S.) clinical experience, repeated median nerve decompression should always be performed in combination with an ancillary technique to enhance scar-free healing of the nerve. For patients with recalcitrant carpal tunnel syndrome, multiple operations and excessive scarring of the nerve, we perform revision decompression, repeated neurolysis of the median nerve (external as well as possible internal) with autologous vein wrapping of the median nerve and coverage with hypothenar fat pad flap.

In summary, both experimental and clinical studies demonstrate that autologous vein wrapping is an efficacious/excellent adjuvant procedure for the treatment of recurrent carpal tunnel syndrome secondary to scarring of the median nerve.

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Synovial Wrap in Revision Carpal Tunnel Surgery

22

Ryosuke Ikeguchi

Introduction

The surgical management of recurrent carpal tunnel syndrome remains a challenge for hand surgeons as there is no standardized procedure to treat the condition [1]. In 1972, Langloh and Linscheid [2] published a series of 34 recurrent and unrelieved carpal tunnel syndrome cases. They reported that fibrous proliferation within the carpal tunnel is the most common factor implicated in recurrent carpal tunnel syndrome. Millesi et al. [3] published a biomechanical study of the surrounding tissues on the tensile properties of peripheral nerves. They reported that scar tethering of the median nerve in the carpal tunnel leads to stiffening and increases the loading on the nerve, which results in pathological nerve changes and the development of an epineural fibrous fixation syndrome called "traction neuropathy." In revision carpal tunnel surgery, hand surgeons should take this pathophysiology into consideration in order to prevent this condition.

A 10-year review of revision carpal tunnel surgeries revealed that the common intraoperative findings in revision surgery are incomplete release of the flexor retinaculum and scarring of the median nerve [4]. In terms of outcomes of surgical treatment for revision carpal tunnel syndrome, it was reported that decompression followed by additional vascularized flap coverage appears to have a higher success rate than simple decompression [5]. The principles of surgical revision for recurrent carpal tunnel syndrome involve flexor retinaculum release, median nerve decompression, scar tissue removal, external neurolysis, and median nerve coverage with vascularized flap, which prevents perineural scarring, enables neovascularization, and permits nerve gliding.

Numerous surgical procedures have been described in the literature that involves wrapping the median nerve in the carpal tunnel, including vein grafts [6], implants [7], reverse radial artery perforator fascial flaps [8], abductor digiti minimi muscle flaps [9], pronator quadratus muscle flaps [10], palmaris brevis muscle flaps [11], flexor digitorum superficialis muscle flaps [12], hypothenar fat flaps [13, 14], synovial flaps [15, 16], and free flaps [17]. Among these procedures, this chapter focuses on the synovial flap and describes its anatomical considerations, surgical techniques, and outcomes.

R. Ikeguchi (✉)
Department of Orthopaedic Surgery and Rehabilitation Medicine, Kyoto University Graduate School of Medicine, 54 Shogoin-Kawahara-cho, Sakyo, Kyoto 606-8507, Japan
e-mail: ikeguchi@kuhp.kyoto-u.ac.jp; ikeguchir@me.com

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Anatomy

Various researchers have performed anatomical studies of the synovial vascularization of the wrist. Zbrodowski et al. [18] reported that the synovial sheath at the level of the wrist is mostly supplied by direct branches of the radial and ulnar arteries and that the superficial palmar arch is predominant at the distal part of the carpal tunnel to vascularize the flexor synovial sheath. In the blood supply for the synovial sheaths of the hand, the radial and ulnar arteries supply the proximal area of the superficial part of the synovial tendon sheaths [19]. The deep layer of the carpal synovial tendon sheaths is supplied by the palmar carpal arch, and the deep palmar arch provides the blood supply for the palmar parts of the synovial tendon sheaths. De la Garza et al. also reported that the ulnar artery supplied the medial part of the synovial flexor tendon sheath. Pelissier et al. [20] dissected 24 fresh adult cadavers. They injected colored latex solutions in the radial and ulnar arteries of 18 upper limbs and a radiopaque mixture of barium sulfite and blue dye in the radial and ulnar arteries of six limbs. They reported that, at the level of the wrist and carpal tunnel, the synovial sheath is supplied by direct branches from the ulnar artery (Figs. 22.1 and 22.2). These direct branches originate from the ulnar artery 2–5 centimeters proximal to the pisiform bone and run between the flexor tendons of the ring and small fingers as far as the superficial palmar arch. Mean artery diameter was 0.8 mm (range: 0.6–1.2 mm). A flap microangiogram revealed the vascular network within the flap. The mean flap length and width were 4.8 cm (range: 4.2–6 cm) and 3.5 cm (range: 3.1–4.5 cm), respectively. These studies showed that the synovial flap is consistently supplied by a vascular pedicle arising from the ulnar artery above the proximal border of the transverse carpal ligament.

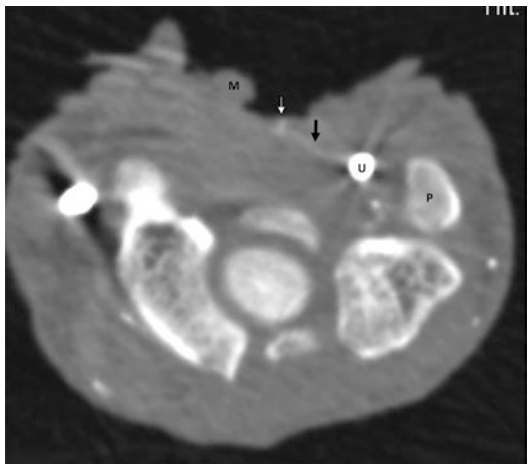

Fig. 22.1 Intraoperative computed tomography (CT) angiogram at the level of the pisiformis after performing external neurolysis of the median nerve (Artis Zeego, Siemens AG, Germany). The direct branch of the ulnar artery to the flexor synovium is identified. *P* pisiform, *M* median nerve, *U* ulnar artery, *Large arrow* the direct branch of the ulnar artery to the flexor synovium, *Small arrow* artery in the flexor synovium

Indications and Contraindications for the Synovial Flap Technique

In revision carpal tunnel surgery, incomplete release of the flexor retinaculum in the previous surgery and scarring of the median nerve to overlying structures are common findings [4]. Perineural fibrosis of the median nerve, which involves dense scar tissue surrounding the median nerve trunk, makes the median nerve adhere to the wall of the carpal tunnel. The synovial flap is indicated in cases in which relatively

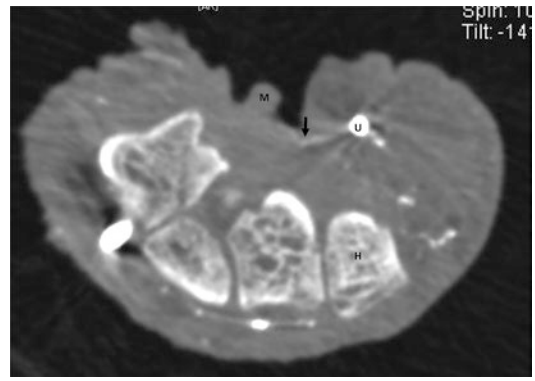

Fig. 22.2 Intraoperative CT angiogram at the level of the hamate after performing external neurolysis of the median nerve. Another direct branch of the ulnar artery to the flexor synovium is identified. *H* hamate, *M* median nerve, *U* ulnar artery, *Arrow* the direct branch of the ulnar artery to the flexor synovium

small perineural fibrosis in the carpal tunnel is identified at the time of revision surgery. A particularly good indication is perineural fibrosis at the palmar side of the median nerve, which makes the median nerve affix to overlying structures. After complete release of the median nerve, synovial flap coverage of the palmar side of the median nerve can be easily performed. These procedures provide reliable symptomatic relief with minimal additional dissection.

When the area of the perineural fibrosis of the median nerve is large or circumferential (affecting the dorsal and palmar side of the median nerve), the synovial flap is not large enough to cover the area of the median nerve adhesion. In these cases, larger flaps such as radial artery perforator adipofascial flaps should be considered. Other reasons for revision carpal tunnel surgery such as intraneural fibrosis and neuroma of the palmar cutaneous branch of the median nerve are relative indications for the synovial flap technique. Synovial flaps can be used in these cases to restore a good gliding tissue cover, to reduce the risk of adhesions of the median nerve, and to ensure neovascularization to improve nerve regeneration.

Contraindications of the synovial flap technique are cases that involve rheumatoid arthritis or synovial tumors in which pathological tenosynovitis causes carpal tunnel syndrome. In these cases, surgeons should perform a tenosynovectomy to prevent median nerve compression. If perineural fibrosis of the median nerve is identified, other flap techniques such as that involving the hypothenar fat pad flap should be considered to restore protective coverage of the median nerve.

Surgical Technique

In revision carpal tunnel surgery, the skin incision is made longer than the previous surgical scar, starting more proximally and distally, working toward the zone of previous surgery. For safe dissection, the median nerve should be identified in the areas without scar, i.e., proximal and distal to the prior surgical scar zone. After identifying the median nerve proximally and distally, dissection is performed into the carpal tunnel. Opening the carpal tunnel at the ulnar palmar side facilitates the identification of the median nerve without injuring the median nerve branches [21]. Careful dissection is important when moving from normal nerve to adhered nerve. Safe dissection through the scar tissue that has caused recurrent compression or traction neuropathy can be very challenging. External neurolysis of the median nerve is usually required in order to free the nerve from both compressive and traction forces. The complete visualization and release of all potential sites of residual compression is critical (Fig. 22.3). It is sometimes necessary to include other procedures such as neuroma excision and nerve grafting.

After careful dissection and mobilization of the median nerve from the scar tissue, coverage of the median nerve is performed with a synovial flap that can provide interposition and neovascularization to the scarred median nerve. A vascularized synovial flap can keep the median nerve within scar-free tissue and protect it against new scar compression. A wide flap of synovial tissue

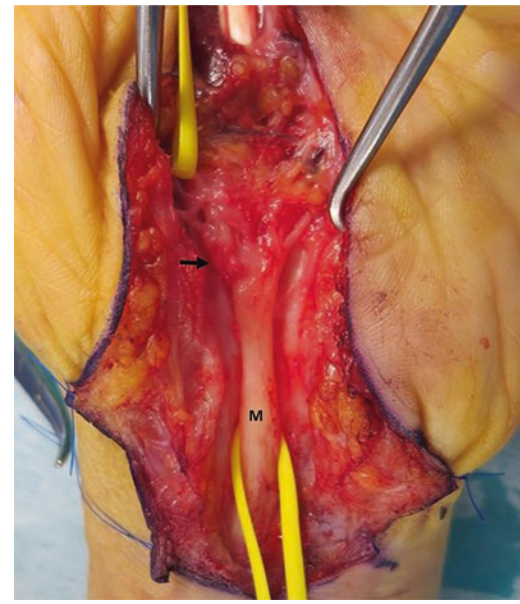

Fig. 22.3 A 71-year-old patient's left hand in revision carpal tunnel surgery after external neurolysis of the median nerve was performed. Perineural fibrosis is observed. *M* median nerve, *Arrow* perineural scar around the median nerve

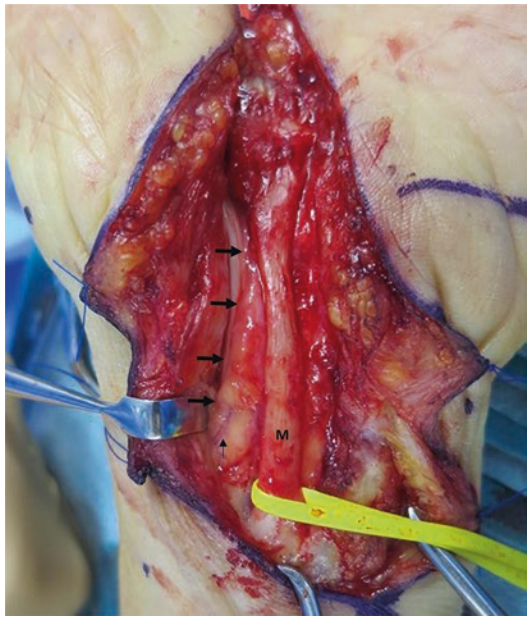

Fig. 22.4 Elevating the synovial flap from the radial side. *Large arrow* the line to incise the synovium, *M* median nerve, *Small arrow* artery in the flexor synovium

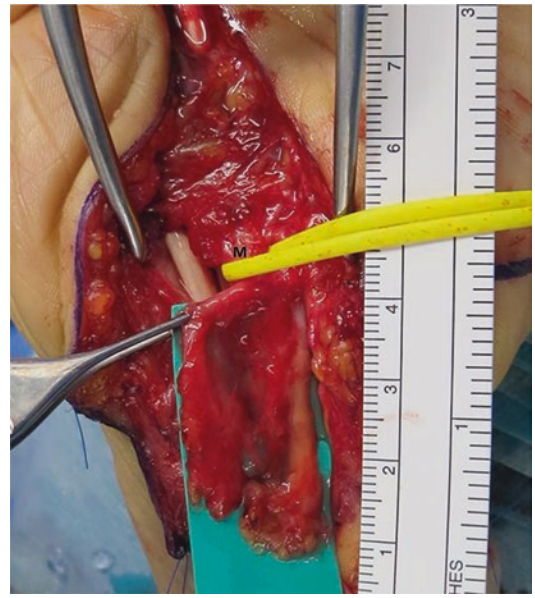

Fig. 22.5 The elevated synovial flap after dissection from the radial border. The pedicle is distally based from the ulnar artery. *M* median nerve

deep to the median nerve is elevated from the radial to the ulnar direction, utilizing the ulnar aspect as the vascularized pedicle because the synovial flap is consistently supplied by a vascular pedicle from the ulnar artery (Figs. 22.4 and 22.5). Because the vascular pedicle runs between the superficial flexor tendons of the ring and small fingers, the flap elevation has to be stopped over the tendon of the ring finger. The flap is then placed superficial to the median nerve, turned radially, and fixed to the radial wall of the carpal tunnel with absorbable stitches (Fig. 22.6). The advantage of this flap is that it provides vascularized interposing tissue to the median nerve through the same operation field without the need for extensive further dissection. The flexibility of the tenosynovial tissue can provide a wide flap to wrap the median nerve without excessive tension. Frequent intraoperative checks must be performed to ensure that the fingers are passively mobilized in flexion through extension. This motion must not cause any tension to the synovial flap because tension of the flap over the median nerve can cause new nerve compression. If tension is identified, further dissection of the

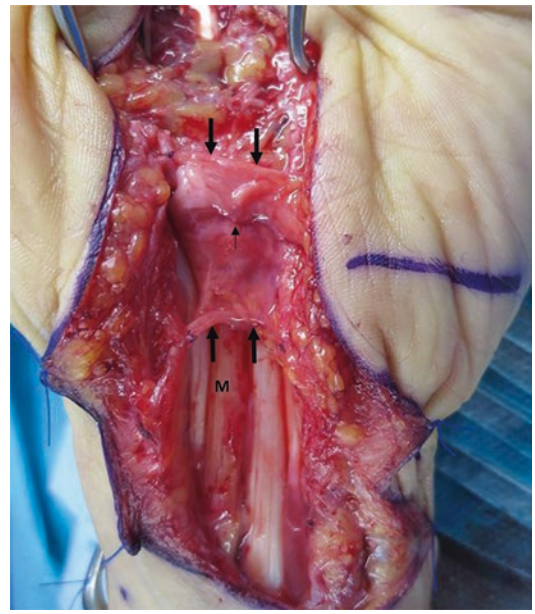

Fig. 22.6 Wrapping the median nerve with the synovial flap. The flap is turned around the median nerve, and small stiches are made on the radiopalmar wall of the carpal tunnel. *Large arrow* distal and proximal border of the synovial flap, *Small arrow* artery in the synovial flap

synovial flap is necessary for flap mobilization and tension reduction.

After placing the drain, the wound is carefully closed with skin stitches to prevent median nerve compression, postoperative fibrosis, and hematoma. After applying a bulky dressing, a short arm splint is implemented to immobilize the arm.

Postoperative Care

After the operation, to prevent edema and finger contracture, active finger exercise is encouraged as soon as possible. Nonsteroidal anti-inflammatory drugs help enable the patient to exercise with active finger flexion and extension. Two weeks after the operation, the splint is removed, and there is complete wound healing. The patient is then encouraged to move both their fingers and wrist actively.

Complications and Side Effects

Extensive exposure of the median nerve is necessary, and the dorsal aspect of the median nerve must be dissected to free the median nerve to elevate the synovial flap. These large access incisions and extensive tissue dissection carry a risk of triggering new adhesions and scar formation around the median nerve.

The elevated synovial flap is turned and placed over the median nerve to prevent adhesion and scar tissue formation around it. This wrapping of the median nerve carries some risk of creating new iatrogenic compression of the nerve.

During the flap elevation, if mobilization is insufficient or tension over the median nerve is identified, further dissection is necessary. Extensive dissection of the flap can cause circulatory disorders. Wrapping the median nerve with the synovial flap with inadequate circulation can result in new fibrous scar formation around the nerve, leading to median nerve disturbance and symptoms.

Outcomes

Revision carpal tunnel surgery remains a challenge for hand surgeons because of inconsistent outcomes due to the large variety of etiologies and clinical symptoms, non-standardized treatments, and lack of gold standard procedures [22]. Some articles have described flap coverage techniques after neurolysis of the median nerve in revision carpal tunnel surgery, such as the hypothenar fat pad flap [13, 14], the radial artery perforator flap [8], the reverse radial forearm flap [23], the palmaris brevis flap [11], and the synovial flap [15, 16]. Despite the variety of procedures, the outcomes following reoperation for recurrent carpal tunnel syndrome are variable. Many patients experience some improvement, with persistent symptoms reported in 41–90% of cases [22]. It has also been reported that, in terms of outcomes of surgical treatment for revision carpal tunnel syndrome, decompression followed by additional vascularized flap coverage appears to have a higher success rate than simple decompression [5].

Several reports have described the results of the synovial flap technique in revision carpal tunnel surgery [15, 16]. Wulle reported the results of 27 patients who underwent revision carpal tunnel surgery with the synovial flap technique [15]. After an interval ranging from 1 month to 14 years (average: 3.1 years), the patients showed excellent (6), good (16), satisfactory (3), and poor (2) results. Wulle reported that there was no correlation among the results related to the interval between the initial operation and the reoperation, the reoperation and the follow-up examination, or the severity of preoperative findings. He reported that, except for one patient, all had increased sensibility and strength, less pain, and no recurrence of night pain.

Stütz et al. [16] compared the synovial flap and hypothenar fat flap technique for treating patients with previous failed carpal tunnel decompression. Using synovial flap coverage, they treated 15 patients in whom the median nerve was significantly enveloped in scar tissue

because of nerve tethering attributable to the position within the scar. In the synovial flap group, they reported reduced brachial nocturnal pain (25%), pillar pain (25%), a positive Tinel's sign (25%), a positive Phalen's test (13%), thenar atrophy (44%), and paresthesia (62%). The overall patient satisfaction was 56%, and the disabilities of the arm, shoulder, and hand score was 37 points in the synovial flap group. Nerve conduction tests demonstrated significant improvement when comparing pre- and postoperative measurements, and distal motor latency significantly decreased in the synovial flap group (from 6.04 to 4.43 ms). The authors concluded that coverage by an ulnar-based hypothenar fat flap appeared to produce superior clinical results compared to coverage with synovial tissue from adjacent flexor tendons, although a conclusive statistical evaluation of clinical outcomes was not possible.

As for clinical results, there is no evidence that synovial flaps are superior or inferior to other flaps in revision carpal tunnel surgery. Further studies are needed to identify the difference in clinical improvement between synovial flaps and other flaps.

Conclusions

In revision carpal tunnel surgery, several procedures that provide median nerve coverage have been developed to prevent adhesion of the median nerve to the surrounding tissues. These flap coverage procedures reconstruct both the epineural barrier of the median nerve and the gliding tissue around the nerve in the surgical management of recurrent carpal tunnel syndrome. The synovial flap technique is one such option that is as effective as other nerve-wrapping procedures which satisfy the need to protect the median nerve from perineural scarring. The synovial flap is quickly removed from the synovial sheath of the superficial flexor tendons at the level of the carpal tunnel without any additional skin incision or extended surgical exploration. The synovial flap is a simple and effective technique for protecting the median nerve in revision carpal tunnel surgery.

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The Use of Microneurolysis

23

Scott Swanson and Anthony A. Smith

Recurrent Carpal Tunnel

Carpal tunnel syndrome was first described by Sir James Paget in 1854, and carpal tunnel syndrome is the most common compressive neuropathy of the upper extremity. Carpal tunnel release is one of the most frequently performed surgical interventions by hand surgeons today [1]. Recurrent carpal tunnel is defined as symptom resolution after surgery with subsequent recurrence after a set time interval [2]. Failed carpal tunnel surgery accounts for approximately 10% of cases and is most often attributed to incomplete release [3]. A second operation to divide the accumulated scar tissue and "re-release" the ligament is often required and considered a secondary carpal tunnel release [4]. Secondary carpal tunnel surgery can have unfavorable results with up to 95% of patients having persistent symptoms [5]. Furthermore one must differentiate between unrelieved carpal tunnel syndrome and recurrent carpal tunnel being that in recurrent carpal tunnel syndrome, there is complete resolution of symptoms for a period of at least 3 months [6]. Postoperative outcomes for recurrent carpal tunnel syndrome surgery produce up to 40% of patients with poor result, being either those who experienced no symptom relief, new related symptoms, or worse symptoms [1]. This is likely why no procedure remains superior, and many approaches have been purposed. However, there are two main principles that remain central to the treatment of recurrent carpal tunnel. These are neurolysis with restoration of median gliding and coverage of the median nerve with a native tissue flap to prevent internal scar recurrence. It is the author's proposal that the extent of the neurolysis should include intrafasicular release to the bands of Fontana with accompanied vascularized flap coverage for prevention of adhesions and allowing for neovascularization of the perineural tissue [7]. Good to excellent results are reproducible and acceptable, as defined by some relief of symptoms to allow for daily activity, and thus it should be considered the procedure of choice in recurrent carpal tunnel [8].

The normal median nerve longitudinally slides several millimeters in its bed with wrist flexion and extension [9]. Through biomechanical and cadaveric studies, a common pathology for recurrent

S. Swanson
Department of Surgery, Maricopa Medical Center, 2601 East Roosevelt Street, Phoenix, AZ 85008, USA

A.A. Smith (✉)
Department of Surgery, Mayo Clinic Hospital, 5777 East Mayo Boulevard, Phoenix, AZ 85253, USA
e-mail: smith.anthony@mayo.edu

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carpal tunnel syndrome, was elucidated as a "traction neuropathy" that was purposed to prevent median nerve gliding through the tunnel, leading to increased load transmission on the median nerve with wrist motion [10]. This also has been characterized by the findings intraoperatively of the adherence of the nerve to the radial leaflet of the transverse carpal ligament. Additionally, there was a complete encasement of the median nerve by fibrosis [8]. In an undefined period of time, the nerve then experiences pathological changes indicating decreased bands of Fontana with exposure to tensile forces [11].

Patients with recurrent carpal tunnel syndrome typically report a prior carpal tunnel release with at least 3 months of partial clinical relief and then subsequent return of symptoms that are similar before surgery or worse. Patient symptoms are reported to consist of paresthesia in median nerve distribution, numbness, aching pain, and nocturnal awakening due to pain. Although these symptoms are often associated with primary carpal tunnel syndrome, a noted difference is pain with active extension of wrist and fingers. Since only approximately 50% of patients with recurrent carpal tunnel have a positive Phalen's or Tinel's sign [1], recurrent carpal tunnel is diagnosed through symptoms consisting of median nerve hypersensitivity at the wrist and scar, without damage to the palmar cutaneous branch [3]. The physical diagnosis is further supported with noted physical compression of the nerve just proximal to the carpal tunnel, while holding the forearm in maximum supination, with resulting paresthesias in the median nerve distribution. Other forms of provocation such as resisted pronation and resisted superficialis muscle strain may also produce symptoms if entrapment of the nerve exists just proximal to the carpal tunnel [12]. The thenar muscle abduction test is another method used to clinically detect recurrent carpal tunnel syndrome. This involves detected weakening of the abduction of the thumb against resistance in a position of forearm supination, wrist and finger extension, and thumb abduction in setting of prior carpal tunnel release [7].

Conservative measures of splinting, stretching therapy, scar massage, and activity modifications may provide temporary relief; however, symptoms frequently recur with cessation of therapy or return despite these significant measures. More aggressive therapy solutions promote a "work hardening" program with compensatory activities that can themselves lead to competing compressive neuropathies such as radial nerve compression from supination exercises [7]. Furthermore, limitation of forearm activities persuades one to use more shoulder and neck motion that can lead to "brachial plexus traction problem" exercises [7]. This leads patients to consider surgery as a potentially longer-lasting solution.

Electromyography results in recurrent carpal tunnel syndrome are often variable. Some nerve conduction velocity studies show abnormal conduction velocity and prolonged latency in both motor and sensory values [13]. Other studies note EMG/NCV studies with high patient variability ranging from unchanged conduction velocities to worsening velocities, to signs of denervation of the thenar muscles [14]. In other instances while the initial EMG may be normal, it can become positive after exercise and positional stress testing [7]. It is notable that the variability in electromyography depends on the prior median nerve compression and scarring that occurs after surgery. Often comparison of pre- and post-initial carpal tunnel release EMG/NCV studies shows continued decreased sensory and motor latencies in setting of prior improvement [15].

Another consideration is the response to steroid injection. Patients responding to surgical intervention responded to initial carpal tunnel injection with symptomatic improvement [16].

Surgical intervention varies widely among practicing hand surgeons. Simple reopening of the carpal tunnel results in disappointing results, with between 25%–95% persistent symptoms [17]. It was the addition of vascularized flap coverage that provided a higher success rate in addition to extensive external neurolysis [18]. Procedures have included vein graft wrapping the median nerve, implant application, reverse radial artery perforator flaps, abductor digiti minimi flaps, pronator quadratus muscle flaps, palmaris brevis flaps, hypothenar flaps, and synovial flaps. In this book chapter, we will focus on the hypothenar fat

pad flap and microneurolysis for treatment of recurrent carpal tunnel syndrome [8].

In assessing the surgical approach to recurrent carpal tunnel syndrome, one must take into consideration the anatomy. Injection studies of the hypothenar fat pad demonstrated segmental perforators, every 1 cm, from the ulnar artery, as it lies distal to the wrist crease and travels through Guyon's canal [19]. Furthermore, the hypothenar skin flap is perfused by the subdermal plexus that prevents donor site skin loss and permits raising a pedicled flap [20]. One must be conscious of the nerves to the ring and small fingers while undermining the flap in the deep ulnar direction [21]. Also it becomes necessary to excise the ulnar leaflet of the transverse carpal ligament to allow advancement of the pedicled flap over the entire median nerve.

The technical finer points of the dissection include the release of Guyon's canal, isolation of the fat pad with preservation of the subdermal plexus to the skin of the hypothenar area, resection of the residual ulnar portion of the transverse carpal ligament, coverage over the median nerve, and securing the flap to the radial aspect of the tunnel [20].

The tissue forms external and internal restrictions to median nerve gliding motion due to adhesions, causing a traction neuropathy, thus, the need for microneurolysis and hypothenar fat pad flap.

While external neurolysis consisting of release of the surrounding epineurium from the scar tissue provides mobilization of the median nerve and restoration of gliding motion of the nerve, it fails to address internal restrictions that can account for further lack of stretch resistance of the nerve. The decreased frequency of the undulations is often seen in response to tensile load exposure and dissection until confirmation of the bands with normal spacing may lead to improved resistance to biomechanical forces [11]. The use of microscope to aid in dissection can confirm the presence of the normal fascicular architecture and restoration of normal undulations, consisting of the bands of Fontana. Furthermore, neuroma excision and even nerve grafting may be necessary.

Postoperative care consists of a graft dressing and splinting of the wrist in neutral position and subsequent conversion to nocturnal splinting for 2 additional weeks. Patients are restricted from heavy lifting for 8 weeks. Occupational therapy is instituted to allow for finger motion immediate postoperatively, and then wrist motion began after 4 weeks of splinting [8].

It goes without saying that every procedure has its inherent complications. The complications can be divided into those resulting from internal and external neurolysis and those with regard to soft tissue coverage of the median nerve. The most notable complication associated with fat pad harvest includes partial and total flap loss. This is often attributable to surgical technique, poor perforator supply, or underlying vessel compromise [14]. Complications of neuronal transection can be minimized with careful technique; however, the recurrence of scar tissue with external and internal neurolysis is often unpredictable. Taking all this into consideration, the most significant complication is not just failure of symptomatic relief of carpal tunnel symptoms but also worsening of symptoms without an inherent explanation. There remain no predicative factors to identify these patients preoperatively. Often therapy becomes a necessary adjuvant in our armamentarium to deal with these patients.

The true measure of the success of any operation is noted by patient satisfaction through symptom relief and measurable increase in preoperative hand-specific parameters. One can expect the results to demonstrate improvement in grip strength by an average of 10 kg, pain to diminish by an average of 93%, tingling to resolve completely in 50% of patients, and numbness to disappear in 42% [8].

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Reconstruction of the Flexor Retinaculum

24

Anthony Montanez and Angela Wang

Carpal tunnel syndrome (CTS) affects over 60 million people worldwide [1]. Traditional open carpal and endoscopic carpal tunnel release (CTR) require the division of the transverse carpal ligament (TCL). According to some authors, this may result in an increased carpal canal volume and possibly decreased grip strength after surgery. Several reasons have been postulated as to the potential cause of weakness in grip strength after CTR. One theory is that release of the transverse carpal ligament leads to flexor tendon bowstringing and loss of grip strength. Another theory is that release of the TCL leads to widening of the carpal arch, thereby causing altered mechanics of the thenar and hypothenar muscles. Weakness in grip following carpal tunnel release was a known issue and highly debated subject in the late 1970s [2], and several authors have described different techniques of reconstruction of the TCL over the years. This chapter will look into surgical techniques and outcomes of flexor retinaculum reconstruction after CTR.

A. Montanez • A. Wang (✉)
Department of Orthopaedic Surgery,
University of Utah, 590 Wakara Way,
Salt Lake City, UT 84108, USA
e-mail: Anthony.montanez@hsc.utah.edu;
angela.wang@hsc.utah.edu

Grip Strength Following Carpal Tunnel Release

In an effort to better understand weakness following carpal tunnel release, Gartsman et al. [3] showed in a retrospective review a direct relationship between widening of the transverse carpal arch and loss of grip strength. They examined 50 patients who underwent open CTR and measured the distance between the palmar tips of the trapezium and the hook of the hamate on a standard carpal tunnel view radiograph. They found a mean widening of the transverse carpal arch of 2.7 mm (range 0–8.5 mm) or an average of 13.6% (range 0–52%) after CTR. Patients with widening less than 10% had an average decrease grip strength of 3.6%; 10–20% widening decreased grip strength 8.4%, and patients with greater than 20% widening of the transverse carpal arch showed an average decrease in grip strength of 25.9%. They concluded there was a direct relationship between widening of the transverse carpal arch and loss of grip strength.

Llurch [4] also demonstrated loss of grip strength following open carpal tunnel release. They looked at 220 hands an average of 3 years and 10 months after surgery. Grip strength was measured at 20 degrees of extension and 20 degrees of flexion. In comparison to the non-operated hand, the operative side showed a 16% loss of grip strength in extension and a 24% loss in flexion.

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Other studies, however, have not demonstrated decreased grip strength following CTR. Gellman et al. [5] prospectively evaluated 24 wrists in 21 patients who underwent open CTR. They showed that grip strength was 28% of preoperative values at 3 weeks, 73% at 6 weeks, 99% at 3 months, and 116% at 6 months. Pinch strength achieved 74% of preoperative values at 3 weeks, 96% at 6 weeks, 108% at 3 months, and 126% at 6 months. Viegas et al. [6] prospectively reviewed 87 endoscopic carpal tunnel releases performed by a modification of the Chow [7] technique. Three weeks after surgery, pinch strength was 102% and grip strength at 86% compared to preoperative levels. At 6 weeks postoperatively, pinch strength was 106% and grip strength was 121% of preoperative values. Thus, the data seem inconclusive as to whether or not open CTR affects grip strength.

Altered Carpal Tunnel Morphology After Flexor Retinaculum Release: Radiographic Studies

Open CTR

Some authors have studied the morphologic effects of the carpal tunnel after release of the TCL. Llurch [4] were the first to publish their study in which CT scans were obtained in 13 patients to measure the transverse diameter of the carpal tunnel from the radial border of the hook of the hamate to the ulnar border of the trapezium. Nine patients had measurements done after release using the opposite hand used as a control, while the remaining four patients had measurements done before and after release. The average measurement of the carpal tunnel was 20.2 mm (range 18–23 mm). After release of the TCL, the diameter increased 1 mm in the transverse direction.

As magnetic resonance imaging (MRI) became clinically more available in the 1980s, Richman et al. [8] described the first study using MRI to assess changes of the carpal tunnel after CTR. MRIs were obtained before and 6 weeks after open CTR in 15 hands in 12 patients. At 6 weeks postoperatively, there was a 24.2 ± 11.6% increase in the carpal canal volume and anterior displacement of the carpal canal contents of 3.5 ± 1.9 mm from their original position ($p < 0.001$). At 8 months follow-up, however, there was no significant increase in carpal arch width. They concluded the volumetric increase was from anterior displacement of the carpal contents and not from increased width of the arch.

Endoscopic CTR

Other authors have examined the morphologic changes of the carpal tunnel after endoscopic carpal tunnel release (eCTR) to see if a difference exists with this technique. Viegas et al. [6] were the first to report on 87 endoscopic carpal tunnel releases performed by a modification of the Chow [7] technique with respect to postoperative widening of the transverse carpal arch using radiographs. The average postoperative widening of the arch was 0.17 cm (7%, range 0–0.5 cm). Seventy percent of patients showed 0–10% widening, 26% showed 10–20% widening, and 4% showed greater than 20% widening of the transverse carpal arch. They showed the dimensions of the carpal arch widen after endoscopic carpal tunnel release but to a lesser extent when compared with open carpal tunnel release data from Gartsman et al. [3].

Kato et al. [9] evaluated ten patients with MRI obtained before and after eCTR. Cross-sectional area of the carpal canal increased 33% ± 15%. However, there was no increase in the width of the carpal canal, which is consistent with the previous reported MRI results by Richman et al. [8] in open CTR.

In an effort to determine if the type of eCTR release affected carpal canal volume, Ablove et al. [10] compared a single vs. two-incision eCTR technique. Seventeen patients (18 hands) were followed for an average of 24 weeks. Eleven had a single incision eCTR, while seven patients had the two-incision Chow technique [7]. Preoperative and postoperative MRI scans were obtained. Canal volume, carpal arch width, median nerve palmar displacement, and cross-sectional area were measured. Volume increase

for the single incision was 23% ± 12% and 26% ± 13% for the two-incision technique. These increases were comparable to the previously published volume data for open carpal tunnel release by Richman in 1988 (24% ± 12%). Additionally, neither group showed in a significant change in carpal width, again consistent with previously published data. Ablove et al. concluded that endoscopic and two-incision techniques were equivalent to an open technique with regard to change in carpal canal width and volume.

Open CTR vs. eCTR

Recently, Aslani et al. [11] looked prospectively at 48 patients with CTS and randomized them into open CTR and endoscopic CTR groups. Carpal canal shape and volume were analyzed using CT scans prior to and 6 weeks after surgery. Preoperative carpal arch widths were 21.5 ± 1.9 mm in the open group and 21.7 ± 1.1 mm in the endoscopic group ($p = 0.66$), with no significant difference in carpal width in either the open or endoscopic group.

Thus, there does not seem to be any significant difference in volumetric change of the carpal tunnel when comparing open or endoscopic CTR, by any technique.

Open CTR vs. TCL Reconstruction

In a three-part study by Netscher et al. [12, 13], MRIs were obtained pre- and postoperatively of 45 patients with CTS in a 45° flexed position, 45° extended position, and a neutral position. The data from the extended position group was not used due to poor image quality. In the first group, 15 patients underwent open CTR with no reconstruction. In the second group 15 patients underwent repair with a radially based segment of the TCL sutured to the palmar aponeurosis (Fig. 24.1). In the final group, 15 patients underwent repair with a transposition flap (a partial slit was cut in the TCL to lengthen it, Fig. 24.1). Carpal tunnel cross-sectional area increased in all groups but only achieved significance in the open group without reconstruction in the flexed position.

Cadaver Studies

Pavlidis et al. [14] performed a cadaver study looking at four different surgical lengthening techniques and compared the carpal tunnel volume of each using a simulated mathematical computer model method. Thirty-eight cadaveric wrists were divided into groups each having a

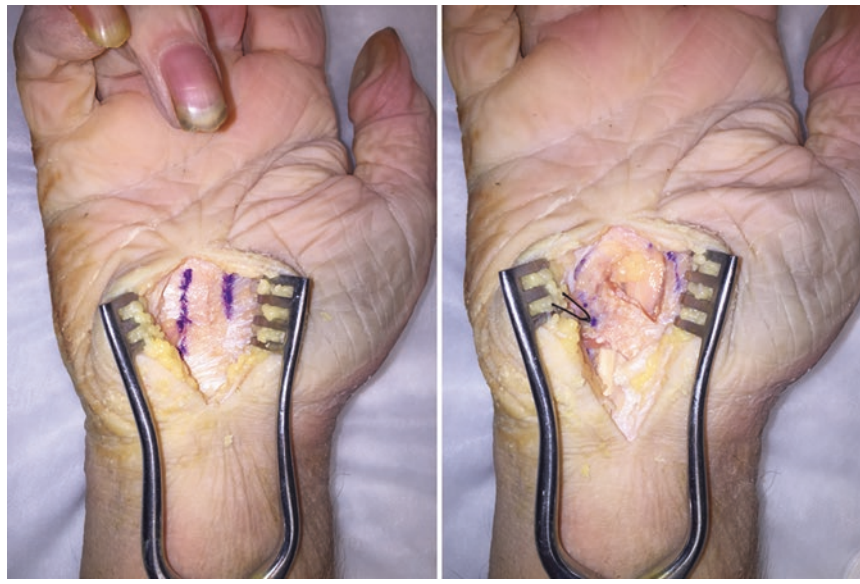

Fig. 24.1 Reconstruction with a radially based segment of the TCL

different type of retinacular reconstruction. There was an increase of carpal tunnel volume among all techniques with a range of 31–44%, but there was no statistically significant difference between the four techniques ($p = 0.097$).

Altered Flexor Tendon Function After Flexor Retinaculum Release: Cadaver Studies

Several authors have examined alterations in flexor tendon function after division of the transverse carpal ligament. Kiritsis et al. [15] using a cadaver model compared the biomechanical changes after carpal tunnel release in three different groups: open CTR, eCTR, and open CTR with retinacular repair by step-cut lengthening. In the open CTR group, there was a 26% increase in tendon excursion in flexor digitorum profundus (FDP) and 18% increase in flexor digitorum superficialis (FDS). In the endoscopic group, there was a 21% increase in tendon excursion in FDP and 15% increase in FDS, and in the step-cut group, there was a 21% increase in FDP and 16% increase in FDS. Therefore, all three groups showed an increase in tendon excursion: step-cut lengthening and ligament reconstruction did not demonstrate a significant improvement in flexor tendon biomechanics when compared to the open and eCTR groups.

Netscher et al. [12, 13] looked at eight fresh frozen cadavers and examined flexor tendon excursion with the wrist at 30° extension, neutral, 30° flexion, and 60° flexion in four different groups. Group one had an intact ligament, group two had a sectioned ligament with no repair, group three had an aponeurotic repair, and group four had a transposition flap. In the 30° wrist-extended position, the mean distance by which the fingertip failed to make contact with the palm was 3.41 cm with no repair, 2.15 cm for the aponeurotic repair, and 1.8 cm in the transposition flap ($p < 0.05$). In the 60° flexed position, the mean distance by which the fingertip failed to make contact with the palm was 6.03 cm with no repair, 3.0 cm for the aponeurotic repair, and 2.03 cm in the transposition flap ($p < 0.05$). He concluded the transverse carpal ligament functions in a similar way to the digital pulleys, providing a biomechanical advantage for the flexor tendons, and that division of the ligament decreases the amplitude of flexor tendon excursion at varying angles and wrist position.

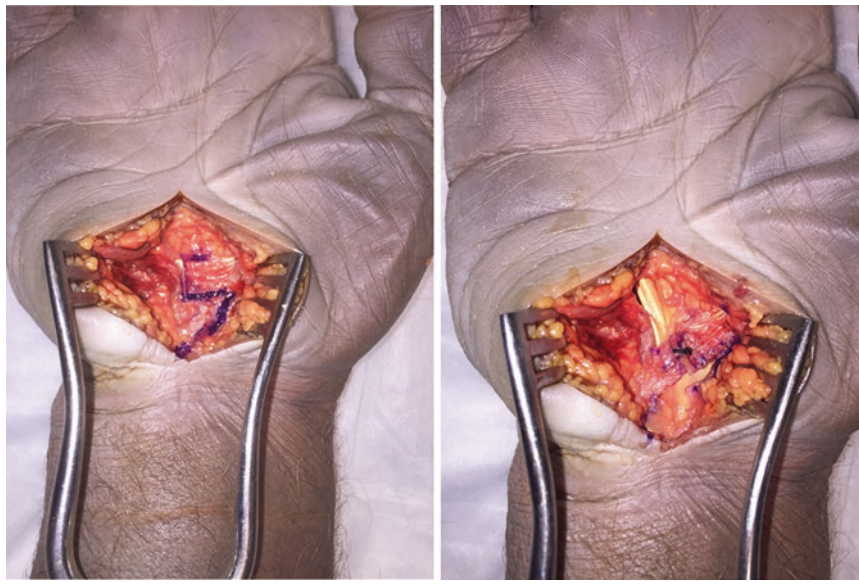

Fig. 24.2 Reconstruction of the TCL with a two-flap technique described by Jakab et al. [21]

Surgical Techniques

Several techniques have been described to reconstruct the transverse carpal ligament after CTR. Lluch [16, 17] described the first technique by sectioning the TCL in an oblique fashion from the ulnar side of the distal edge to the radial side of the proximal edge. The edges were then allowed to slide past each other and sutured together, thereby increasing the volume of the carpal tunnel. Hunter [18] also advocated this type of reconstruction.

Senwald [19], Kapandji [20], and Jakab et al. [21] all have described variations on a Z-plasty of the retinaculum, either with two (Kapandji and Jakab, Fig. 24.2) or three (Senwald) flaps also with the goal of reconstructing the TCL with an expanded volume in the carpal canal.

Implants have also been described, with the purpose of extending the TCL. In 2010 Duché & Trabelsi ([22]) published his cohort of 400 patients using the Canaletto implant which is composed of silicone and polyethylene and is used to add length to the TCL for repair.

Results After Flexor Retinaculum Reconstruction

Studies described up to this section have been mostly radiographic or cadaver studies. In this section, we will examine clinical results after reconstruction of the TCL.

In a retrospective review of 99 patients with follow-up of 4–8 years, Karlsson et al. [23] compared ligament lengthening versus classic open carpal tunnel release with respect to return to work. They found the group which had ligament lengthening had a significantly longer sick leave than the group without reconstruction ($p < 0.01$). They concluded there was no advantage to reconstruction of the transverse ligament.

Netscher et al. [12, 13] looked at 51 patients with carpal tunnel syndrome with 13 having open release with no reconstruction, 16 had open release with an aponeurotic repair, and 17 had an open release with transposition repair. At 12 weeks all groups surpassed preoperative grip strength and by 6 weeks all groups surpassed preoperative pinch strength. The transposition flap group had improved grip and pinch strength at 12 weeks when compared to the other groups.

Netscher et al. [24, 25] also looked at the length of time postoperative before grip and pinch strength was restored following carpal tunnel release. He looked at three groups: the first group had reconstruction of the transverse carpal ligament by a two-flap technique [21]. The second group has ligament lengthening by transposition flap repair technique [24, 25]. The third group simply had release of their carpal ligament with no reconstruction. All groups surpassed preoperative grip strength by 12 weeks, but the transposition group did recover faster and surpassed preoperative grip strength values at 6 weeks post-op.

The results of the Canaletto implant were examined by the designer's group in a prospective study with 400 cases using standard open CTR and another 400 using the Canaletto implant with average follow-up of 31 months. They reported an equivalent subjective improvement of paresthesias, but quicker recovery of grip strength in the implant group: at 1 month postoperatively, 80–100% of preoperative strength was regained in 67% of the Canaletto implant group compared to 33% in the open group.

Jakab et al. [21] retrospectively reviewed 110 hands (79 patients) with CTS who were treated using their technique of TCL lengthening (Fig. 24.2). One hundred and four hands (73 patients) were available for follow-up at a minimum of 2 years, and they found 93% had complete resolution of symptoms. Those having a unilateral reconstruction (60%) had no decrease in grip strength when compared to the contralateral unoperated hand ($p < 0.05$). They theorized this finding was due to the reconstruction stabilizing the carpal arch, providing protection to the median nerve, and preventing bowstringing of the flexor tendons.

Xu et al. [26] compared coronal Z-type lengthening of the TCL to traditional open CTR in a double-blinded randomized trial of 58 patients. They showed improved recovery rate in the Z-lengthening group at 6 and 12 months compared with the conventional group (71.2% vs. 36.0% ($p < 0.01$) at 6 months and 68.8% vs. 38.5% ($p < 0.01$) at 12 months). They also showed improved satisfac-

tion when performing activities of daily living in the Z-lengthening group compared with the conventional group at 6 and (32.7 ± 7.1% vs. 24.8 ± 7.0% ($p < 0.01$))12 months. They concluded the Z-type lengthening group restored anatomy of the carpal tunnel, kept the pulley function of the transverse carpal ligament in preventing flexor tendon bowstringing, and restored grip strength better than the conventional release.

The most recent paper was by Zhang et al. [27, 28] comparing subneural reconstruction of the TCL to open release without reconstruction. They looked at 213 patients with CTS and randomized them into three groups. The first group had 68 patients and underwent open carpal tunnel release with subneural reconstruction. The second group consisted of 92 patients who had an open carpal tunnel release with no reconstruction. The third group had 53 patients who underwent endoscopic carpal tunnel with no reconstruction. Functional recovery was measured by Boston Carpal Tunnel (Levine-Katz) Questionnaire pre- and postoperatively. Flexor tendon bowstringing was determined clinically as protrusion of the flexor tendons during flexion of the wrist. All groups obtained similar improvements in symptoms and key pinch strength. Those that underwent CTR with subneural reconstruction had better functional recovery, flexor tendon bowstringing, and Michigan hand outcome scores according to the author.

Conclusion

Reconstruction of the transverse carpal ligament following carpal tunnel release is not widely performed. The available evidence for reconstruction of the transverse ligament following carpal tunnel release is limited, with only a few prospective studies supporting this technique. The preventative loss of grip strength remains largely theoretical, and the morphologic changes that occur after any type carpal tunnel release may not translate clinically. Reconstruction of the TCL does not seem to adversely affect the improvement in paresthesia after surgery. Some studies do support a quicker recovery in the short-term postoperative period with TCL reconstruction, but its overall benefit to functional outcome in the long-term remains largely unproven.

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Biomechanical Effects of Transverse Carpal Ligament Release

25

Souichi Ohta

The transverse carpal ligament (TCL) is thought to maintain the size and shape of the carpal tunnel. Surgical release of the TCL results in morphological, and subsequent biomechanical, changes to the carpal tunnel and surrounding structures that may have adverse effects.

Stability of the Carpal Arch

The stability of the carpal arch differs between its distal and proximal parts. The distal carpal arch is formed by the hamate, capitate, trapezoid, and trapezium bones; these are tightly intercalated by strong intercarpal ligaments, especially the capitohamate ligament [1, 2]. The proximal carpal arch is formed by the scaphoid, lunate, triquetrum, and pisiform bones, which are also intercalated by ligaments that allow and regulate their mobility [3]. The distal side of the TCL is thicker than the proximal side and is reinforced by additional fibers that originate from the palmar aponeurosis [4]. The proximal side of the TCL is usually separated from the palmar aponeurosis by loose, fatty connective tissue. This arrangement results in the carpal tunnel having significantly greater stability distally than proximally. In a cadaver study, scaphoid extension during ulnar deviation of the wrist was reported to increase after TCL release [5]. The stability of the proximal carpal arch was insufficient to maintain normal palmar rotational forces to the scaphoid. The extrinsic ligaments, such as the scapholunate, long radiolunate, and radioscapholunate ligaments, did not prove to contribute to carpal arch stability [5–8].

Transverse Widening of the Carpal Arch After TCL Release

Some studies have demonstrated that TCL release causes slight widening of the carpal arch [9–11]. A radiographic study using tunnel views of dorsiflexed wrists showed an average 3 mm increase in the distance between the scaphoid and pisiform after TCL release [10]; however, this increase might have been overestimated because the measurement was performed under axial loading, the degree of dorsiflexion was unclear, and ulnar subluxation of the pisiform occurred in 12% of the cases. Another radiographic study used tunnel views to examine the distance between the palmar tip of the ridge of the trapezium and the hook of the hamate bone in the affected and unaffected wrists [11]. Postoperative values were compared with control values, which

S. Ohta (✉)
Department of Orthopaedic Surgery,
Kyoto University, 54 Shogoin-Kawahara-cho,
Sakyo-ku, Kyoto, Japan
e-mail: sota@kuhp.kyoto-u.ac.jp

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were measurements of the unaffected contralateral wrists. Control values ranged from 16.2 to 31.3 mm, and widening of the transverse carpal arch was shown as a percentage of the control value. At a mean of 16.3 months after the open TCL release, the mean width of the TCL had increased by 2.7 mm. In 40% of the patients, there was a 0–10% widening, 28% had 10–20% widening, and 32% had a greater than 20% widening. In another intraoperative study, the distance between the trapezium and the hook of the hamate was investigated by measuring the distance between two K-wires percutaneously inserted into each bone [9]. The distance was measured with the wrist in neutral, flexed, and extended positions before and after open TCL release. After TCL release, 19 of 21 hands showed an 11% mean increase in the width of the transverse carpal arch, while two hands showed no widening. In most of the wrists, the transverse carpal arch was narrowed in both flexed and extended positions compared to the neutral position regardless of whether the TCL had been released or not.

In endoscopic TCL release, fewer soft tissue structures are released than in open TCL release. After endoscopic TCL release, the average radiographically evident widening of the transverse carpal arch was 1.7 mm [12, 13]. Seventy percent of patients showed 0–10% widening, 26% showed 10–20% widening, and 4% showed more than 20% widening of the transverse carpal arch. The degree of widening was less than previously reported for open TCL release [11].

Palmar Displacement of the Released Edges of the TCL

The volume of the carpal tunnel has been reported to increase after both open and endoscopic TCL release [14]. Although there is some controversy regarding the origin of the increase in carpal tunnel volume, it seems to be a consequence of palmar opening of the edges of the released TCL, which increases the palmar area of the carpal tunnel [13, 15]. A magnetic resonance imaging (MRI) study at 8 months after open TCL release showed an approximately 25% increase in carpal tunnel volume, although the width of the carpal arch was unchanged [15]. This increased volume resulted not from changes to the carpal arch structure but from palmar displacement of the newly formed TCL. Another MRI study performed after endoscopic TCL release showed a 33% increase in the cross-sectional area of the carpal tunnel; this increase was mainly due to an increase in palmar carpal cross-sectional area (PCCSA) [13].

To measure the dorsal carpal cross-sectional area (DCCSA) and PCCSA, a cross-sectional image of the carpal tunnel was divided into two areas by drawing a straight line between the attachments of the TCL to the beak of the trapezium and the hook of the hamate and then measuring the areas of the dorsal and palmar regions separately. Although there was no significant difference between the preoperative and postoperative DCCSA, the more convex shape of the postoperative TCL resulted in 3.6 times increase in the PCCSA from its preoperative value (Fig. 25.1).

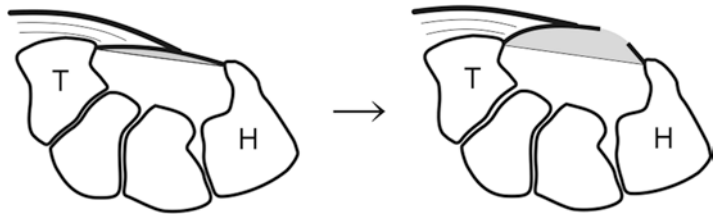

Fig. 25.1 Cross section of the carpal tunnel before (*left side*) and after (*right side*) the TCL release. After the TCL release, the more convex shape of the TCL resulted in an increase of the palmar carpal cross-sectional area (PCCSA). There was no significant difference between the preoperative and postoperative dorsal carpal cross-sectional area (DCCSA) because of a slight widening of the carpal arch

Biomechanical Effects on the Flexor Tendon Pulley System

The transverse carpal ligament is thought to have an important role in the pulley system for the digital flexor tendons at the wrist [16]. This ligament prevents bowstringing of the digital flexor tendons and allows maximum finger flexion while the wrist is flexed. A fresh-frozen cadaver study demonstrated approximately 5 mm of palmar displacement of the flexor digitorum tendons after TCL release [17]. Other MRI studies have demonstrated significant volar displacement of the median nerve (3.3 mm) and flexor digitorum tendons (2.4 mm) in both neutral and flexed wrist positions after open TCL release [18]. Palmar displacement of the flexor digitorum tendons has been shown to increase the distance between the tendons and the center of rotation of the wrist, thus increasing the amount of flexor tendon excursion necessary to achieve fingertip-palm contact during wrist flexion. This increase in excursion was less in the ECTR group than in the open TCL release group and was noted after 20–30 degrees of wrist flexion as tendon bowstringing occurred [19]. Although power grasping is usually performed with the wrist in extension, many of the activities of daily living require wrist flexion [20]; thus, palmar displacement of the flexor digitorum tendons after TCL release could affect some postoperative activities.

TCL Release and Trigger Finger

The incidence of trigger finger within a year of open TCL release has been reported to range from 5.9 to 22% [21, 22]. One cause of this phenomenon is thought to be increased friction at the A1 pulley due to the increased entrance angle of the flexor tendons [22]. In a cadaver study, TCL release changes the entrance angle of the flexor tendons to the A1 pulley in all five fingers, especially the middle finger (Fig. 25.2) [23]. In the case of the flexor pollicis longus tendon, the mean entrance angle to the A1 pulley was 10°. The release of only the TCL caused the entrance angle to increase to a mean of 20°. Additional release of the distal forearm fascia caused a further increase in the entrance angle to a mean of 28°. In the other fingers, TCL release increased the mean entrance angles to the A1 pulley by 12, 27, 12, and 3° in the index, middle, ring, and little fingers, respectively. Additional release of the distal forearm fascia further increased these angles by 4, 4, 9, and 2°, respectively.

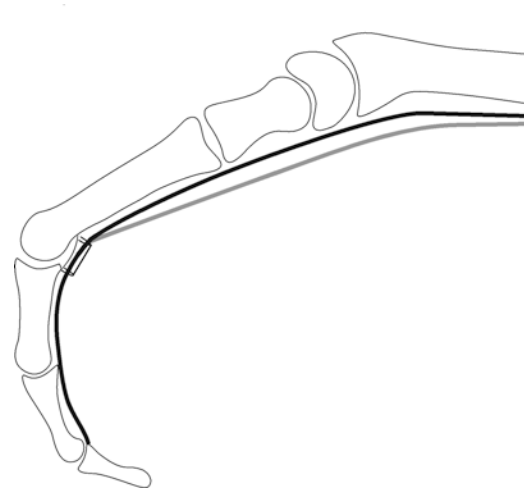

Fig. 25.2 Sagittal section of the hand and finger. After the TCL release, the palmar displacement of the flexor tendons resulted in an increase of the flexor tendon's entrance angle to the A1 pulley. A *gray line* is the postoperative position of the flexor tendon

The Transverse Carpal Ligament and the Thenar Muscles

Approximately two-thirds of the thenar muscles, and almost half of the hypothenar muscles, originate on the volar surface of the TCL [24]. Release of the TCL causes palmar displacement of some of the sites of origin of the thenar and hypothenar muscles and thus shortens their length [25]. The muscle shortens by as much as 25% in the superficial head of flexor pollicis brevis, 20% in the ulnar part of abductor pollicis brevis, 20% in opponens pollicis, and 10% in opponens digiti minimi [26]. After TCL release, the forces associated with gripping and pinching will be transmitted preferentially to the thenar and hypothenar muscles that originate from the carpal

bones rather than the TCL; this could lead to increased stress on the origins of these muscles and may cause pain [24]. Release of the TCL may also change pisotriquetral joint alignment and tracking of the pisiform, which induces pain at the base of the hypothenar area [27].

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Carpal Tunnel Syndrome After Fractures and Other Trauma

26

Brady T. Evans, Shaun P. Patel,
and Tamara D. Rozental

Introduction

Carpal tunnel syndrome (CTS) is a compressive neuropathy of the median nerve that occurs at the level of the flexor retinaculum of the wrist. The borders of the carpal tunnel are the flexor retinaculum volarly; the carpal bones dorsally; the hook of the hamate, the triquetrum, and the pisiform ulnarly; and the scaphoid and trapezium radially. Compression of the median nerve within this relatively fixed space can lead to CTS. This is likely due to an increase in pressure in the carpal tunnel and compromised epineural blood flow from intrinsic or extrinsic causes. CTS is most commonly recognized in the setting of overuse injuries and systemic diseases but can also result from acute trauma to the upper extremity. CTS can thus present as a chronic, slowly progressive condition, or as a rapidly evolving, acute problem.

Carpal tunnel syndrome has been recognized as a complication of upper extremity trauma for over a century. In fact, the first reported instance of median neuropathy was by Paget in 1854, who noted an association with distal radius fractures [1]. Since then, many different presentations of CTS in the setting of trauma have been described and studied.

The mechanism and severity of related trauma vary widely, as does the time from injury to development of symptoms. Patients may present with acute carpal tunnel syndrome (ACTS) immediately following trauma, but may also present in a delayed fashion. Prior trauma ranging from distal radius fracture to electrical burn can also predispose patients to the development of chronic CTS.

While some instances of CTS related to trauma may necessitate urgent surgical release, others may be managed in the same manner as atraumatic cases. It is also important to distinguish median nerve contusion from carpal tunnel syndrome requiring urgent surgical treatment. This chapter will review common traumatic causes for carpal tunnel syndrome and their treatment recommendations.

Diagnosis

The diagnosis of CTS in the setting of trauma is largely dependent on the acuity of presentation. Chronic CTS with a delayed presentation after trauma is often diagnosed and managed in the same fashion as other forms of CTS. In the case of ACTS related to trauma, the diagnosis and decision for surgery is often clinical, but

B.T. Evans • S.P. Patel • T.D. Rozental (✉)
Department of Orthopaedic Surgery, Harvard Medical School, Beth Israel Deaconess Medical Center,
300 Brookline Avenue, Boston, MA, USA
e-mail: trozenta@bidmc.harvard.edu

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there are some potentially valuable diagnostic modalities.

Patients presenting with chronic CTS and a history of trauma to the affected extremity often report similar symptoms to patients without a history of trauma. These may include pain, numbness, and paresthesias in the median distribution, especially at night or with daytime activities involving significant or frequent wrist flexion or extension. Physical examination of these patients may reveal diminished two-point discrimination as well as positive provocative signs including Phalen's test and Durkan's median nerve compression test. Electromyography (EMG) may be used to confirm the diagnosis [2].

Carpal tunnel syndrome in acute trauma often presents in a rapidly progressive fashion within a few hours. The symptoms of ACTS are similar to compartment syndrome and are characterized by unremitting pain and progressive dysesthesias and neurologic dysfunction in the median nerve distribution. The cause of ACTS in trauma is likely related to edema and hemorrhage. The carpal tunnel has been described as similar to a fascial compartment [3], and given its limited space, relatively small increases in fluid can compress the median nerve and cause symptoms of ACTS. The symptoms of ACTS in acute trauma are therefore generally slightly delayed in onset from the time of injury and progress over hours, which is important in distinguishing ACTS from nerve contusion, which is immediate in onset and typically nonprogressive [4]. This distinction is important in the diagnosis of ACTS as nerve contusions are typically observed, while ACTS requires urgent surgical decompression. Physical exam in ACTS may reveal increased pain with passive motion of the digits as well as loss of two-point discrimination. Direct pressure measurements within the carpal tunnel may be helpful [5]. Electrodiagnostic testing is not typically obtained in acute cases since it takes time to obtain, and signs of compression and denervation may take several weeks to appear. In the setting of an acute traumatic injury, CTS thus remains a purely clinical diagnosis.

Etiology

Distal Radius Fractures

Distal radius fractures are the most commonly associated upper extremity fracture leading to both acute and chronic CTS [5–9]. More severe fractures place patients at higher risk of developing ACTS. In a retrospective study by Itsubo et al., patients with ACTS had predominantly AO C-type fractures (68%) and were often due to a high-energy mechanism (46%) [7]. While significant edema and hemorrhage in the carpal canal are the most likely causes of ACTS in these cases, the degree of displacement of the initial fracture also plays an important role. In particular, volarly displaced fracture fragments can come into direct contact with the median nerve, increasing the risk of developing ACTS [10]. Significant flexion or extension of the wrist and injection into fracture hematoma during closed reduction has also been shown to increase the pressure within the carpal tunnel, but the hypothetical risk of ACTS related to these maneuvers has not been directly studied [8]. Nevertheless, care should be taken with injection and wrist positioning when performing closed reduction, and patients should not be splinted in hyperflexion or hyperextension.

In managing patients with distal radius fractures, clinicians should maintain a high degree of suspicion for ACTS. While management pathways vary, Mack et al. suggest an algorithm for evaluation and management of ACTS in their study of median nerve neuropathy after wrist trauma. They suggest performing any necessary reduction in the usual fashion, while having a high degree of suspicion for ACTS in any patient with severe wrist or hand pain and sensory deficits following reduction. In these patients, conservative measures including elevation and splint release should be attempted for up to 2 h. If these measures fail, they recommend measurement of the carpal tunnel pressure and release within 8 h for pressures greater than 40 mmHg. If the pressure is found to be normal, further observation can be performed [9]. While this algorithm is a useful framework, measurement of carpal tunnel pressure may not be

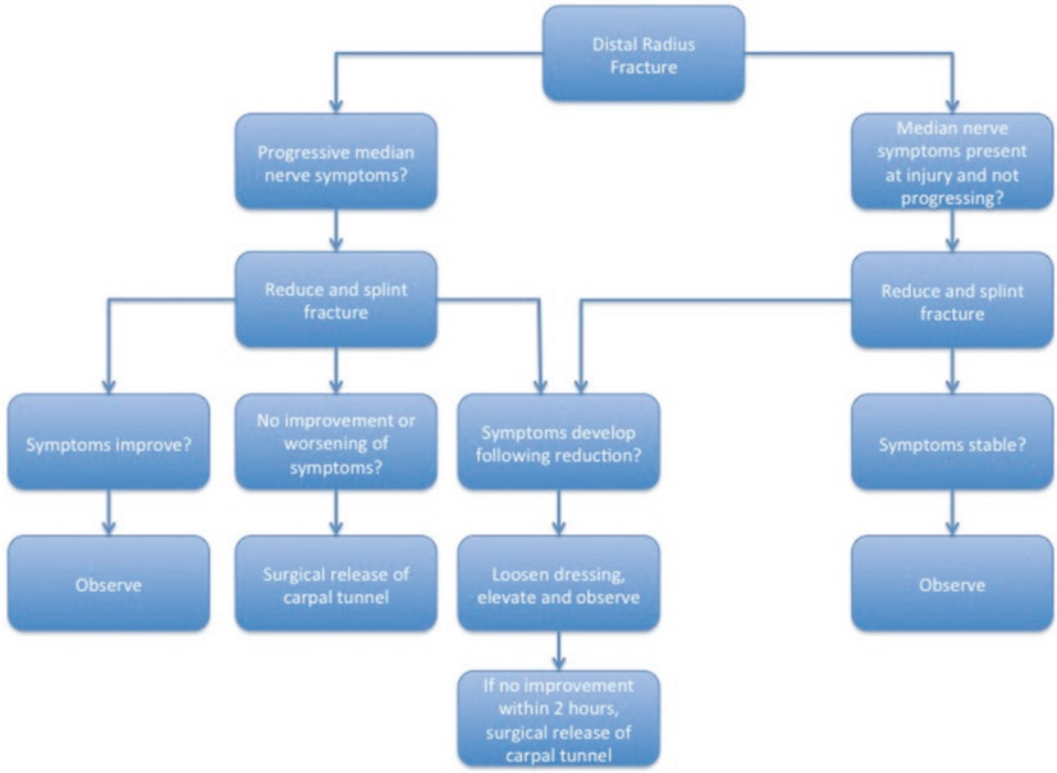

Fig. 26.1 Management of distal radius fractures in patients with symptoms concerning for ACTS

feasible in all settings, and catheter placement is not always reliable. Many surgeons thus prefer to rely on clinical judgment for the diagnosis of ACTS and proceed with release when symptoms continue after a brief period of observation. Our management algorithm for CTS and distal radius fractures is presented in Fig. 26.1.

Acute carpal tunnel syndrome can also occur following surgery about the wrist and is also most commonly associated with open reduction and internal fixation (ORIF) of distal radius fractures. Although some surgeons advocate for carpal tunnel release (CTR) at the time of distal radius ORIF even without previous signs of CTS, this is not the norm in clinical practice with most performing CTR only when clinical symptoms are present. The outcomes following carpal tunnel release at the time of surgical fixation seem to be similar to elective CTR. Chauhan et al. retrospectively compared patient-reported outcomes in elective CTR to those in CTR performed at the time of distal radius ORIF and found that patients experience similar subjective recovery, but no prospective studies have been performed [6].

In patients with subacute presentation (defined as 1–12 weeks post-fracture), Itsubo et al. showed that 79% had AO A-type fractures and greater than 90% were due to a low-energy mechanism. Furthermore, in patients with delayed onset (greater than 12 weeks), the rate of distal motor latency of the median nerve on the contralateral side was 71%. Such a high rate of CTS on the contralateral side suggests that these patients had other etiologies of carpal tunnel syndrome that were unrelated to their injury. They also examined the quality of reduction and found that greater than 62% of the wrists in all three groups (acute, subacute, and delayed) had unacceptable alignment, suggesting a possible relationship between continued deformity and median nerve compression [7].

Carpal and Metacarpal Fractures and Dislocations

In addition to distal radius fractures, fractures and dislocations of the metacarpals and carpal bones can also lead to ACTS. Gong and Lu reviewed a series of 382 metacarpal fractures and reported seven cases of ACTS in metacarpal shaft fractures and four cases of ACTS in fractures of the metacarpal base [11]. Kannan et al. describe a single case of volar fracture dislocation of the scaphoid leading to ACTS [12]. Olerud and Lonnquist report a single case of a patient with minimally displaced scaphoid and fifth metacarpal fractures that resulted in ACTS. During surgical release, a fracture hematoma was found in the carpal tunnel [13]. Others report cases of metacarpal or combined carpal and metacarpal fracture dislocations that resulted in ACTS necessitating surgical release [5, 14].

Carpal bone dislocations have also been associated with ACTS. Of these, perilunate fracture dislocations are perhaps the most common injury leading to ACTS. According to a prospective study of complex wrist injuries by Shivanna et al., the most common late presentation of perilunate dislocation was due to symptoms of ACTS. They reviewed 15 cases of carpal dislocations, and six had median nerve compressive symptoms. All six cases of median nerve compression were due to perilunate fracture dislocation, and all were delayed in presentation and underwent surgical fixation with carpal tunnel release [15]. The management for ACTS in perilunate dislocations is similar to that previously presented for distal radius fracture. Focus should be on first reducing the injury and monitoring for symptom improvement before performing carpal tunnel release in patients whose symptoms do not improve.

Given the frequency of median nerve compression in patients with perilunate fracture dislocations, some clinicians may elect to perform a carpal tunnel release at the time of surgical fixation even in patients without symptoms, particularly if a volar approach to the wrist is planned as part of the fixation. In a retrospective review of 32 patients, the authors noted that many patients who underwent carpal tunnel release at the time of fracture fixation had persistent symptoms even after a mean of 65 months of follow up. Six of the 32 patients had these persistent symptoms, and five of them had undergone release at the time of surgery. Three patients also developed delayed CTS. The reason for these continued symptoms is unclear, but the authors postulate that they are due to a chronic neural lesion rather than compression with the carpal tunnel [16]. In patients with symptoms of ACTS at the time of injury, carpal tunnel release should be performed at the time of surgery, and patients should be counseled that their symptoms might persist after surgery. The data is not clear whether or not release should be performed at the time of fixation of asymptomatic patients with perilunate or other carpal dislocations, and surgeons should continue to use their own clinical judgment.

Tendon Ruptures

Other reported causes of ACTS include acute tendon ruptures within or in proximity to the carpal tunnel. Flexor pollicis longus and palmaris longus tendon ruptures have both been reported to induce ACTS. Tendon ruptures may be caused acutely or may be the result of attritional changes following a prior fracture or dislocation [17, 18]. In these cases, patients with a prior fracture may develop ACTS years later when they suffer attritional tendon rupture. The cause of ACTS in this case is likely due to subsequent edema formation within the carpal tunnel. The treatment in these cases often includes excision of the tendon stump, tendon repair, or tendon transfer as well as a carpal tunnel release.

Burns and Thermal Injury

Burns and thermal injury can cause significant swelling, edema, and scar that may result in both acute and chronic presentations of carpal tunnel syndrome. In a review of seven patients treated for median neuropathy following flame burns that encompassed the hand and wrist, surgical

release revealed excess fluid in the carpal tunnel occasionally requiring delayed closure [19]. Smaller surface burns to the hand can also lead to CTS. Bache and Taggart reported a case of partial thickness burns of the thumb and volar wrist with superficial burns to the dorsum of the hand that resulted in ACTS. Again, edema was seen within the carpal tunnel during surgical release [20].

Carpal tunnel syndrome can also be a late finding in burn injuries. In a retrospective review by Ferguson et al., the average time to release following burn injury was 249 days. The delayed presentation is likely due to ongoing scar formation in the region of the carpal tunnel. The overall incidence of CTS in upper extremity burns is estimated at 2–15%. Management of CTS in these cases is generally similar to other causes of chronic CTS [21].

Other Soft Tissue Trauma

Blunt trauma in the absence of fracture or dislocation has also been reported as a cause of acute presentation of carpal tunnel syndrome. This can occur in hyperextension injury in falls or direct blows to the hand or wrist that lead to intraneural or carpal tunnel hematoma or swelling. In 1949, Watson-Jones reported a case of ACTS in a cricket player who stopped a ball with his hand. Carpal tunnel release relieved the patient's symptoms [22]. Faithfull and Wallace reported a case of median artery rupture from a fall that resulted in delayed presentation of CTS. Intraneural hematoma was found on surgical exploration, and neurolysis and carpal tunnel release also resolved the patient's symptoms [23]. Treatment in these cases consists of conservative measures and observation for symptom improvement. If symptoms continue or worsen, urgent surgical decompression is warranted.

Snake and Insect Bites

Other reported traumatic causes of CTS include snakebites, particularly by venomous snakes in which swelling and hemorrhage are common sequelae. In a review of 79 victims of snakebite in Turkey, only one patient developed ACTS, and in a similar review in Greece, three in 147 developed ACTS, making this a very uncommon scenario [24, 25]. Lazaro also reported a single case of ACTS following an insect bite [26]. While the common pathway appears to relate to edema formation related to venomous bite, these cases are rare, and thus treatment algorithms have not been established, and the need for carpal tunnel release is left to the surgeon's discretion.

Surgical Management

The decision to proceed with surgical management of carpal tunnel syndrome in the traumatic setting varies little from other situations. However, patients are more likely to present with ACTS in the setting of high-energy trauma. In the case of an injury that would not otherwise be treated surgically, the clinician may be driven to perform urgent release of the carpal tunnel in patients who develop ACTS. The decision is more easily made in patients who require surgical treatment for their injuries, with most surgeons erring on the side of performing carpal tunnel releases in symptomatic patients at the time of the index procedure.

When performing surgical release of the carpal tunnel at the same time as surgical stabilization of a traumatic injury, care must be taken with regard to the surgical approach. For instance, some surgeons may prefer to perform two separate incisions for volar plating of a distal radius fracture and concurrent carpal tunnel release. However, some authors argue that an extensile incision crossing the wrist allows for better visualization to ensure both full release of the TCL and antebrachial fascia, as well as evacuation of hematoma, if necessary [5]. To date no studies have demonstrated the superiority of a one- versus two-incision approach. Because of the anatomic deformity and ensuing hematoma potentially compromising visibility, we recommend avoiding endoscopic carpal tunnel releases in an acute traumatic setting. Regardless of surgeon preference for incision, it is advised that

surgeons ensure the proximal aspect of the antebrachial fascia is released [9, 27].

In patients who develop late subacute or chronic CTS following trauma, symptoms can be managed in the same way as other presentations of CTS. These patients may improve with conservative measures such as nocturnal wrist splints, NSAIDs, activity modification, and steroid injection. Surgical release should be reserved for patients that fail conservative measures [2].

Summary

Carpal tunnel syndrome is commonly associated with traumatic injuries, especially fractures and dislocations of the hand and wrist. While carpal tunnel syndrome at the time of injury is more common, subacute and chronic presentations related to prior trauma also occur. It is thus important to be vigilant in diagnosing ACTS and differentiating ACTS from median nerve contusion. Treatment of ACTS usually consists of an urgent open surgical release, while chronic cases may be first addressed with conservative measures. The index of suspicion for patients with high-energy trauma and progressive symptoms should be high, and treatment for ACTS should not be delayed.

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27 Biologics, Conduits, Allografts, and Autografts in Carpal Tunnel Syndrome

Jonathan E. Isaacs and Shuhao Zhang

Introduction

Most surgeons do not immediately think about biologics, conduits, or nerve grafts when considering the treatment of carpal tunnel syndrome. With more than 366,000 cases performed in the United States each year, the surgical treatment of median nerve entrapment is remarkably safe and predictable [1]. Unfortunately, failures and complications do occur, and in these settings, the surgeon must be familiar with all of the available tools to remedy the situation. Early scarring as a direct result of postoperative infection or wound dehiscence and delayed idiopathic perineural scarring can lead to recurrent nerve constriction. Complete and partial nerve lacerations are also rare but devastating complications that must be dealt with. Unfortunately, these are often not detected at the time of injury so that a sharp "surgical" nerve transection becomes retracted and fibrotic, requiring more complex reconstruction.

J.E. Isaacs (✉)
Division of Hand Surgery, Department of Orthopaedic Surgery, Virginia Commonwealth University Health System, Richmond, VA 23298, USA
e-mail: jonathan.isaacs@vcuhealth.org

S. Zhang
Division of Plastic Surgery, Department of Surgery, Virginia Commonwealth University Health System, Richmond, VA 23298, USA

Scarring

Carpal tunnel incisions, like any surgical violation of the skin, can lead to postoperative infection. While incidence of infection has been reported to range from 0 to 8%, this is generally cellulitic in nature and can be successfully treated with oral antibiotics [2–7]. Deeper and more serious infections are more common in patients suffering from some level of immunocompromise, such as diabetes and rheumatoid arthritis, or patients on immunosuppressive medications. Abscesses around the wrist or in the hand can spread to a virgin carpal tunnel resulting in acute carpal tunnel syndrome. Intravenous drug abusers or neglected septic flexor tenosynovitis patients are classic examples at risk for this scenario. Though prompt recognition, incision and drainage, and antibiotics are the well-known treatment principles of deep infections involving the carpal tunnel, once the infection has cleared, fibrosis and adhesions often form around the median nerve.

Spontaneous wound dehiscence, in the absence of infection, has been reported in less than 1% of carpal tunnel releases [6, 7] though in our experience may be more common (Fig. 27.1). Again, while diabetics, rheumatoids, and immunocompromised patients are at greatest risk, this postoperative complication can be seen in otherwise healthy patients as well. Surgical decolonization followed by reclosure is an option, though most frequently, the wound is

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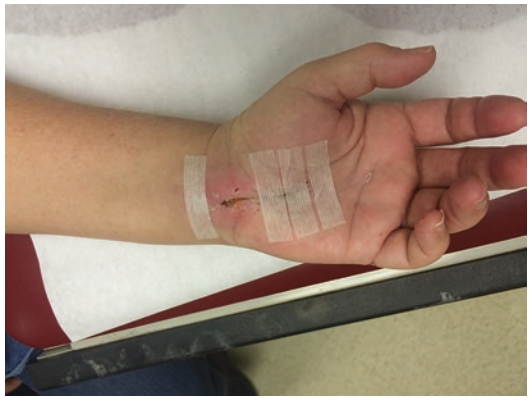

Fig. 27.1 Mild wound dehiscence following carpal tunnel release

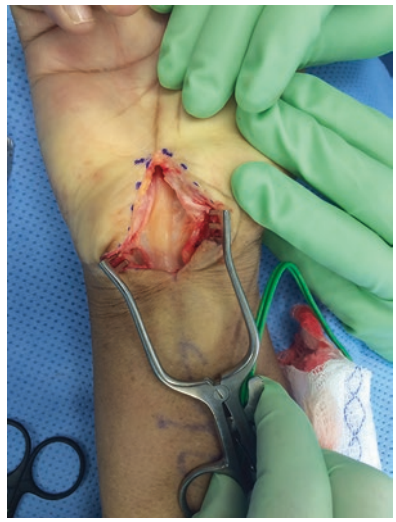

Fig. 27.2 Dense adhesions between the median nerve and surrounding tissue including flexor tendons. Finger motion caused pain compatible with traction neuritis

allowed to heal by secondary attention. This strategy often results in complete healing and a successful outcome, but can occasionally result in excess median nerve scarring.

Cicatrix that has formed around the median nerve becomes problematic when it constricts the nerve or prevents the normal glide of the nerve such that regular wrist and finger motion pulls and stretches the nerve (Fig. 27.2). The constrictive effect of a contracting scar tissue is relatively intuitive and, similar to other forms of nerve compression, inhibits nerve perfusion. If severe enough, this leads to demyelination, axoplasmic transport dysfunction, and even axon loss [8]. Early stages of this process are responsive to decompression and neurolysis [9, 10]. However, delayed treatment can lead to end-stage fibrosis of the median nerve with little chance of recovery even with surgical intervention. The morbidity associated with the loss of nerve glide is a less familiar concept. Normally, the median nerve glides 2 cm through the total arc of wrist motion and 1 cm with full finger motion [11–13]. This gliding is important since nerves tolerate stretch quite poorly with as little as 8–15% of stretch disrupting blood flow [14]. This number is even lower when the nerve is already fibrotic [14]. Adhesions formed around a scarred median nerve to surrounding structures therefore can result in both mechanical irritation and symptom producing nerve ischemia with wrist or finger motion. Dense adhesions between the median nerve and surrounding tissue including flexor tensons was noted and explained the traction neuritis pain noted with finger motion [15].

Nerve Injury

Carpal tunnel release surgery has the simple and straightforward goal of "helping" the median nerve. So when the nerve is instead injured or transected, it is especially devastating and frustrating for both the patient and the surgeon. Incidence of nerve injury is a key point in the debate over open, mini-open, and endoscopic release techniques. The literature suggests a near equivalency in complication rates between procedures, including major nerve lacerations and injuries, when transient neuropraxia is excluded [16]. Though certainly injury can occur with any technique, our own observation would be that endoscopic-associated injuries generally involve the distal median nerve as it branches, while an open release risks proximal injury particularly when the distal antebrachial fascia is released using an open scissor "push" technique. Acute postoperative neurologic deterioration, fortunately, does not guarantee nerve transection. Neuropraxic injuries, presumably from "blunt trauma" to the nerve and more common after

endoscopic carpal tunnel release, have good neurologic recovery [16].

Diagnosis

Though a detailed discussion of the workup of recurrent carpal tunnel syndrome is included in the other chapters of this book, a few points regarding the diagnosis of scarring around the median nerve are warranted here. Persistent symptoms following uncomplicated carpal tunnel release can be explained by incomplete release, incorrect diagnosis, proximal or secondary nerve entrapment, or neural damage associated with severe or prolonged median nerve compression. Worsening of symptoms should always be worrisome and may suggest injury to the median nerve. Though nerve contusion resulting in neuropraxia can occur, a high index of suspicion for nerve transection must be maintained. Initial but temporary improvement followed by gradual worsening of symptoms is most compatible with postoperative scarring especially in the presence of infection or wound healing problems.

Positive provocative signs may or may not be present depending on the severity of nerve dysfunction. Patients will not experience a "worsening of numbness" with these maneuvers if they are already anesthetic. Percussion sign, in our experience, is more often positive but is a relatively nonspecific finding. Regardless, its presence or absence is not reliable enough to be considered absolutely diagnostic for nerve injury or regeneration. Increased pain with wrist and finger extension is suggestive of traction neuritis and perineural scarring.

Nerve conduction studies and electromyography add further information but should be interpreted in the context of the other physical and clinical findings. We evaluated a patient ultimately found to have a partially transected nerve who underwent three "reassuring" nerve conduction studies after acute exacerbation of paresthesias following a "difficult" carpal tunnel release. The evaluator tested sensory conduction off the ulnar aspect of the middle finger each time—representing the only area with persistent nerve continuity (Fig. 27.3). Worsening of conduction parameters across the wrist compared to preoperative studies certainly would support a diagnosis of perineural scarring, while loss of all conduction would suggest nerve damage. Failure of the nerve study to improve is the most difficult to interpret and can be found in several clinical scenarios—including technically and/or clinically successful nerve decompression.

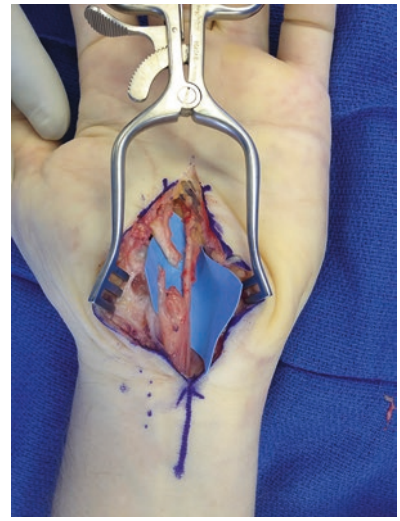

Fig. 27.3 Median nerve lacerated during endoscopic release. Nerve conduction studies of the middle finger were reassuring (note that this portion of the median nerve remained intact)

Nerve imaging may be particularly helpful in sorting between these three general differential diagnoses. Ultrasound has the advantages of being able to follow a nerve longitudinally and is quicker and less expensive than MRI [17]. Especially in thinner patients and with more superficial nerves (such as the distal median nerve), it is excellent for seeing nerve enlargement which can be associated with scarring, entrapment, but also with neuroma in continuity. MRI's superior resolution may be better at differentiating between injury and entrapment [18]. Both modalities can identify loss of nerve continuity, although based on our own experience, both can potentially miss partial transection injuries.

Treatment

Obviously, if nerve transection is recognized intraoperatively, repair should be performed immediately or as soon as feasible (if appropriate equipment and surgical "skill set" are not immediately available). Likewise, if nerve injury is suspected, early exploration may increase the likelihood of successful nerve repair. Several biological and practical principles support the benefits of not delaying exploration. Failure to improve after carpal tunnel release offers a more difficult decision tree, and further treatment depends ultimately on the identification of correctable lesions. Symptomatic "scarring" of the median nerve can be treated by therapy, observation, or revision neurolysis typically with placement of a scar barrier. What appears to be early scarring may represent inflammation and edema, and certainly we have seen this resolve with the tincture of time (though pain medications including gabapentin, amitriptyline, tramadol, and even narcotics may be necessary as well). Therapy focusing on nerve gliding can be helpful as well though may be limited by pain. Surgical neurolysis may be pursued when nonoperative treatment has failed.

Primary (Acute) Nerve Repair

Direct nerve repair is generally only possible when the iatrogenic nerve laceration is immediately recognized. The principles of nerve repair including adequate debridement of damaged nerve (usually not necessary following inadvertent sharp "surgical" transection), maintenance of alignment, and tensionless approximation certainly apply. The well-defined fascicular anatomy of the median nerve at this level facilitates alignment, and for acute clean lacerations, tension is not typically an issue. Microsuture repair is still considered the gold standard though repairs can be reinforced and tidied with either fibrin glue or short conduits applied as coaptation aids rather than as "gap-bridging" devices.

Fibrin Glue

Advocates of fibrin glue-assisted nerve repair note that fibrin glue is atraumatic, quick, and easy to apply. If fibrin glue drips in between the nerve interface, it will not block regenerating axons [19]. Even though nerve repair should be considered an off-label use (commercially available fibrin glue does not have Food and Drug Administration approval for this application), a recent survey indicates that many surgeons incorporate it into their repair strategy [20]. Animal data where fibrin glue is used instead of microsuture repair in general indicates a similar efficacy though intermittent reports of complete nerve dehiscence are concerning [21–29]. The nerve repair is weakest within the first 2 weeks, and studies comparing load to gap and load to failure have shown fibrin glue is inferior to suture repair in the first 2 weeks but similar thereafter [30–32]. Alternatively, fibrin glue can be used to augment suture repair, allowing fewer sutures to be used, which was shown to have similar functional outcomes but less scarring and better axonal alignment [33]. A biomechanical cadaver study demonstrated effective resistance to gapping but no significant augmentation of actual holding strength over minimal suture coaptation [34]. While there are no published clinical outcomes studies, fibrin glue augmentation does appear to be useful at least to control gapping and maintain fascicular alignment when used in addition to standard suture repair.

Autologous fibrin glue can be prepared in the operating room using the patient's own blood (to be mixed with pooled blood bank thrombin) though this does not appear to be as effective as commercially available product [34]. Commercially available fibrin glue comes as two separate syringes containing different components of the clotting cascade. The syringes are depressed simultaneously (either using a double syringe holding bracket or by coordinated effort), and as the contents of the two syringes mix at the application site, a gel-like clot is formed. A piece of Esmarch or similar material placed behind approximated nerve ends (typically following at least partial suture neurorrhaphy) can act as a temporary mold to shape the gel as it is applied so that an adhesive cylinder forms around the coaptation site. The gel is firm enough to augment the repair after about 3 min. Commercially available fibrin glue should be used with caution in patients with aprotinin sensitivity.

Nerve Connectors

Nerve connectors are simply conduits applied over approximated or nearly approximated nerve ends. Any biologic or commercially available nerve tube can be trimmed and applied in this capacity although currently one product is specifically marketed for this purpose. The many potential advantages of this technique include the creation of a concentrated neurogenic milieu within the protected microenvironment at the enclosed coaptation site, the blockage of escaping axons, and a barrier to invading scar tissue [35, 36]. There is some evidence that the small gap between the nerve ends may encourage end-organ specificity in which axons self-direct to the appropriate target (though this is typically felt to be a limited process at best) [37]. With fewer microsutures required to maintain the coaptation, the theoretical harmful effects of "suture trauma" and foreign material reaction can be blunted and at least partially shifted away from the regenerating axons. The anchoring sutures at the connector ends can redistribute tension, which has been shown in animal models to improve nerve regeneration by allowing maximal angiogenesis at the repair site. In a rat model, Schmidhammer demonstrated that splinting the nerve repair by suturing the distal silicone tube to the nerve epineurium 3 mm distal to the tube, thereby relieving tension at the nerve repair site, led to the highest rate of angiogenesis and nerve function recovery [38]. Perhaps most importantly, the enveloping connector seems to direct and align the nerve fascicles which may be especially helpful with multifascicular nerves such as the median nerve at the wrist.

Added cost and lack of proven (as opposed to theoretical) benefit are the primary disadvantages of incorporating nerve connectors into a median nerve repair, though several clinical reports on "conduit repairs" of larger peripheral nerves involve such small gaps that they could be considered connector-assisted repairs. In a randomized control trial, Lundborg found similar outcomes at both short- and long-term (5-year) follow-up on silicone tube repairs versus suture repairs of median and ulnar nerves at the wrist or distal forearm across gaps of only 3–5 mm [39, 40]. Another randomized study comparing collagen conduits (bridging gaps of 6 mm) to suture repair of median or ulnar nerves in the distal forearm showed no difference in outcomes after 24 months [41].

Currently, only one commercially available nerve connector is available (*AxoGuard Nerve Connector*, AxoGen, Inc., Alachua, FL). It is manufactured using tissue-engineered acellular porcine small intestine submucosa and can be applied in a variety of ways. Though pre-soaking has been recommended by the manufacturer to soften the product, implantation in the dry and rigid state facilitates passage of the nerve stump into the short tube. Once positioned, either the natural moisture within the body or normal saline irrigation will soften the material enough to allow suture passage. Nerve stumps can be pulled into the connectors using horizontal or "U" stitches placed through the end of the connector, through the outer epineurium, and back through the connector similarly to more conventional nerve conduit application. As the suture is pulled snug, the nerve stump can be guided into the tube though this can be an exercise in frustration without at least a semiskilled assistant. If using the more popular 10 mm long connectors (it is also available in a 15 mm length), the sutures should be placed 2–2.5 mm from the end of the connector and 2–2.5 mm from the end of the nerve so that once secured, about 4–5 mm of nerve stump will be held within the tube. When repeated with the second nerve stump, the nerves should be ideally just barely touching. A perfectly sized tube (they come in a variety of diameters, and picking the correct size can be challenging) will hold the fascicles in end-to-end alignment. If the connector is too big, the "slack" can be taken out of the side by pinching the excess material and fastening with hemoclips or sutures (Fig. 27.4). Alternatively, the nerve stumps can be inserted into the tube and held in place with two or three simple stiches placed through the end of the connector and the underlying epineurium. This technique can work well when the nerve is stiff, such as larger diameter nerves like the median nerve, and the repair is completely tension free as in acute injuries with generous mobilization.

Nerve connector can also be combined with epineurial sutures to consistently control rotational

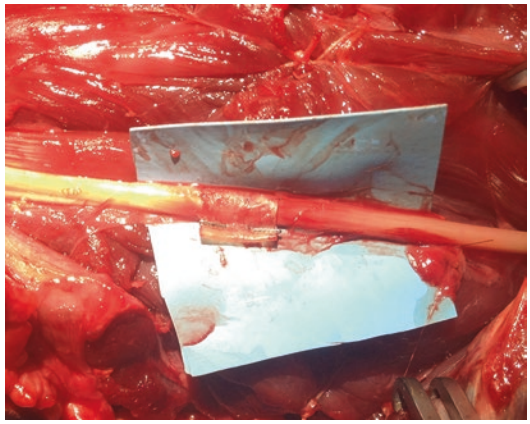

Fig. 27.4 Though not a median nerve at the carpal tunnel, this illustrates a primary repair reinforced with a nerve connector. Note the sutures at the end of the connector "unloading" the repair site and the hemaclips taking slack out of the oversized connector

and longitudinal fascicular alignment. One of the nerve stumps is inserted into the connector which is slipped completely over the end of the stump and onto the nerve trunk. The nerve ends are lined up, and a few simple epineurial stitches are placed so that the ends are barely touching. The connector is then slid back over the neurorrhaphy site so that the inner surface of the tube molds the nerve ends to further enhance end-to-end approximation. Simple sutures placed at the end of the connector relieve tension at the nerve face and reinforce the repair.

Conduits

Any biotolerant tubular structure can theoretically be used as a nerve conduit if nerve stumps can be inserted into and secured within the ends. In fact, some surgeons routinely use local veins to bridge defects in small caliber nerves [42]. However, in an effort to improve surgical efficiency and avoid "donor" morbidity, most conduit nerve repairs are performed using one of several commercially available versions.

In addition to the practical advantages of speed and convenience, the principle advantages of conduit repair are similar to those discussed regarding nerve connectors. Conduit application is technically straightforward, and the protected microenvironment established between the nerve stumps contains concentrated neurotrophic factors. The main difference between connectors and conduits is that a fibrin clot must form between the separated nerve stumps to act as a biological scaffold supporting Schwann cell migration and subsequent axon elongation across the nerve gap [43]. In other words, if the fibrin clot does not form, nerve regeneration will not occur. Commercially available nerve conduits are made of one of three materials: polyglycolic acid, collagen, or polycaprolactone. All share the common characteristics in that they are semirigid, to resist collapse and kinking; semipermeable, to allow diffusion of oxygen and nutrients to support nerve regeneration; and absorbable, to avoid long-term irritation.

In the right circumstances, conduits have an established track record. Conduits consistently support the formation of nerve regenerate across a 1 cm defect in rodent sciatic nerves [44]. Human data is more variable with several studies supporting nerve regeneration in small caliber nerves across short defects. Rinker et al. reported sensory recovery after repair of digital nerves with gaps averaging 9 mm [42]. Similarly, Taras et al. and Haug et al. reported good results for digital nerve repairs for gaps averaging 12 and even 19 mm [45, 46]. On the other hand, Battiston et al. had only 4/19 good or excellent results using similar criteria as other published studies [47], and Lohmeyer reported no recovery in defects greater than 15 mm [48].

The fibrin clot formation essential for successful nerve regeneration becomes less stable and therefore less predictable with longer gaps and larger diameter nerves. Moore et al. reported on four failed conduit major nerve repairs [49], and Chiriac et al. reported a satisfactory recovery in only 1 out of 12 conduit major peripheral nerve repairs [50]. Both recommended against conduit repair of major peripheral nerves. With gaps more than a few millimeters, therefore, conduits would not be considered a reliable way to repair the median nerve trunk but could be considered for gaps up to a couple of centimeters in the terminal branches.

Secondary (Delayed) Repair

Frequently, especially with endoscopic or mini-incision carpal tunnel releases, the injury to the

median nerve is not immediately recognized. Even if complaints at the first postoperative visit prompt an urgent re-exploration, this delay of only 10–14 days is enough to allow nerve retraction and early fibrosis. Most frequently, the delay is much longer to allow a suspected neuropraxia to resolve, or the surgeon adopts a defensive "wait-and-see" attitude. Fairly rapidly, fibrosis of the retracted nerve makes mobilization more difficult, and end bulb neuromas develop, requiring nerve resection at the time of repair. Adequate resection of scarred and neuromatous nerve tissue and avoidance of excessive tension at the repair site are essential for successful nerve regeneration so that the gap between nerve ends (or between sections of the nerve if only partially cut) demands some form of bridging construct. Current options include conduits, nerve autograft, or acellular nerve allograft. As stated in the previous section, the indication for conduit repair of the median nerve is very limited and is not practical for delayed repairs where a significant gap exists.

Processed Nerve Allograft (PNA)

Processed human nerve allograft (PNA) offers many of the advantages as conduits regarding off-the-shelf convenience and avoidance of donor morbidity associated with autograft harvest. The bioengineering process that renders the allograft immunotolerant by necessity removes all cells (including Schwann cells) but maintains much of the internal architecture of normal nerve tissue. This architecture acts as the scaffold to support migrating Schwann cells necessary to support axon elongation across the graft. Some guidance cues such as laminin and growth factors such as brain-derived growth factors are also retained by the allograft nerve tissue to further enhance the neuro-supportive environment. The only commercially available processed acellular nerve allograft product (Avance, Axogen, Inc., Alachua, FL) incorporates an additional enzymatic removal of chondroitin sulfate proteoglycans. Chondroitin sulfate proteoglycans inhibit axon regeneration, and treated allograft in experimental models supports superior axon regeneration compared to untreated allograft [51]. Gamma irradiation sterilizes the tissue without significantly altering the infrastructure.

PNA is available in a variety of sizes from 15 mm to 7 cm and diameters of 1–2 mm, 2–3 mm, 3–4 mm, and 4–5 mm (ranges used since human tissue does not come in "exact" sizes!). The tissue must be maintained at −40 °C until time of usage and is thawed for several minutes in normal saline prior to implantation. Handling characteristics are very similar to autograft, and the PNA is inset into the nerve defect in an analogous fashion (using sutures, nerve connectors, or fibrin glue).

While there is extensive data on nerve allograft, the information available on nerve tissue processed in an analogous fashion to the commercially available product is more limited. Processed allograft and autograft performed similarly across a 14 mm gap and 10 mm gap at 3 months in a rodent sciatic nerve repair model based on histology and muscle force recovery. Autograft was superior to allograft across a 28 mm gap though there was some axon regeneration even in this group. Conduit repairs were significantly inferior at all three lengths [52–54]. While this data has limited application toward the repair of the median nerve or its branches based primarily on the size discrepancies between a rat and human nerve, there is a growing body of human evidence offering better guidance. Karabekmez et al. reported 10 successful digital and sensory nerve repairs across digital nerve gaps up to 3 cm [55]. Similarly, Taras et al. achieved 83% of good to excellent recovery across gaps of up to 3 cm in 21 digital nerve repairs [56]. However, most of the relevant information comes from an ongoing multicenter data acquisition study. In this study, treatment algorithms are determined by the surgical team, but if allograft is used, the manufacturer (AxoGen) supports and maintains an active database. The first publication generated from the first 132 nerve repairs out of this source included 22 median nerves (not necessarily at the carpal tunnel) with quantitative data available for eight repairs. The average nerve gap was 33 mm, ranging from 10 to 50 mm. Meaningful recovery (S3 or M3 and above) was achieved in 75% of these median nerve repairs [57]. Though the data showed a 91% meaningful

recovery rate across all nerve repairs of gap size 30–50 mm, the gap size of the two unsatisfactory median nerve repairs are unknown. Of note, there were no reported implant complications, tissue rejection, or adverse events related to use of the nerve allografts.

Though some critics have raised concerns regarding the effective length of acellular nerve allograft, this should not be an issue with median nerves injured during carpal tunnel releases. Though defects of up to 5 cm would not be unusual in neglected injuries, convincing clinical data support allograft reconstruction to at least this size gap. Allograft repairs of 7 cm defects in nerves damaged in oral surgeries have achieved complete sensory recovery in 5/7 patients [58]. In the rare circumstance that a longer median nerve defect is identified, nerve autograft would be the preferred reconstructive tool.

Processed allograft is available in diameters of up to 4–5 mm which may offer an appropriate size match to the median nerve in smaller patients. For thicker median nerves, or if the injury is at the distal carpal tunnel, smaller allografts can be cabled (stacked) together to facilitate group fascicular repair between the trunk and distal branches (Fig. 27.5a, b). Alternatively, the consistent and predictable topography of the distal median nerve lends itself to isolation and separate repair of the sensory and motor components—a strategy that has resulted in improved recovery [59], though not yet demonstrated with allograft-assisted repairs.

Autograft

Despite advances in both conduit technology and bioengineering of nerve tissue, autograft remains the gold standard for bridging nerve gaps. In addition to a favorable architecture, autograft contains guidance cues, growth factors, and Schwann cells which all stimulate and guide axon elongation. Donor nerves are typically expendable sensory nerves which are all associated with at least some morbidity but definitely increased surgical time, effort, and expense. Many patients object to the second surgical site. Although medial antebrachial, lateral antebrachial, and superficial radial nerves have all been described as donor nerves, taking a sensory nerve from an extremity missing sensation (as in the case of median nerve damage) is somewhat counterintuitive. The sural nerve is the most common source of graft material with incidence of morbidity such as neuroma, neuropathic pain, or problems from anesthesia in the foot around 5–10% [60]. Though upwards of 30 cm of sural nerve can be obtained per leg, graft quantity is not typically an issue for the types of median

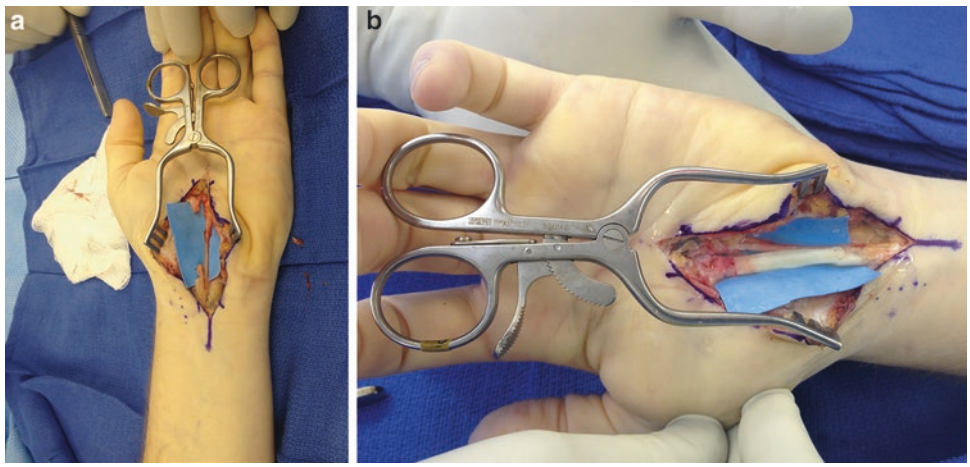

Fig. 27.5 Surgical images of the median nerve damaged during endoscopic release (Fig. 27.3). (**a**) Damaged nerve tissue has been excised; (**b**) processed acellular nerve allograft has been trimmed to fit the defect, sutured into place, and the neurorrhaphy sites reinforced with nerve connectors

nerve injuries associated with carpal tunnel complications. Depending on where the median nerve is injured, grafts can be used to reconstruct the proximal common or proper digital nerves, to connect the trunk to injured branches, or stacked together into a "cable" to reconstruct the median nerve trunk. When cable grafting, the strands of graft material can be "bound" together using fibrin glue and inset "en bloc" as opposed to suturing in individually.

Recovery after median nerve repair is dependent on patient's age, gap size, level of injury, associated injuries, and timing of repair [61]. A meta-analysis of forearm nerve repairs revealed that functional motor and sensory recovery, defined as M4 or S3+ (Medical Research Council Criteria) and better, was achieved in 52% and 43% of the cases [61]. In a study specifically looking at repair of the median nerve at the wrist level, 10 of 13 injuries repaired with autograft had S3 functional recovery [62].

The answer to the difficult but imminent patient question regarding allograft versus autograft "what do you recommend?" at this time seems to come down to preference. Animal data suggests that the autograft may be a little better especially as gap size increases. The clinical literature lacks a prospective comparative study, but published results following allograft repair of major peripheral nerves appear equivalent to autograft repair outcomes. For digital nerves, the clinical data is even stronger for allograft. Many patients when given this information will express the desire to avoid a second incision and others will express apprehension about having a cadaver nerve implanted into their bodies—both providing clear guidance to the surgeon.

Scarred Nerve

The surgical relief of adhering or strangulating scar tissue is relatively straightforward. The original incision is extended proximally and distally so that the dissection can progress from normal to abnormal tissue. The adhesions are sharply released circumferentially (taking care not to transect the nerve, in particular the motor branch) until the nerve is completely freed. If a thick rind encompasses the nerve, this can be carefully incised and dissected away from the underlying tissue utilizing microinstruments and microscope magnification (Fig. 27.6a, b). Many advocate some form of scar barrier to prevent recurrent scarring.

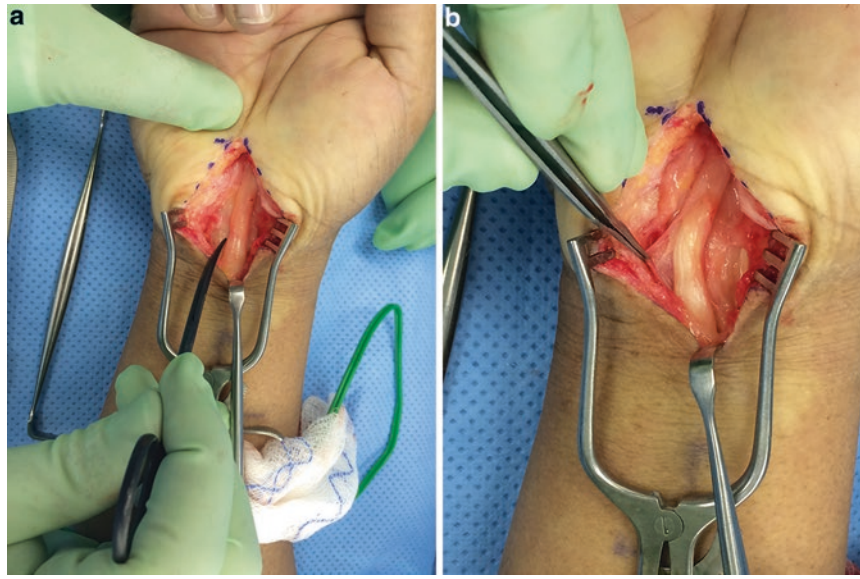

Fig. 27.6 Surgical images of neurolysis of scarred median nerve (Fig. 27.2). (**a**) Adhesions have been removed, and (**b**) a rind of scarred epineurium is carefully removed

Porcine Submucosa

Submucosa extracellular matrix (SEM), manufactured from laminated layers of processed acellular porcine small intestine submucosa vacuum pressed together, has been marketed specifically as a nerve-wrap scar barrier *(AxoGuard Nerve Protector*, AxoGen, Inc., Alachua, FL*)*. This is the same material as used in commercially marketed nerve connectors. This material is a tough, flexible sheet used in many other applications throughout the body including hernia repair, dural repair, and incisional closure. As such, there is a large combined clinical experience attesting to its overall biocompatibility and safety (Fig. 27.7). Kokkalis et al. further demonstrated the safety of this material as a nerve wrap in a rabbit model [63]. Though this animal model was chosen for a propensity to develop scar tissue, no difference was noted in adhesions or nerve function between wrapped nerves and control limbs. The material was noted to revascularize and incorporate into the mesoneurium. The same senior author published his favorable clinical experience using this scar barrier in revision cubital tunnel surgery though currently a similar series for carpal tunnel revision is lacking [64].

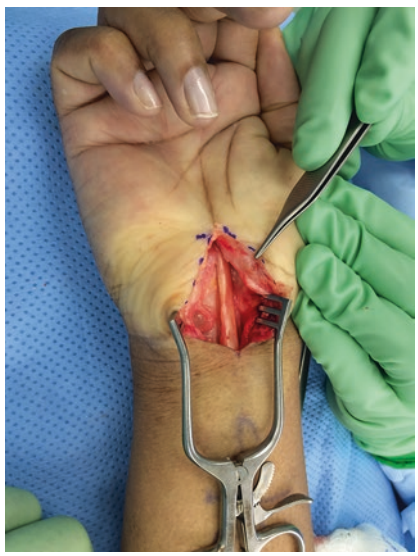

Fig. 27.7 Commercially available porcine submucosa extracellular matrix sheeting wrapped around the nerurolysed median nerve as a scar barrier

Collagen Wrap

Even less published data supports the use of collagen-based wraps as perineural scar barriers. Presumably, a natural extension of the broad clinical experience with purified type I collagen-based nerve conduits, the collagen sheets are applied in an analogous fashion as the SEM wraps. Cited advantages therefore include biocompatibility and tissue isolation. Soltani et al. presented 15 patients who received collagen sheet wrapping of either the median or ulnar nerve during revision release. Subjective improvement was noted in 89% of cases [65].

Conclusion

Median nerve dysfunction as a result of iatrogenic injury or chronic scarring poses a challenging problem for the carpal tunnel surgeon. Acute injuries can often be repaired primarily if recognized in a timely fashion, with or without the use of adjunctive methods such as fibrin glue and nerve connectors. Small nerve gaps may be amenable to repair with conduits; however the indication for their use in median nerve repair is limited. Unfortunately, delayed repair of median nerve injuries inevitably results in retracted nerve endings with a nerve gap that needs to be bridged. Though nerve autograft remains the gold standard for repairing large nerve gaps in major peripheral nerve injuries, data demonstrating similar effectiveness using nerve allografts are now emerging. Lastly, the use of off-the-shelf nerve wraps for preventing recurrent scar formation after neurolysis of the median nerve is promising though extensive data is lacking. The development of these off-the-shelf products has expanded the armamentarium of the hand surgeon, who must become facile with the different options to provide exceptional care for the complicated carpal tunnel patient.

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Median Compressive Neuropathy Proximal to the Carpal Tunnel

28

Michael G. Galvez and Jeffrey Yao

Anatomy

The median nerve originates from the lateral (C5, C6, and C7) and medial cords (C8 and T1) of the brachial plexus. The median nerve enters the arm from the axilla at the inferior margin of the teres major muscle and then courses down with the brachial artery on the medial aspect of the arm between the biceps brachii and the brachialis muscles. The median nerve may then pass deep to an anatomic variant, known as the ligament of Struthers, that extends from a small supracondylar process on the humeral shaft to the medial epicondyle of the humerus. At the elbow joint, the median nerve crosses anteriorly to run medial to the artery in the distal arm, passing under the bicipital aponeurosis (lacertus fibrosus), and through the antecubital fossa (Fig. 28.1a).

M.G. Galvez
Division of Plastic and Reconstructive Surgery, Stanford Hospital and Clinics, 770 Welch Road, Suite 400, Stanford, CA 94304, USA
e-mail: mggalvez@stanford.edu

J. Yao (✉)
Department of Orthopaedic Surgery and Surgery, Robert A. Chase Hand and Upper Limb Center, Stanford Hospital and Clinics, 450 Broadway Street, Suite C442, Redwood City, CA 94063, USA
e-mail: jyao@stanford.edu

The median nerve then enters the forearm between the superficial humeral and deep ulnar heads of the pronator teres muscle (Fig. 28.1b). The nerve passes between the proximal arch of the flexor digitorum superficialis (FDS) and travels between the FDS and the flexor digitorum profundus (FDP) muscles. The median nerve innervates the pronator teres, flexor carpi radialis, and the palmaris longus in the superficial aspect of the volar forearm. In the intermediate aspect of the volar forearm, the median nerve innervates the FDS.

The anterior interosseous nerve (AIN) then branches from the median nerve, approximately 4 cm distal to the medial epicondyle (Fig. 28.1c). The AIN arises from the radial aspect of the nerve and passes beneath the deep head of the pronator teres and the FDS arch to course along the interosseous membrane and supplies the deep muscles in the volar forearm. The AIN innervates the flexor pollicis longus (FPL), FDP to the index finger and the middle finger, and the pronator quadratus. There may be median and ulnar nerve crossover in the forearm, known as a Martin-Gruber anastomosis, which is a variant that may result in incomplete palsies [1].

The palmar cutaneous branch of the median nerve (PCBMN) branches from the median nerve before it continues through the carpal tunnel into the wrist. The PCBMN branches from the radial aspect of the median nerve approximately 5 cm proximal to the distal flexion crease of the wrist

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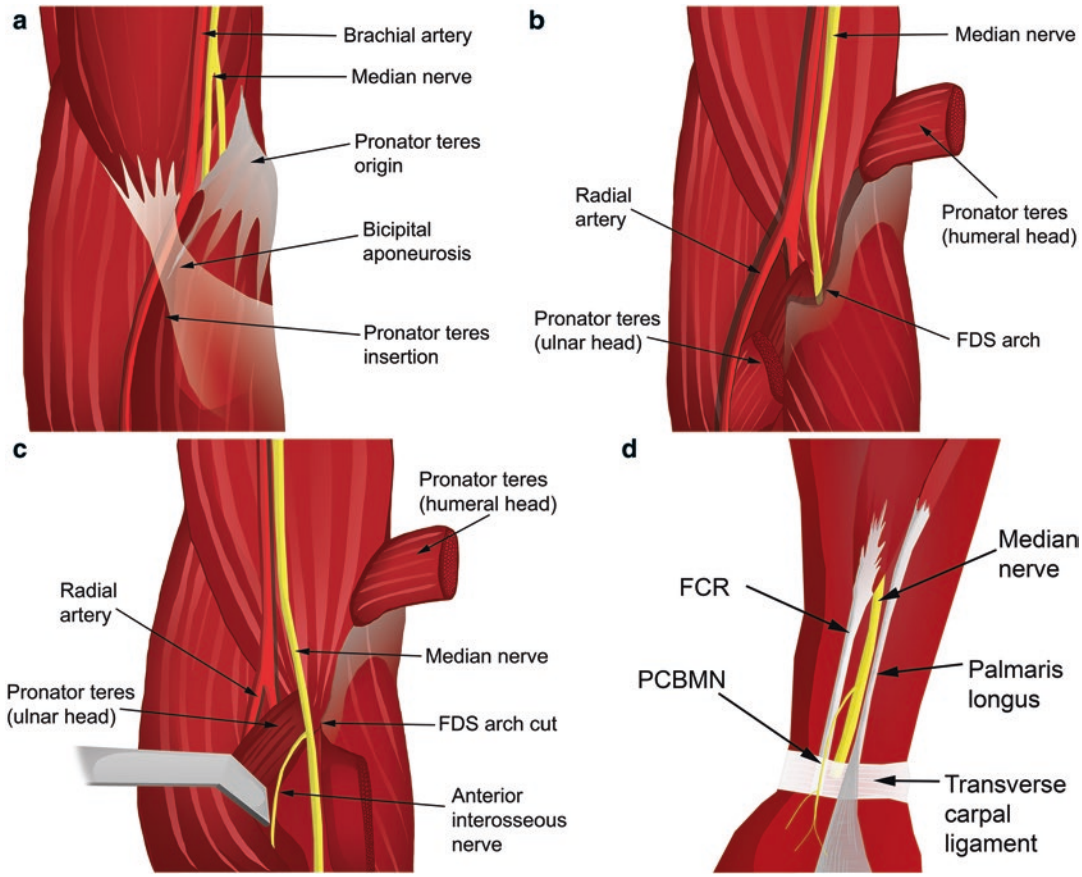

Fig. 28.1 Anatomy of the median nerve. (**a**) Illustration demonstrating the course of the median nerve as it passes through the antecubital fossa. The nerve runs deep to the bicipital aponeurosis (lacertus fibrosus) and medial to the both the biceps and the brachial artery. (**b**) Illustration demonstrating the course of the median nerve as it passes beneath the proximal fibrous arch of the flexor digitorum superficialis (FDS). (**c**) Illustration demonstrating the course of the anterior interosseous nerve as it branches off on the radial aspect of the median nerve (approximately 4 cm distal to the medial epicondyle) and passes beneath the deep head of the pronator teres and the FDS arch. (**d**) Illustration demonstrating the course of the palmar cutaneous branch of the median nerve (PCBMN) as it passes between the flexor carpi radialis (FCR) tendon and the palmaris longus tendon and travels through the brachial fascia and superficial to the transverse carpal ligament to supply the thenar eminence and the palmar skin

(Fig. 28.1d) [2]. This nerve provides sensation to the thenar eminence and palm.

Overall, compressive neuropathies involving the median nerve proximal to the carpal tunnel are relatively uncommon. Their etiology is typically idiopathic; however, the compressive effect of a mass on the median nerve must always be considered [3].

Pronator Syndrome

Pronator syndrome is a compressive neuropathy of the median nerve at the elbow and refers to a constellation of signs and symptoms. This syndrome was initially attributed to entrapment of the nerve by the pronator teres muscle. However, there are several potential sites of compression [4–9]. These include the ligament of Struthers (a fibrous band from an anomalous supracondylar process of the distal humerus to the medial epicondyle), the proximal fibrous arch of the pronator teres, intramuscular aponeurotic bands of the pronator teres, the proximal arch of the FDS (which may be an indistinct fibrous arch), and the leading edge of the bicipital aponeurosis (lacertus fibrosus). Additionally, a mass effect, caused by an accessory head of the flexor pollicis longus (Gantzer's muscle), or vascular structures

such as a persistent median artery are other potential causes of compression [10–12].

Patients with pronator syndrome typically complain of vague aching pain of the proximal forearm and the antecubital fossa, as well as numbness and paresthesias that emanate to the radial 3½ digits. Frequently, these complaints may be mistaken for carpal tunnel syndrome. However, these symptoms are exacerbated by use and rarely occur at night. Additionally, there is decreased sensation over the palm and thenar eminence due to disruption of the innervation of the palmar cutaneous branch of the median nerve over this area, differentiating it from more distal compression (carpal tunnel syndrome).

This syndrome generally occurs in physically active patients such as professional bicyclists. Additionally, motor weakness is generally absent in pronator syndrome. Tenderness in the antecubital fossa and a positive Tinel sign over the course of the nerve in this area may further differentiate pronator syndrome from carpal tunnel syndrome.

There are several clinical maneuvers described in the literature to determine if a patient has suspected pronator syndrome. However, there is no evidence regarding the diagnostic performance characteristics of these tests. The pronator compression test is performed by manually compressing the median nerve at the proximal aspect of the pronator muscle for 30 s and is positive if paresthesias result [13]. There are several other provocative tests that can be performed including resisted forearm pronation with the elbow extended, resisted forearm supination, and resisted middle finger proximal interphalangeal flexion, which are positive if they result in paresthesias in the median nerve distribution. Electrodiagnostic studies may be obtained to rule out more proximal compression or carpal tunnel syndrome at the level of the wrist. Notably, only 30–65% of abnormalities are seen in electrodiagnostic studies for patients with suspected pronator syndrome including slowed conduction velocity in the forearm [14]. In one particular study, there was no significant difference in the success of median nerve decompression when comparing patients who had abnormal nerve conduction studies with patients who had normal studies [15].

In general, given the lack of objective evidence for pronator syndrome, the diagnosis and treatment are controversial, especially since operative findings are subjective (pathology seen at the described sites of nerve compression) [16]. The initial treatment for pronator syndrome is typically nonsurgical (with a period of at least 3 months). This includes a combination of rest, activity modification, splinting, and anti-inflammatory medications, which may result in symptom relief in approximately 50% of cases. Injection into the tender site of the pronator teres muscle with a corticosteroid and local anesthetic (0.7 ml of betamethasone 6 mg/ml and 0.7 ml of 1% lidocaine hydrochloride) may be useful both diagnostically and therapeutically if the pain continues.

In refractory cases, surgical management is performed through a curvilinear incision across the antecubital fossa, starting 5 cm proximal to the elbow and extending distally to the midforearm. All potential sites of compression are then released from the ligament of Struthers, through the heads of the pronator teres and through the FDS arcades. The AIN is also identified and decompressed through its path deep to the head of the pronator and the FDS arch. After surgery, active range of motion as early as day 2 and full return to activity by 6–8 weeks has been advocated [17]. Overall, several case series have demonstrated that 70% of patients that had undergone nerve decompression had either complete resolution or reduced symptoms [5, 6, 15]. Several groups have also demonstrated endoscopically assisted decompression (with a 4.0 mm endoscope), with a 3 cm longitudinal incision, may be adequate and safe [18, 19].

Anterior Interosseous Nerve Syndrome

AIN syndrome is a compressive neuropathy of the AIN (as it branches off the median nerve 4 cm distal to the medial epicondyle) that results in the loss of motor function of the FPL, FDP to the index finger and the middle finger, and the pronator quadratus. The most noticeable sign is FPL weakness manifesting as difficulty with pinch. Although some pain in the antecubital

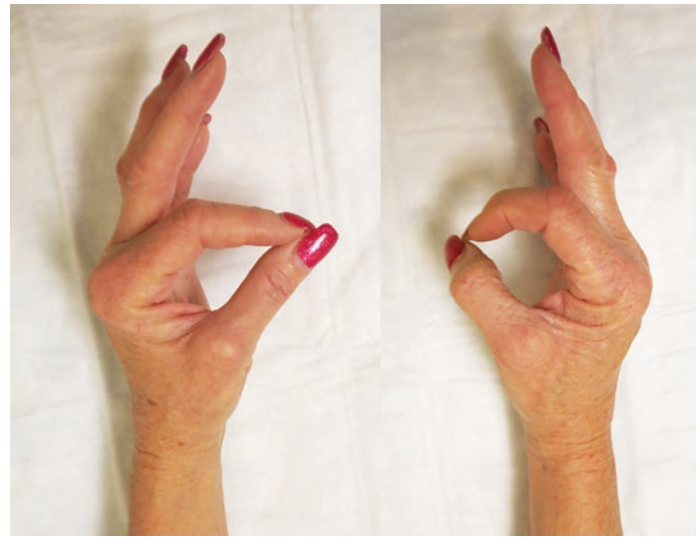

Fig. 28.2 Left side AIN syndrome with inability to make an "OK" sign. A characteristic physical finding in a patient with AIN syndrome on the left compared to the normal exam on the right. On the left the patient is unable to flex her thumb interphalangeal joint and index finger distal interphalangeal joint to make an "OK" sign

fossa may be present, given that the AIN is a motor nerve, the paresthesias or sensory loss that is typically seen in carpal tunnel and pronator syndrome are absent in AIN syndrome.

AIN syndrome results in patients having difficulty flexing the thumb interphalangeal (IP) joint and index finger distal interphalangeal joint (DIP) joint, which results in difficulty when asked to create an "OK" sign (Fig. 28.2). Long finger DIP joint flexion weakness is typically less severe when compared to the index finger. Testing the pronator quadratus is performed by resisting forearm pronation with the elbow in full flexion (which relaxes the pronator teres).

Given that AIN syndrome may result as a compressive neuropathy, other etiologies such as compression of the median nerve more proximally, or a peripheral neuritis (that may mimic the clinical manifestations of AIN neuropathy), have been reported in the literature as causes of AIN dysfunction resulting in an unclear natural history [20, 21]. Parsonage-Turner syndrome (neuralgic amyotrophy) is an autoimmune inflammation of the brachial plexus (with varying degrees of weakness of the scapular muscles) of unknown etiology. This may be considered if the patient has sudden symptom onset accompanied by severe pain and often following a viral illness [22, 23]. Trauma is another cause of AIN dysfunction [24, 25] due to a penetrating laceration of the nerve or an iatrogenic injury during elbow arthroscopy [26, 27]. Additionally, attritional ruptures of the FPL and FDP may be seen in settings of rheumatoid arthritis and may mimic the motor deficits seen in AIN syndrome. When diagnosing AIN syndrome, tendon integrity should be confirmed with an intact thumb and index finger tenodesis effect with wrist extension.

Electrodiagnostic studies may confirm the diagnosis and objectively assess the severity of neuropathy. The affected muscles will exhibit fibrillations, abnormal latency, and abnormal compound motor action potentials on electrodiagnostic testing [28].

Given the natural history of AIN syndrome has not been fully elucidated and often due to a neuritic etiology, the treatment of AIN syndrome is typically nonsurgical given the high probability of resolution after one year of onset of symptoms. Most patients will improve without surgical intervention [29–31]. Periods of at least 3 months and even up to 12 months of nonsurgical management have been recommended given the favorable natural history. However, if there is a compressive lesion or no signs of motor improvement after 6–12 months, then surgical management should be undertaken.

Surgical management consists of median nerve decompression as done similar to that

described for pronator syndrome. The median nerve is identified proximally and then all potential sites of compression are released, including the AIN released through the pronator teres and FDS arcade. Overall, in several case series, patients that had undergone release had improved symptoms, although these outcomes are controversial given the concern for the natural history of the disease process [17, 30–32]. Additionally, there have also been reports of the use of endoscopic decompression of the AIN [33].

Palmar Cutaneous Branch

Compression or injury of the palmar cutaneous branch of the median nerve (PCBMN) may also be a source of pain and discomfort in the forearm and palm. The PCBMN is a sensory nerve that branches from the radial side of the median nerve approximately 5 cm proximal to the distal wrist flexion crease and supplies the thenar eminence and the palmar skin. Six zones of compression have been previous been described by Al-Qattan et al. [34]. Dysfunction of the PCBMN has been found to be secondary to several etiologies including compression from a mass, compression from fascia, trauma, etc. [35–38]. Additionally, posttraumatic neuropathy may present with pain, hypoesthesia, and a positive Tinel sign [39]. The treatment for this compressive or traumatic dysfunction is also typically conservative, involving observation, scar massage, and injections of steroid or botulinum toxin into a neuroma involving the PCBMN, if present. Surgical interventions consist of neurolysis, neuroma excision with burying, or nerve grafting of the neuroma if one is encountered.

Diagnostic Imaging

There is no clear consensus for the use of imaging to help diagnose the etiology of these median compressive neuropathies. One case study described a patient with pronator syndrome with a T2 MRI of the upper extremity demonstrating increased signal intensity in the pronator teres, flexor carpi radialis, and the proximal portion of the FDS [40]. This patient had a surgical release and was found to have diffuse fascial bands around the median nerve and tight superficial fascia of the pronator teres. One study looking at upper extremity MRIs of patients with AIN syndrome demonstrated that patients with surgically confirmed AIN compression had edema (T2 fat-saturated images) of the pronator quadratus in all of these patients and atrophy and fatty involution in 43% of these patients [41]. Theoretically MRI may provide an advantage of increased sensitivity over electrodiagnostic studies after nerve injuries given that alterations of signal intensity can be seen as early as 4 days after injury (compared to electromyography which would require 2–3 weeks); however, this is unlikely to affect the treatment course (unless a mass or tendon ruptured is diagnosed). Lastly, MRI may be useful if there is concern for a diagnosis of a tendon rupture.

Conclusion and Future Directions

Compressive neuropathies of the median nerve in the forearm are far less frequent than those of the wrist. However, knowledge of these sites of compression are essential in the differential diagnosis when evaluating median nerve dysfunction in the upper extremity. Initially, conservative management including rest, activity modification, anti-inflammatory medications, etc. should be undertaken for any presumed compressive median neuropathy. If symptoms persist despite these measures, then surgical nerve decompression may be effective.

There are several limitations to the studies on median nerve neuropathies proximal to the wrist. Most studies are retrospective in nature, have a lack of control group, and are without clear exclusion and/or inclusion criteria. There is also no high-quality evidence for determining the appropriate duration of nonsurgical management and timing/indications for definitive surgical management. Therefore, randomized controlled studies comparing patients with the diagnosis of either syndrome that have

undergone conservative management versus median nerve decompression or even potentially sham surgery may be valuable.

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Median Nerve Tumors

29

Omkar Baxi and Irfan H. Ahmed

Introduction

Carpal tunnel syndrome is one of the most prevalent debilitating disease treated by orthopedic surgeons. The vast majority of carpal tunnel release is performed for idiopathic and long-standing symptoms of paresthesias and motor involvement in the median nerve distribution. However, not all cases of median neuropathy are caused by the mechanical carpal tunnel syndrome, and surgeons should be careful not to overlook more sinister pathology. In one series of 32 hands, carpal tunnel syndrome was noted to occur with the concomitant presence of a mass in the wrist. While 27 of these were extraneural lesions leading to nerve compression, five cases were due to intraneural tumors. The authors cautioned that tumor etiology should specifically be excluded in carpal tunnel syndrome presenting with unusual epidemiology—young, male, or no history of repetitive work or manual labor [1]. In this review, we discuss the major intraneural pathologies that may affect the median nerve. Schwannoma and neurofibroma are the two most common types of nerve tumor, but the rarer lipofibromatous hamartoma has a particular predilection for the median nerve. In addition, the malignant peripheral nerve sheath tumor is a rare but lethal malignancy that may affect the median nerve. General principles of presentation, diagnosis, and treatment for each of these conditions are discussed with a focus toward median nerve involvement.

O. Baxi • I.H. Ahmed (✉)
Orthopedic Surgery, Rutgers NJMS University Hospital, 140 Bergen Street, ACC D1610, Newark, NJ 07103, USA
e-mail: ahmedi2@rutgers.edu

Schwannoma

Schwannoma, or neurilemmoma, is the most common nerve sheath tumor encountered in the upper extremity. The primary cell of origin for this benign tumor is implied by its nomenclature—the Schwann cell. The clonal proliferation of mainly the Schwann cells leads to clear distinguishing factors between the Schwannoma and the closely related neurofibroma.

The vast majority of schwannomas present as sporadic, solitary lesions. These tumors are typically seen in patients 20–40 years of age and present equally in men and women. While the tumor may occur anywhere that nerves are present, they are more common in the head and neck areas, paraspinal areas, and upper extremities [2]. In the upper extremity, schwannomas have been reported to arise mainly from the median and ulnar nerves. In the Gosk cohort of peripheral nerve tumors, 25 of the 51 tumors affecting major nerves were schwannomas [3]. The presenting symptoms of schwannomas are

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typically a painless mass or neuropathic symptoms from nerve compression as the main nerve becomes entrapped between the tumor and other structures.

About 4% of schwannomas are associated with neurofibromatosis-2 or schwannomatosis. Both conditions are characterized by multiple schwannomas throughout the body, but presence of acoustic schwannoma confers the diagnosis of neurofibromatosis-2.

Multiple schwannomatosis is characterized by multiple non-acoustic or intradermal schwannomas, usually affecting one extremity or spine segment. Recently, the INI1 gene has been implicated as a genetic factor of the condition, but further work is necessary to fully delineate the pathogenesis of this disorder [4]. The diagnosis of definitive schwannomatosis is based on the presence of two or more non-intradermal schwannomas, age over 30, and no evidence of neurofibromatosis-2 [5, 6]. Patients with this condition tend to be younger and have more aggressive tumors. In addition, the propensity to have parapsinal involvement has led to the recommendation of obtaining an MRI of the spine regardless of the location of the index lesion [7].

Neurofibromatosis-2(NF-2) arises from a germline mutation of the NF-2 gene, reducing the amounts of the MERLIN (moesin-ezrin-radixin-like protein) or schwannomin protein that links the cell membrane and cytoskeleton, interacting in intracellular signaling pathways [6, 8]. Patients meet the NIH criteria for NF-2 if they have bilateral acoustic schwannomas. Alternatively, they may present with unilateral acoustic schwannoma or two or more schwannomas, meningiomas, gliomas, or neurofibromas and a family history of NF-2 relatives.

As with all nerve tumors, the gold standard for imaging the schwannoma is MRI. The characteristic findings are a fusiform lesion arising from the nerve itself (Fig. 29.1). Tumors demonstrate low to medium intensity on T1 and high intensity on T2. The definitive diagnosis of the schwannoma is based on biopsy. Due to the clonal proliferation of Schwann cells, the tumor homogenously stains positive for S-100. It is also characterized by the dichotomous nature of the Antoni A–highly cellular and Antoni B–predominantly myxoid areas (Fig. 29.2). Verocay bodies of elongated and palisading nuclei are also seen [9].

Schwannomas are typically observed unless the tumor is causing significant pain or neurologic symptoms affecting quality of life and function. When indicated, the schwannoma is enucleated en bloc from the parent nerve. These tumors are eccentrically located on the nerve and excision is typically safe for the parent nerve with minimal disruption of functional fibers (Fig. 29.3). However, several case reports describe that the

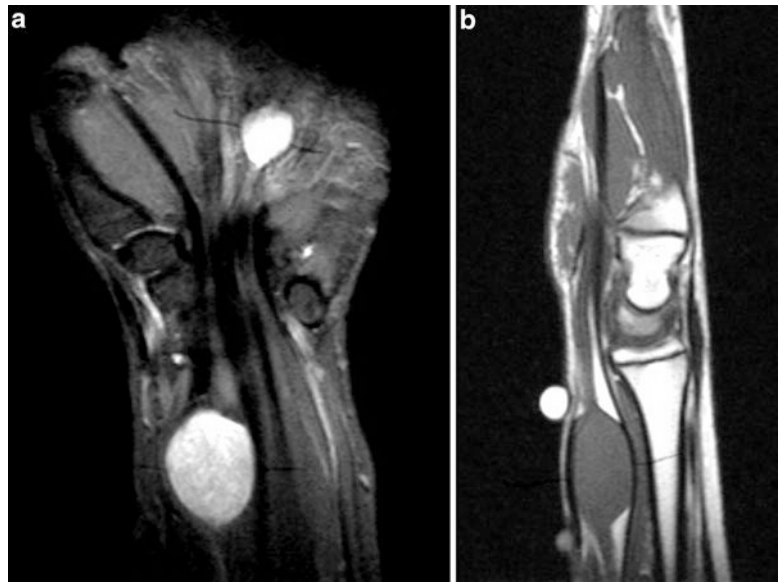

Fig. 29.1 (**a**) T2 coronal MRI showing high intensity mass in distal forearm (Schwannoma). (**b**) T1 sagittal MRI showing a medium intensity mass in distal forearm (schwannoma)

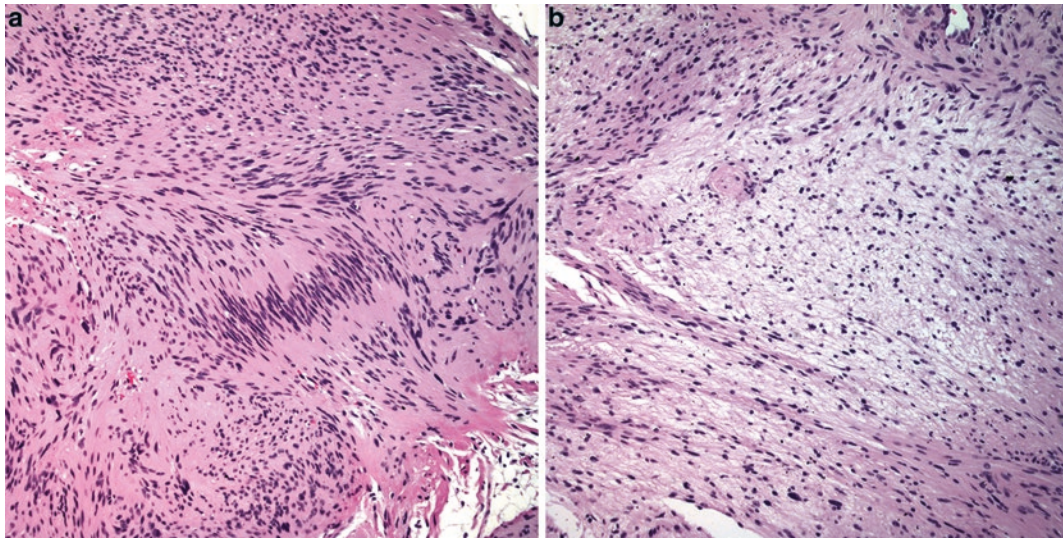

Fig. 29.2 (**a**) Schwannoma with Antoni A cells. (**b**) Schwannoma with Antoni B cells

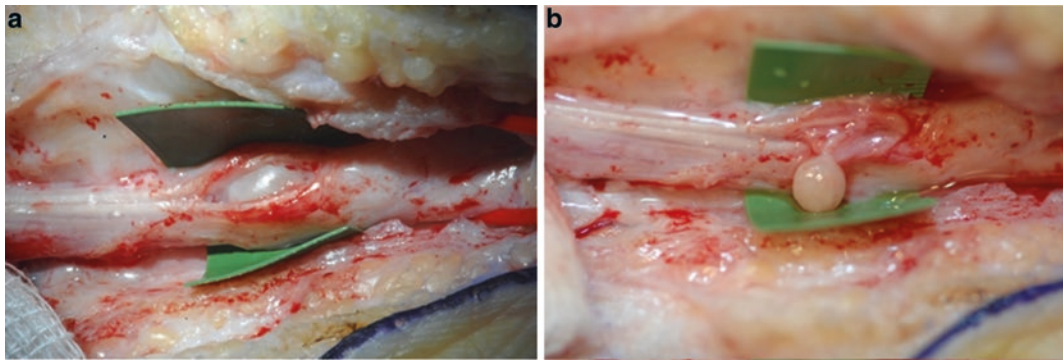

Fig. 29.3 (**a**) Schwannoma of median nerve evidenced by mass involving periphery of nerve. (**b**) Schwannoma of median nerve after epineurium opened. Classic morphology of schwannoma is seen with growth peripheral to the main nerve trunk

classical pattern may not be true as schwannomas can show fascicular involvement.

Tang and colleagues [10] noted that in their center 75% (6 of 8) patients with schwannoma had fascicular involvement. They recommend that the possibility of nerve graft should always be discussed with schwannoma patients, particularly if the tumor involves a mixed or motor nerve.

Ozdemir and colleagues [11] reported their series of 14 cases of schwannoma, 10 of which involved the median nerve. They report that the most common complication of enucleation was postoperative transient hypoesthesia, occurring in seven patients. Hypoesthesia appeared to be related to the level of involvement with more proximal nerves demonstrating more vulnerability to hypoesthesia; there were no differences between outcomes of cases from the median nerve compared to ulnar nerve. All but one of the patients regained normal sensation within 9 months.

The proposed etiology of symptoms, as mentioned earlier, is that the functional nerve becomes entrapped and compressed by the tumor. Accordingly, researchers have speculated that the predilection of schwannomas in the distal upper extremity may be due to greater symptomatology resulting from decreased space in the wrist and hand. In particular, for the median nerve,

schwannomas have also been reported when arising at the carpal tunnel. Aydin and colleagues [12] report a rare case of hemorrhagic rupture of a schwannoma at the proximal edge of the carpal tunnel causing sudden symptoms of median nerve involvement.

Neurofibroma

Neurofibroma is the second most common peripheral nerve sheath tumor and closely related to the schwannoma. The main distinguishing factors, however, are more intimate involvement of the parent nerve and a greater relationship to neurofibromatosis-1. Neurofibromas may occur at any age but are most predominant in patients 20–40 years of age. Presenting symptoms are similar to other nerve tumors with early painless growth followed by neuropathic symptoms from nerve compression. Tinel's sign is frequently positive with reports of 100% presence in neurofibroma. Up to 33% may also present with motor deficits [13]. The majority of neurofibromas are sporadic lesions, but approximately 10% present in patients with neurofibromatosis-1 [13].

Neurofibromatosis-1 (NF-1) is an autosomal dominant inherited neurocutaneous disease with a large spectrum of clinical manifestations. The *NF-1* gene on chromosome 17 has been found to be the genetic basis of NF-1 with mutations leading to decreased function of the neurofibromin protein. While the exact genetic pathogenesis remains elusive, the protein is known to be part of the Ras signaling pathway with decreased levels leading to clinical NF-1 [14]. The diagnosis is confirmed when patients have two of the following: six or more cafe-au-lait spots, a plexiform neurofibroma or two neurofibromas, axillary or inguinal freckling, Lisch nodules, optic gliomas, or orthopedic manifestations. The bony lesions seen in neurofibromatosis-1 include sphenoid wing dysplasia, congenital tibial pseudarthrosis, and scoliosis. Patients with neurofibromatosis-1 carry about a 10% risk of malignant transformation of their neurofibromas [15, 16].

Both solitary and NF-1-associated neurofibromas can be classified into four major categories: localized intraneural, localized cutaneous, diffuse neurofibroma, and plexiform. Localized intraneural neurofibroma is the most common entity and presents as a nodular expansion in the peripheral nerve. Diffuse neurofibroma typically involves subcutaneous tissues rather than major peripheral nerves. The plexiform subtype is pathognomonic for NF-1 and accordingly carries a higher risk for malignant transformation. This subtype involves multiple nerve branches and is classically described as a "bag of worms" [1, 15].

In the upper extremity, neurofibromas appear to have a predilection for small nerve branches. In Gosk's review of 72 upper extremity nerve tumors, only 12 of the 51 major nerve tumors were neurofibromas, while 39 of the 50 small nerve tumors were neurofibromas [3].

The work-up for neurofibroma is similar to all suspected nerve tumors with MRI as the gold standard for imaging. Similar to the schwannoma, neurofibromas appear as growths from the parent nerve with low or medium intensity on T1 and high intensity on T2. The target sign, an axial image of central low intensity with surrounding high intensity, has been shown to be nonspecific but still classically associated with neurofibroma [13].

On gross pathology, neurofibromas tend to be unencapsulated and are intimately involved with the nerve fascicles. Unlike the eccentric growth of schwannomas, neurofibromas are more likely to have fusiform growth with entanglement of the nerve fascicles. Biopsy provides definitive diagnosis of the neurofibroma with several distinguishing factors. Unlike the schwannoma, neurofibromas have a more heterogeneous cell population with fibroblasts and Schwann cells contributing to the tumor (Fig. 29.4). Thus, the histology appears more myxoid and has more variable staining with S100 unlike the homogenous S100 staining of schwannoma [14, 15].

Due to the greater involvement of nerve fascicles, enucleation of the neurofibroma is technically more challenging and sacrifice of functional nerve is considered likely. As a result, more conservative measures are indicated, and surgery is delayed unless pain is intolerable. In one series of 37 neurofibromas, only 8% could be resected without any nerve damage. Sixteen

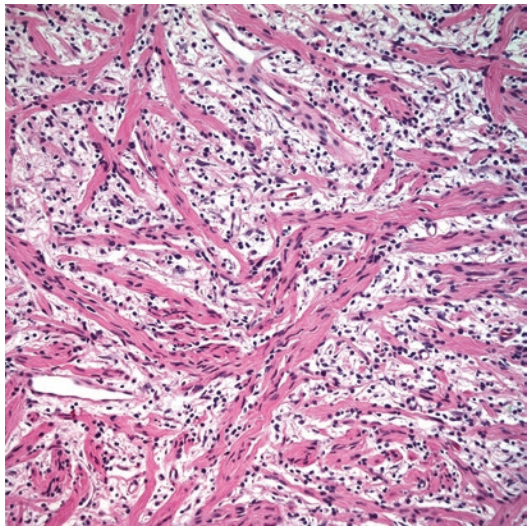

Fig. 29.4 Fibroblasts and Schwann cells are seen in Neurofibromas

percent sustained significant damage involving more than two fascicles; 33% of the total cases required nerve grafting or direct repair due to excision of functional fascicles. Motor function is commonly lost with reports describing 15–50% of patients having loss of at least one motor strength [3, 17]. Nerve repairs and grafts have not been shown to definitively improve or sustain function but do serve to reduce painful neuroma formation and are therefore recommended. Several reports advocate the use of intraoperative neural monitoring for neurofibroma excision as an effort to minimize trauma to the functional nerve. However, when performed for pain relief, neurofibroma excision appears to have varied efficacy with reports of 50–100% pain relief [3, 17].

Lipofibromatous Hamartoma

The lipofibromatous hamartoma (LFH) is a tumor of unknown origin that preferentially affects the median nerve, typically in the palm or forearm. Most cases present before age 30, with an equal incidence in both genders. The most common presenting symptom is a soft, mobile, nontender, nonfluctuant mass in the volar forearm, wrist, or hand. Symptoms from nerve compression may also occur with tumor growth but paresthesia has been reported to present in only 39% of patients [18].

Up to two-thirds of patients also have macrodactyly in the involved region, although researchers have advocated classifying the presence of macrodactyly as a separate variant of lipofibromatous hamartoma [18, 19]. The hypertrophy of all tissues such as adipose, muscle, and skeletal in a particular neural distribution has led to a classification as "macrodystrophia lipomatosa." While definitive basic science research is lacking, researchers have hypothesized "sclerotomes" in addition to dermatomes and myotomes that may respond to pathology in a particular nerve branch with hyperplasia in the given innervated area. A case of "dual pathology" to the median nerve in which the patient had a distal LFH in addition to compression on the median nerve from coronoid osteochondroma has been debated as an example of this nerve-distributed macrodactyly [20, 21].

Ultrasound may be used in the diagnosis of this tumor, especially since the major differential diagnosis includes hemangiomas and ganglion cysts which may be readily diagnosed with ultrasound. LFH on ultrasound is described as a fusiform mass with longitudinal nerve bundles and alternating hypoechoic and hyperechoic bands. However, as with all nerve tumors, MRI remains the imaging gold standard. LFH is commonly seen as a fusiform or hourglass enlargement of the nerve on coronal sections with serpentine nerve bundles surrounded by fat, leading to a "spaghetti-like" appearance. On axial views, the tumor is described as a "coaxial cable" with nerve bundles separated by fat [18, 19]. These findings are pathognomonic for LFH, and given the possibility of nerve compromise with biopsy, invasive diagnostics is typically not necessary or recommended.

While not routinely performed for diagnostic purpose, histology will also confirm LFH as a tumor characterized by mature adipose and

fibrous tissue infiltrating the potential space between the epineurium and perineurium of nerve fascicles.

As described by Tahiri, the treatment of LFH follows four major treatment goals: symptom prevention, symptom relief, aesthetic concerns, and avoidance of functional impairment [18]. Currently, treatment paradigms appear to be more conservative in nature with expectant management until symptom presentation as the prevailing treatment. Once indicated, the most common treatment modalities are carpal tunnel release for decompression to alleviate neuropathy. Resection of the tumor may not represent a cure in comparison to other nerve neoplasms. Mahan and colleagues reported a case wherein LFH recurred at the nerve graft with fibrofatty proliferation throughout the graft and its distal branches. The authors speculate that microscopic residual tumor is present despite a macroscopic total resection, allowing for progression and recurrence of tumor [22]. In the presence of macrodactyly, epiphysiodesis may be attempted in skeletally immature patients. In adults with severely limiting macrodactyly, surgeons may perform arthroplasty or may even consider ray amputations [18].

MPNST

The most common malignancy of neural tissue and the median nerve in particular is malignant peripheral nerve sheath tumor (MPNST). MPNST may arise sporadically but more commonly develops from malignant degeneration of a schwannoma or neurofibroma. It is estimated that up to 50–60% of MPNST occur in patients with NF-1, who carry about a 13% lifetime risk of developing the malignancy [16, 23]. The overall incidence of this rare tumor is estimated to be one per million in the American population. MPNST is typically seen in patients 20–50 years of age, although it may present earlier in those with neurofibromatosis.

The rapid growth or sudden symptom generation from an otherwise dormant nerve growth may indicate malignant degeneration and necessitates aggressive work-up. Biopsy of the tumor shows neoplastic changes in the Schwann cell population with invasion of local nerve fascicles (Fig. 29.5). The tumor may also exhibit spread along the nerve sheath and lymphatics leading to failures with resection and frequent recurrence [16]. Goertz noted that in 65 cases of MPNST, 9% had lymph node involvement and 28% developed metastatic disease. As with most sarcomas,

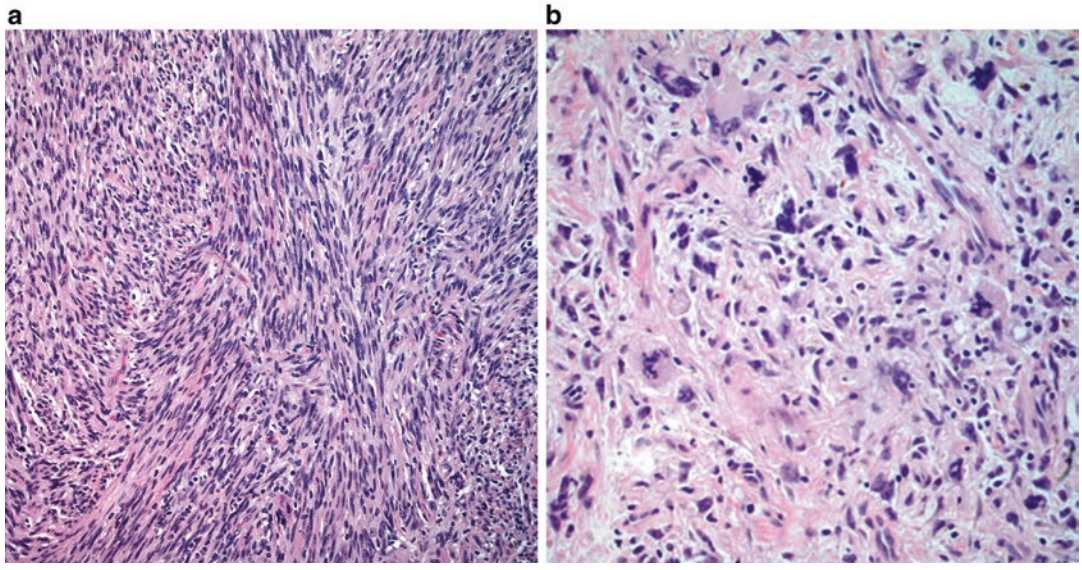

Fig. 29.5 (**a**) Low-grade MPNST. (**b**) High-grade MPNST

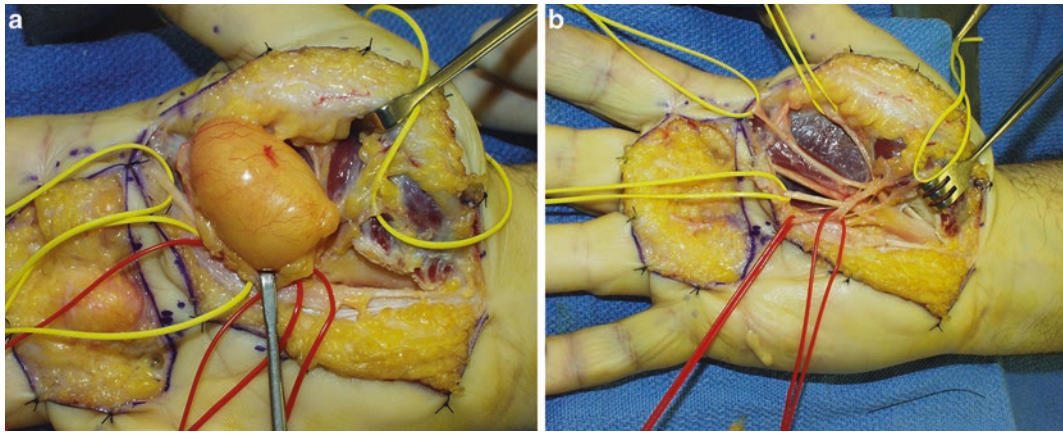

Fig. 29.6 (**a**): Lipoma in palm causing compression of median nerve. (**b**) Nerve decompressed after excision of lipoma

the lungs are the most common location of spread, contributing to the high mortality rate. Indeed, metastatic disease has been identified as the most significant prognostic indicator for death. Current data indicate that 5-year survival for MPNST is approximately 45% [23, 24].

Imaging of MPNST may show some signs of malignancy such as an irregular shape, invasive margins, intratumoral lobulation, or high intensity areas on T1 with inhomogeneous contrast enhancement. While some reports have estimated MRI sensitivity for MPNST as high as 79%, most cases of MPNST are still intraoperative or postoperative diagnoses [17].

Radiotherapy and chemotherapy for MPNST have not been effective to date and current treatment for the malignancy rests on surgical control. Due to the significant ability to spread, radical resection or amputation may be required for adequate control. However, Goertz and colleagues note that the trends toward limb-sparing surgery have led to local resection as the most common treatment approach for MPNST. They note that their series with local resection in 65 cases has survival comparable to historic literature with more radical surgery [23]. The predilection of MPNST for major nerves and the necessity of adequate resection often lead to sacrifice of neural tissue and ensuing functional deficit. However, given the low life expectancy of most patients with MPNST, tendon transfer is recommended over nerve repair or grafting to treat the possible functional deficits [23].

Lipoma

Lipomas are the most common benign tumors of the body but frequently present more often in the trunk and lower extremity rather than the distal upper extremity. Lipomas account for less than 5% of the benign tumors encountered in the hand [25]. However, as evidenced by multiple case reports, the presence of a lipoma in the carpal tunnel or distal forearm can cause compressive symptoms of the median nerve, mimicking carpal tunnel syndrome (Fig. 29.6) [25, 26]. In addition, the lipoma may present in an occult manner with the strong palmar fascia obscuring the typical physical exam findings of a rubbery well-fixed mass characteristic of a lipoma. MRI is the gold standard diagnostic exam for lipoma since it can provide definitive diagnosis on the basis of a well circumscribed, discreet mass with T1 hyperintensity. Biopsy confirms the diagnosis (Fig. 29.7). Lipomas larger than 5 cm are termed giant lipomas and should raise concern for malignancy [26]. However, the majority of these tumors may be excised with few complications and good prognosis.

Arteriovenous Malformation

The hemangioma and arteriovenous malformation is a vascular anomaly resulting in a benign space-occupying mass. Clemens and colleagues present a concise update on the pathology and

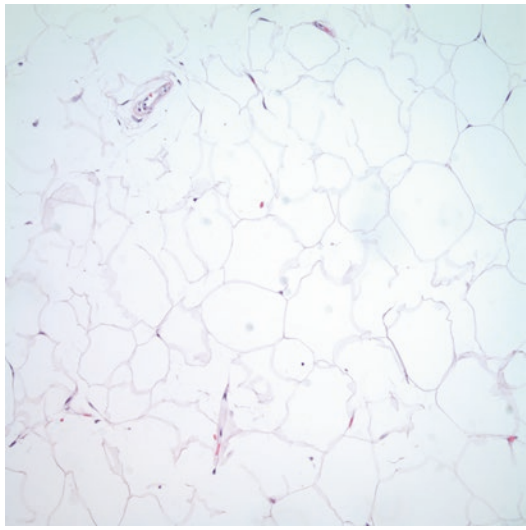

Fig. 29.7 Benign features in a lipoma

treatment of the vascular malformations [27]. Within the scope of this article, hemangiomas may mimic intraneural tumors of the median nerve and cause compressive neuropathy at the median nerve. Carpal tunnel syndrome caused by hemangioma is rare, with few reports in the literature. However, as pointed out by Meena and colleagues, the vascular malformation should be kept on the differential for causes of atypical carpal tunnel syndrome [28]. Due to the proximity of the nerve and vessels, tumor arising from the vessel may be mistaken as a nerve tumor both on clinical and radiographic examination, as illustrated by Nuthakki [29]. Despite being discreet in origin from neighboring vessels, reports have shown that the malformation may also encompass and infiltrate the nerve

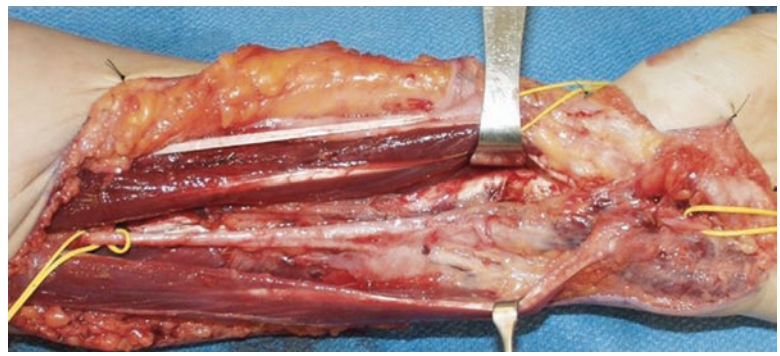

Fig. 29.8 Arteriovenous malformation involving the median nerve at the level of the wrist

(Fig. 29.8) [30, 31]. In addition, the vascular malformation may directly involve the nerve through its vasa nervorum. The primary treatment goal is excision of the hemangioma free from the median nerve in order to relieve symptoms and maintain nerve function. However, if an appropriate plane of dissection is not present, sole decompression of the carpal tunnel may also help to relieve symptoms while preserving the integrity of the nerve. Care should be taken when dissecting the malformation to identify any accessory nerves as reports have indicated an association between vascular malformations and bifurcated median nerves [32].

Conclusion

Tumors involving the median nerve are rare occurrences that may be encountered by the hand surgeon. As such, a good understanding of these disease processes must be maintained in order to avoid missed diagnoses. The most common tumors of the nerve are the schwannoma and neurofibroma, which may be associated with neurofibromatosis. In addition, the lipofibromatous hamartoma has a particular predilection for the median nerve and should be considered on the differential for any enlargement of the median nerve.

More common than true intraneural pathology, tumors of the upper extremity may cause median neuropathy due to compression or irritation of the nerve. Our review highlights the need for careful history and examination to delineate the etiology of median neuropathy. If a mass is encountered in the upper extremity, it may be directly responsible for the neuropathy and appropriate imaging including MRI will aid in the diagnosis of the condition. Carpal tunnel syndrome symptoms that are unilateral and not associated with a typical history should also raise suspicion about possible tumor etiology [33]. Although ultrasound may provide some clarification as to the nature of the mass, we recommend MRI as the gold standard diagnostic test. Excision of the offending mass should be performed, with prognosis dependent on the underlying etiology. Final pathology should always be ascertained in order to develop prognostic goals and to allow more accurate diagnosis in the case of recurrence.

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Electrical Nerve Stimulation for Chronic Median Nerve Pain

30

Takashi Noguchi and Scott F.M. Duncan

Abbreviations

PNS	peripheral nerve stimulation
SG	substantia gelatinosa
TENS	transcutaneous electrical nerve stimulation

Introduction

There are various treatment strategies for chronic pain caused by peripheral nerve disorders, including drug administration, surgery, and physical therapy. One form of physical therapy for chronic nerve pain is electrical nerve stimulation. It is a therapeutic method that reduces the need for large doses of opioids, and which may help curtail the abuse of these drugs, a major social problem globally. In the 1960s, it was shown that electrical nerve stimulation can effectively control pain [1]. Subsequent studies have focused on improving effectiveness and on clarifying the mechanisms underlying the analgesic effects of this method.

Currently, transcutaneous electric nerve stimulation (TENS), in which electrodes are placed on the skin, has gained popularity worldwide. In addition, peripheral nerve stimulation (PNS), in which direct nerve stimulation is performed with electrodes subcutaneously embedded close to the peripheral nerves, has also become popular. Compared to the former, the latter is an invasive treatment. However, PNS can play a critical role in treating intractable chronic pain. In this chapter, we provide an overview of PNS, focusing on its use for the treatment of median nerve pain.

Brief History of Electrical Stimulation Therapy

Electric treatment has been used for analgesia since the time of the ancient Greeks and Egyptians, who used live electric rays and other types of electric fish for pain relief [2]. In the eighteenth century, John Wesley experimented with electrotherapy for persistent pain including sciatic nerve pain. In the nineteenth century, Francis reported that electric stimulation reduced pain during tooth extraction. In 1910, Ravinovitch successfully performed several major lower limb amputations using a modified Leduc's square wave, an intermittent current technique, for inducing local anesthesia; it was reported in the New York Times. In

T. Noguchi (✉)
Department of Orthopaedic Surgery, Boston Medical Center, Boston University School of Medicine, 850 Harrison Avenue, Dowling 2 North, Boston, MA 02118, USA
e-mail: taka1114@bu.edu

S.F.M. Duncan
Department of Orthopedic Surgery, Boston University/Boston Medical Center, Boston, MA, USA

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1948, Paraf reported successful electrical treatment for sciatic pain, lumbago, and postherpetic neuralgia. Prolest reported that 50–100 Hz monophasic and biphasic waves produce pain inhibition, with the pain threshold related to the intensity of the current [2, 3]. Melzack and Wall proposed the gate control theory of electrical stimulation-induced analgesia in 1965 [4]. In 1967, Wall and Sweet showed that treatment with electrical nerve stimulation using square waves induced pain relief in patients with persistent chronic pain [1]. In the following decades, substantial advances were made in the use of electrical nerve stimulation for pain relief, including the work of Meyer and Fields, who successfully treated causalgia with electrical nerve stimulation [5]. Currently, electrical stimulation is well established as an analgesic treatment for chronic nerve pain.

Mechanisms of Pain Relief by Electrical Nerve Stimulation

The mechanisms underlying the analgesic effect of electrical stimulation remain unclear. However, the gate control theory, proposed by Melzack and Wall, and the endogenous opioid theory, proposed by Reynolds [4, 6], provide insight into the mechanisms of pain relief.

Figure 30.1 shows how electrical stimulation may induce analgesia based on the popular gate control theory. Usually, somatosensory stimuli are transmitted to central transmission cells (T cells) in the spinothalamic tract, spinoreticular tract, and spinomesencephalic tract in the dorsal horn. The stimuli are also transmitted to neurons in the substantia gelatinosa (SG) of the dorsal horn of the spinal cord, which act as gatekeepers that modulate the afferent signal. The signal from large diameter myelinated nerve fibers, such as Aβ nerve fibers, activates these neurons in the SG. The afferent stimulation is less likely to reach T cells when there is presynaptic inhibition by SG cells (i.e., when the gate is closed). Conversely, afferent signals through unmyelinated or small diameter fibers, such as C, Aδ fibers (primary nociceptive fibers), suppresses SG cell activity, thereby opening the gate. The pain signal is then conveyed to the T cells. Thus, SG cells provide presynaptic inhibition when large diameter nerve fibers are stimulated. When this occurs, the pain signal through narrow fibers is prevented from reaching the T cells, producing an analgesic effect.

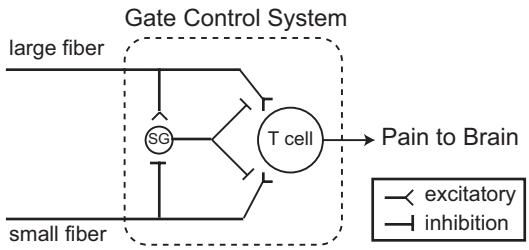

Fig. 30.1 Diagram of the gate control theory proposed by Melzack and Wall. The T cell is a neuron with ascending fibers in the spinothalamic, spinoreticular, and spinomesencephalic tracts. The SG cell is a neuron in the substantia gelatinosa of the dorsal horn. Impulses from large fibers excite SG neurons and T cells. In contrast, impulses from small fibers have an inhibitory effect on SG neurons and an excitatory effect on SG cells. SG cell activity has an inhibitory effect on both large and small fibers

Reynolds reported that electrical stimulation of the periaqueductal gray region of the mesencephalon produces analgesia in rats and Mayer suggested that the mechanism of stimulation-produced analgesia might be similar to one of administrations of morphine [6, 7]. Han et al. showed that electrical nerve stimulation increases the concentrations of β-endorphins and met-enkephalin in blood and cerebrospinal fluid [8]. These researchers also found that administration of a δ-opioid receptor antagonist into the rostroventromedial medulla inhibits the pain relief provided by electrical nerve stimulation [9]. Thus, electrical nerve stimulation may enhance the release of endogenous opioids in the spinal cord as well as activating descending pain inhibitory pathways.

Electrical stimulation may provide pain relief through other mechanisms as well. For example, Linderoth reported that electrical stimulation on the dorsal column induced serotonin and substance P release and pain relief in cats [10]. Sluka and colleagues reported that high-frequency electrical stimulation reduces the expression and secretion of excitatory neurotransmitters, such as glutamate, in the spinal cord in rats [11].

In other studies, Radhakrishnan et al. showed that several types of spinal 5-HT receptor modulated the effect of pain relief induced by TENS, and Sluka and coworkers found that spinal serotonin concentrations increased during and immediately after treatment with low-frequency TENS [12, 13]. Currently, these mechanisms are considered to be part of the more broadly defined gate control theory.

Indications for Peripheral Nerve Stimulation (PNS)

There are many indications for electrical nerve stimulation therapy, including the following:

1. Nerve injury (traumatic or iatrogenic)
2. Mononeuropathy (idiopathic, entrapment)
3. Postsurgical neuropathic pain (post-carpal tunnel release, neurolysis, nerve graft, etc.)
4. Complex regional pain syndrome
5. Plexopathy

Clinicians should examine whether temporary partial or complete analgesia is achieved by xylocaine block of the affected nerves. When the block provides pain relief, electrical nerve stimulation can be expected to have an analgesic effect as well. TENS does not have any predictive value for PNS, even for patients that failed to experience pain relief with TENS [14].

Contraindications

Patients with a number of medical conditions should not undergo electrical nerve stimulation.

These include the following:

1. Any pain of unknown etiology
2. Active infections
3. Any debilitating illness
4. Previous electrical accident
5. Cardiac pacemakers
6. Cardiovascular disease
7. Cerebrovascular disease
8. Pregnancy
9. Epilepsy
10. Metallic implants beneath electrode positioning sites
11. Communication difficulties (including younger children and those with psychiatric disorders)
12. Patients considered otherwise inappropriate candidates by the physician

Furthermore, physicians must consider whether patients with an abnormal coagulation profile or those taking anticoagulants are suitable candidates for treatment.

Complications

Patients undergoing PNS occasionally need revision or removal surgery owing to adverse events, as follows [15–18]:

1. Infection (3.6–17.9%)
2. Migration of the electrodes (9–25%)
3. Leads or device failure (3.6%)
4. Hardware irritation and discomfort (4.5–50%)
5. Postoperative perineural fibrosis (frequency unknown)

Technique

It is recommended that clinicians perform a two-stage surgical protocol for PNS. The first stage is intended to determine whether chronic pain can be alleviated by electrical stimulation therapy.

First Stage of Surgery

Under general anesthesia or regional block, the affected nerve is exposed and neurolysis is performed. Subsequently, the electrodes are placed proximal to the apparent or suggested site of the lesion (Fig. 30.2). Although a percutaneous procedure to locate electrodes can also be used, the complication of electrode migration occurs at a substantially high frequency with this procedure. Furthermore, the direct placement of the electrodes

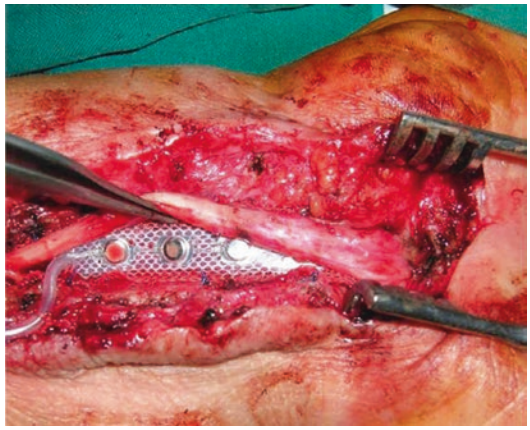

Fig. 30.2 Photograph showing placement of a sheet-type electrode underneath the affected median nerve during surgery. This photograph is taken from the paper by Mirone et al. [19]

can reduce power requirements for stimulating the nerve. Electrodes should be sutured securely to the fascia adjacent to the nerve to prevent migration. The proximal tip of the leads connected to the electrodes can be passed subcutaneously through a small incision in the axillary area. The leads can be connected to an extracorporeal electrical stimulator. After this first stage of surgery, electrical stimulation is performed with different parameter settings (pulse width, amplitude, frequency) to determine the optimal conditions for pain relief. It is recommended that technicians follow the protocols provided by the manufacturers of the electrical stimulating equipment (e.g., Resume, Medtronic, Minneapolis, MN). This procedure can be carried out 1 week to a month prior to the second stage. When the effectiveness of electrical stimulation is confirmed in the patient, the surgery to embed the implantable stimulator, the second stage of the operation, can be performed. In the case of no significant improvement, and in cases where the patient does not consent to further treatment, the electrodes should be extracted.

Second Stage of Surgery

Under general anesthesia, the externalized leads are replaced with new sterile leads to mitigate the risk of infection. The original electrode placement site should be left undisturbed. The new leads are passed subcutaneously from the original incision site in the axial area to a prepared subcutaneous pocket with a small incision in the anterior chest wall. An implanted stimulator can be embedded into the pocket and connected to the leads. The stimulator can be turned on or off and its settings can be adjusted by remote control. A well-trained physician or medical technician can adjust the stimulator settings and instruct the patient to continue the electrical stimulation therapy and to turn the unit off when not needed to preserve battery life and to help maintain the effectiveness of treatment.

Clinical Efficacy of Electrical Nerve Stimulation

Physicians have two options for electrical nerve stimulation therapy. The first is the transcutaneous method (TENS), and the second is direct stimulation (PNS).

Cochrane's review (2008) concluded that there is insufficient clinical evidence to recommend therapy with TENS. The more than 100 reports on TENS reviewed in Cochrane's paper varied substantially in the parameters used for stimulation therapy. This may in part underlie the lack of evidence for the effectiveness of electric nerve stimulation using TENS [20]. However, it may be premature to conclude that TENS has no clinical efficacy, particularly because of the lack of uniform conditions, for instance, stimulation setting or patient selection.

As mentioned previously, an important criterion for the use of PNS is whether pain relief is obtained by a local block. PNS can be an effective treatment in appropriate patients. There are very few reports that focus exclusively on the use of PNS for chronic median nerve pain. Only Deer et al. reported prospective study to evaluate the effect of a new type implantable device named StimRouter (Bioness Inc., Valencia, CA) for the patients with chronic pain due to carpal tunnel syndrome. The study lasted for a very short period because of trial study and included eight patients wherein surgery was performed to insert

the electrode and who underwent daily stimulation for 5 days. The patients presented decreasing pain intensity and opioid consumption during the therapy. After explant of the device and terminated the PNS treatment, the pain intensity increased back, but mean study satisfaction score among all of the patients was 96% [21].

On the other hand, there is a relative large number of retrospective studies on PNS for neuropathic peripheral nerve pain. In some of these studies, the median nerve is also targeted for therapy. Medium-sized cohort studies are shown in Table 30.1. In these studies, most diagnoses were traumatic nerve injury and iatrogenic nerve injury. Campbell and Long reported that PNS provided effective pain relief in close to half of the 33 patients with neuropathic pain [22]. The most substantial pain relief was achieved in patients with traumatic nerve injury. Novak and Mackinnon reported a positive outcome in 11 of 17 carefully selected patients with peripheral nerve injury [23]. Almost all of these patients had an increase in the quality of life and required no narcotics.

In a report by Eisenberg et al., 78% of patients had a good outcome with PNS at 3–16 years of follow-up [24]. However, two patients having previously undergone nerve graft did not achieve pain relief. In addition, PNS for postsurgical complex regional pain syndrome (CRPS) type 2 of the median nerve obtained satisfactory pain relief in the case report of Mirone and colleagues [19]. Only Hassenbusch et al. studied the effectiveness of PNS for CRPS type 1. In their study, 32 patients with CRPS type 1 were treated with PNS, and pain relief was achieved in 63% of these patients [25]. PNS also exhibited effectiveness in CRPS type 1 patients in whom pain was mainly in the distribution of one of the major peripheral nerves.

In the reports of Mobbs et al. and Sterge et al., in which patients with work compensation were a high percentage of the cohort, good analgesia was achieved in 61 and 75% of the patients, respectively [17, 26]. Reverberi et al. reported that seven of nine patients treated with PNS returned to their original work with good pain relief, and narcotic consumption was reduced in 8 of 12 patients [27]. Van Calenbergh et al. reported long-term results with a mean follow-up of 22 years. In this study, five patients obtained excellent or moderate pain relief, and analgesic usage was reduced or withdrawn, although 4 of the 11 patients were removed from the study because of device infection [28]. Kupers et al. reported that in five cases followed up for a period of 20 years, activity changes in the brain were observed in patients that obtained pain relief with PNS. The activity of pain pathways in the brain appeared to be decreased using PET [29]. This indicates that PNS can have long-term therapeutic efficacy.

Outlook

With recent technical advances, the implanted stimulator has become increasingly smaller, reaching thumb size in recent years. This reduces irritation and discomfort at the site of implantation, decreases the risk of complications, and should enhance long-term outcome.

Although surgery costs and initial device cost can be high, an overall reduction in medical cost can be achieved. Mekhail et al. showed that patients using the implanted device can save on the cost of drug treatments and nerve blocks [30]. Furthermore, patients achieving no pain relief can be excluded prior to the second stage of surgery.

To more fully evaluate the effectiveness of electrical stimulation therapy, randomized control trials are ideal but may not be feasible. Because electrode and device implantation is required, a true vs. sham operation comparison, which can more critically evaluate the efficacy of treatment, is difficult to perform and may be unethical as well [31]. Thus, while a large cohort study is still ideal, it will be necessary to combine the results of a number of smaller studies for analysis. In addition, future studies should carefully evaluate the indications as well as the initiation of treatment.

Conclusion

Treatment for chronic peripheral nerve pain, including that of the median nerve, is a complex challenge. PNS surgery should be considered

Table 30.1 Cohort series of PNS

Author	Published year	Diagnosis	Number of patients	Number of median nerve	Result	Period of follow-up	Setting
Campbell	1976	Trauma, tumor, mononeuropathy, spinal cord injury	33	2	24% excellent, 21% good	12 months/52 months	N/A
Sterge	1994	Trauma, iatrogenic, entrapment	24	4	5 patients, excellent; 13 patients, good	32 months	Amplitude, 0.75–2.0; width, 120–210 μs; rate, 75 Hz
Hassenburch	1996	CRPS type 1	32	7	19 patients, long-term relief; VAS, 8.3 to 3.5 ($p < 0.001$)	4 year	Amplitude, N/A; width, 210 μs; rate, 75 Hz
Novak and Mackinonn	2000	Trauma, iatrogenic, entrapment, tumor	17	2	5 patients, excellent; 6 patients, good	21 months	N/A
Eisenberg	2004	Iatrogenic, entrapment, post-nerve graft	46	6	78% of patients, good; CAS, 69–24 ($p < 0.001$)	3–16 years	N/A
Mobbs	2007	Trauma, iatrogenic, entrapment, tumor	45	11	50–77% of patients, good	31 months	N/A
Reverberi	2014	Causalgia, neuropathy	15	1	NRT; 8.46–3.46 ($p < 0.001$) 7 patients return to work	9.3 months	Mean amplitude, 0.9 V; width, 247 μs; rate, 21 Hz

when nonoperative treatments are insufficient. It is interesting that while electrical nerve stimulation achieves pain relief by stimulating the nerve, nerve block using local anesthesia, in contrast, achieves pain relief by interrupting pain signals. The mechanisms underlying the pain relief mediated by electrical nerve stimulation are still unclear and need to be clarified by further study. In the near future, advances in PNS technology should allow physicians to more effectively treat some intractable neuropathic pain.

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Complex Regional Pain Syndrome and Carpal Tunnel Surgery

31

Eduard A. Vaynberg and Anastasios Sakellariou

Introduction

Complex regional pain syndrome (CRPS) was first identified in gunshot wound patients who experienced persistent pain after healing [1]. CRPS, as the name reflects, is a painful condition featuring complex symptomatology that follows a regional pattern. It can have varying degrees of motor, sensory, and autonomic involvement leading to significant morbidity and functional impairment.

There are two types, CRPS 1 and 2, previously known as reflex sympathetic dystrophy and causalgia, respectively. In the majority of the cases, it is difficult to make a distinction between the two types based only on the signs and symptoms. The defining characteristic is the history of injury. In CRPS 1, there is no identifiable nerve injury like a joint sprain, whereas in CRPS 2, there is an obvious nerve disruption, in a gunshot wound or a surgical complication, for example. More than 50% of the CPRS 2 cases involving the upper extremity have a history of injury to the median nerve [2]. Two to five percent of the patients develop CRPS type 2 after carpal tunnel surgery.

Two epidemiologic studies showed 50,000 new diagnosed cases of CRPS in the USA per annum with some evidence indicating that the syndrome could be underdiagnosed outside of pain management centers [3].

Pathophysiology

Extensive attempts at elucidating an exact physiologic basis failed to pinpoint the exact origin of the disease. The evidence from the last several years points toward a multifactorial origin of both CRPS type 1 and type 2. There is rising amount of evidence pointing to recruitment of the central nervous system in addition to peripheral somatic and sympathetic nervous system involvement [4].

Investigators have proposed several different mechanisms of CRPS etiology, the main ones focusing on nerve fiber loss and regeneration, nervous system sensitization, hypoxia, oxidative stress, and endothelial dysfunction.

After the initial traumatic event (most commonly surgery, fractures, crush injuries, sprains), there are repetitive cycles of nerve fiber loss and regeneration [5], predominantly affecting C and Aδ nerve fibers [6, 7] leading to small fiber neuropathy resulting in combination with pain and autonomic dysfunction.

E.A. Vaynberg (✉) • A. Sakellariou
Department of Anesthesiology and Pain Management, Boston Medical Center, Boston University Medical School, 88 East Newton Street, Boston, MA 02118, USA
e-mail: Eduard.Vaynberg@bmc.org

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Sympathetic nervous system malfunction with cutaneous manifestations of altered temperatures, mottling, cyanosis, hypersensitivity to light touch, painful stimuli, or change in ambient temperature, and/or erythema is traditionally considered to be the cornerstone of complex regional pain syndrome pathophysiology.

Peripheral and central nervous system sensitization plays also a key role to the condition. Sensitization is the phenomenon when a neuron continues to fire for a prolonged time after the stimulus subsides. This leads to exaggerated responses to normally non- or mildly painful stimuli, symptoms called allodynia and hyperpathia.

Recently, evidence of inflammatory mechanism involvement in both the peripheral tissues and central nervous system came to light. This was demonstrated by increased levels of pro-inflammatory cytokines in both blood plasma and cerebral spinal fluid of patients affected by both CRPS types [4]. Additionally, on a cellular level, it has been shown that autonomic alterations lead to endothelial damage, free radicals' production, and oxidative stress. *N*-Methyl-D-aspartate receptor activation has also been implicated in the initiation and maintenance of the syndrome's pathology [8].

Diagnosis

There are two groups of criteria most frequently used for the diagnosis of CRPS: the one proposed by the International Association for the Study of Pain (IASP) and the "Budapest criteria" (Tables 31.1 and 31.2) [9, 10]. A study compared the two criteria sets, showing that the IASP criteria have a high sensitivity and low specificity, leading to a high rate of false-positive diagnoses and unnecessary treatments. The "Budapest criteria," on the other hand, have demonstrated an 88% accuracy making them more reliable in the diagnosis and treatment of CRPS patients [11]. After a noxious event, the patient must demonstrate continual pain. The pain is regional, meaning it is not specific to a certain nerve or dermatome [4]. Skin changes may be present at the affected region; these can include edema, flushing, temperature fluctuations, or inappropriate sweating. Other disorders need to be excluded as well. If a patient partially meets these criteria and all other reasons have been ruled out, then one may classify that patient as having CRPS NOS (not otherwise specified) [12]. Although several diagnostic criteria exist, the above are well established in the most recent literature. Some texts include immobility, weakness, and tremor as part of their diagnostic criteria.

Clinical experience indicates that early diagnosis and treatment is vital and leads to improved outcomes. Postoperative pain and loss of function out of norm for a particular surgical procedure, especially if accompanied by autonomic dysfunction and hypersensitivity in the affected extremity, should trigger a referral to a pain specialist to aid in the diagnosis of CRPS type 1 or type 2.

Table 31.1 International Association for the Study of Pain (IASP)

IASP criteria for CRPS	
CRPS type 1 Two to four of the following criteria must be met, with two to four being mandatory	CRPS type 2 All of the following must be present
1. The presence of an initiating noxious event or a cause of immobilization	1. The presence of continuous pain, allodynia, or hyperalgesia after a nerve injury, not necessarily limited to the distribution of the nerve
2. Continuing pain, allodynia, or hyperalgesia where the pain is disproportionate to the inciting event	2. Evidence at some time of edema, changes in skin blood flow, or abnormal sudomotor activity in the region of pain
3. Evidence at some time of edema, changes in skin blood flow, or abnormal sudomotor activity in the region of pain	3. This diagnosis is excluded by the existence of conditions that would otherwise account for the degree of pain and dysfunction
4. This diagnosis is excluded by the existence of conditions that would otherwise account for the degree of pain and dysfunction	

Table 31.2 Budapest criteria

Budapest criteria for CRPS	
All of the following must be satisfied: • The patient has continuing pain that is disproportionate to any inciting event • The patient has at least one sign in two or more of the categories below • The patient reports at least one symptom in three or more of the categories below • No other diagnosis can better explain the signs and symptoms	
Category	*Signs/symptoms*
Sensory	Allodynia (pain to light touch and/or temperature sensation and/or deep somatic pressure and/or joint movement) and/or hyperalgesia (to pinprick)
Vasomotor	Temperature asymmetry and/or skin color changes and/or skin color asymmetry
Sudomotor/edema	Edema and/or sweating changes and/or sweating asymmetry
Motor/trophic	Decreased range of motion and/or motor dysfunction (weakness, tremor, dystonia) and/ or trophic changes (hair, nail, skin)

Treatment

There is no cure for complex regional pain syndrome; treatment is palliative aimed at relieving symptoms and recovering motor and psychological function [12]. Multiple treatment modalities exist for both CRPS types with variable outcomes. These regimens include pharmacological, interventional, and psychological treatments.

Our pharmacological armamentarium includes membrane stabilizers (gabapentin, pregabalin), opioids (without escalation to high doses), tricyclic antidepressants (amitriptyline, desipramine), and alpha-blockers (clonidine) to name a few.

Different intravenous therapies have also been used. IV bisphosphonates seem to lessen the pain associated with the bone loss observed in CRPS. Other IV therapies include ketamine, glucocorticoids, local anesthetics (lidocaine), immunoglobulins, and calcitonin [8].

Interventional options include sympathetic blockade, intrathecal therapy, spinal cord stimulators, and stellate ganglion blocks/radiofrequency neurolysis [13]. Unfortunately, sympathetic chain frequently regenerates, thus limiting long-term usefulness of ablative therapies.

Stellate ganglion blocks for the CRPS of the upper extremity have long been considered pivotal in the diagnosis, prognosis, and management [14]. Sympatholysis may reverse the vasoconstriction mediated hypoxia. Interestingly, many patients with either type of CRPS will respond to sympathetic blockade for a variable duration. Results of the sympathetic blockade could also serve as an indicator of success of the spinal cord stimulation.

Behavioral-cognitive therapy may also help reduce pain [15]. Addressing and managing any psychological features coupled with biomedical components has shown to improve outcome.

CRPS and Hand Surgery

Specific surgical interventions and injuries have a higher incidence in the development of CRPS. High-energy injuries, severe fractures, and the female gender contribute to the development of CRPS type I, especially after the surgical treatment of distal radius fractures [16].

Developing complex regional pain syndrome after surgery is not infrequent, varying with different interventions. There is a 4.5–40% incidence after fasciectomy for Dupuytren contracture, 2–5% after carpal tunnel surgery, and 22–39% after distal radius fracture [17]. Analysis of those patients who developed CRPS after carpal tunnel surgery showed that the choice of anesthetic technique had no relevance [18]. Tse et al. [19], in a series of 1200 endoscopically treated carpal tunnel syndrome cases, reported a 0.9% incidence of CRPS I.

The most important aspect in the management of this complex patient population is timely diagnosis and treatment. Hand surgery experts should include CRPS in their differential diagnosis of persistent postoperative pain, particularly if accompanied with autonomic nervous system dysfunction and cutaneous hypersensitivity prompting early referral to pain management specialists. It cannot

be stressed enough that early multidisciplinary approach, including physical therapy, medical management, and necessary interventional techniques, changes the prognosis dramatically.

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The Indications and Importance of Obtaining Electrical Studies

32

Brian J. Evanson, Steven I. Grindel, and Rick F. Papandrea

EMG and NCS

A basic understanding of the different electrodiagnostic tests is necessary to comprehend and interpret the data measured. The current clinical practice guidelines put forth by the AAOS (American Academy of Orthopedic Surgeons) recommend electrodiagnostic studies in the presence of any thenar atrophy or persistent numbness; additionally, they are recommended with positive provocative tests on physical exam when surgery is being considered [1, 2]. These recommendations most likely are a significant reason in up to 96% of cases [3].

B.J. Evanson
Department of Orthopaedic Surgery, Medical College of Wisconsin, 9200 W. Wisconsin Ave, Milwaukee, WI 53226, USA

S.I. Grindel
Department of Orthopaedic Surgery, Froedtert and the Medical College of Wisconsin, 9200 W. Wisconsin Ave, Milwaukee, WI 53226, USA

R.F. Papandrea (✉)
Orthopaedic Associates of Wisconsin, 28300 Golf Road, Pewaukee, WI 53072, USA
e-mail: rick@papandrea.net

Nerve Conduction Studies

NCS evaluates motor, sensory, and mixed nerves. The motor nerves are evaluated indirectly with large amplitude responses by compound muscle action potentials (CMAPs), and the sensory nerves are assessed directly by sensory nerve action potentials (SNAPs) which are of lower amplitude [4]. The parameters by which these are evaluated include amplitude, duration, latency, and velocity [5]. Amplitude refers to the height of the action potential, latency is a measure of the speed of the fastest conducting fibers, and velocity is a measure of the conduction speed between two points [5]. The main values considered when evaluating median neuropathies are the velocity and distal latency.

Electromyography

EMG evaluates either spontaneous or volitional activity. Fibrillations (the earliest sign of muscle denervation) occur spontaneously, and motor unit action potentials (MUAPs) are seen when the patient is asked to contract [4–6]. The EMG has three parts: observing the muscle at rest, evaluating the insertional activity, and finally analyzing the morphology and recruitment of motor units (MUAPs) with voluntary muscle contraction [5, 6]. MUAPs are evaluated by their amplitude, duration, and phase [4–6]. The amplitude refers to the magnitude of voltage

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produced with voluntary contraction; the duration refers to the length of the response from initiation to completion; and the phase refers to the number of times the waveform crosses the baseline [5, 6].

Limitations

While the use of EMG and NCS is often considered diagnostic in the management of carpal tunnel syndrome, no test is without its limitations. Nerve conduction studies only evaluate large myelinated fibers; these typically include motor and sensory axons relaying vibration and touch but exclude smaller axons for temperature and pain [4–6]. The first changes in unmyelinated fibers in chronic compression are not assessed with electrodiagnostic studies [4–7]. As is the case with many tests, the quality of the electrodiagnostic study is dependent on the skill of the operator as well as the subject's ability to tolerate the test [4–8]. Other factors that may affect the quality of the study include dynamic changes in blood flow, multilevel injury or polyneuropathy, or age of the patient [4–6]. It should also be noted that a false-negative rate in carpal tunnel syndrome has been found to be as high as 8%, and evidence of nerve injury may not be seen until 6 weeks after the event [4–9]. Finally, injection of the carpal canal with corticosteroid prior to EMG/NCS has been demonstrated to alter the results; both the peak sensory latency and distal motor latency have been shown to improve as well as other abnormalities in motor and sensory nerve conduction [10, 11].

Recommended Testing

The American Association of Neuromuscular and Electrodiagnostic Medicine (AANEM), the American Academy of Neurology (AAN), and the American Academy of Physical Medicine and Rehabilitation (AAPMR) have come together and issued a standard practice guideline for electrodiagnostic studies in carpal tunnel syndrome [12–15]. They recommend performing a median sensory NCS across the wrist, a median nerve motor NCS from the thenar muscles, and NCS of another nerve in the symptomatic limb including measurement of distal latency; EMG testing should include sample muscles innervated by the C5-T1 spinal roots and thenar musculature innervated by the median nerve of the symptomatic limb [12–15].

While the contralateral side can be used as a comparison, it is not the current standard of practice [12–15].

Recommended electrodiagnostic testing	
NCS	EMG
Median n. sensory across the wrist	Thenar musculature
Median n. motor to thenar muscles	C5-T1 sample musculature
Motor and sensory testing of another nerve in the symptomatic limb	

Normal Findings and Values

EMG

For an EMG of a normal muscle at rest, the isoelectric line should be silent and no spontaneous electrical activity should be seen [6, 7, 9]. With insertion of the needle, the muscle is depolarized which produces a burst of positive and negative spikes that should cease after the needle stops moving [6]. The MUAPs are then evaluated with voluntary contraction to analyze their amplitude, duration, and phase; MUAPs as recorded by EMG are normally large (300–3000 μV), having three to four phases, and last less than 12 ms [5, 6, 9].

EMG for the median nerve—normal findings	
At rest	Isoelectric
Insertion of needle	Burst of spikes that cease when needle stops moving
Voluntary contraction	Normal MUAPs

MUAPs for the median nerve—normal values	
Amplitude (μV)	300–3000
Duration (ms)	<12
Phases (number)	3–4

NCS

Normal nerve conduction studies of the median nerve are easy to interpret as the velocity and the distal latency should be within their normal ranges—velocity (m/s) 49–70 and distal latency (ms) 2.4–4.4 [5].

NCS for the median nerve—normal values	
Velocity (m/s)	49–70
Distal latency (ms)	2.4–4.4

Abnormal Findings

In the early stages of carpal tunnel syndrome, electrodiagnostic tests may be normal, but as the median nerve continues to be compressed and the loss of myelin progresses, abnormal findings begin to appear. As the conduction velocity slows, NCS become positive and over the course of time, axonal loss propagates leading to positive EMG findings [4–6]. Fibrillation potentials on EMG are regular, bi-, or triphasic waveforms that are associated with axonal denervation; they represent involuntary contraction and intrinsic muscle abnormalities that are pathognomonic for denervation [4–6]. Sharp waves represent an involuntary release of acetylcholine and are evidence of muscle fiber denervation; they are thought to have the same significance as fibrillations though they may appear a few days earlier [5, 6]. Both fibrillation and sharp waves exist where nerve stimulation has been lost due to trauma, inflammatory myopathies, and degenerative myopathies [5, 6]. As mentioned earlier, results may differ depending on the skill of the operator, the amount of blood flow, temperature, and age of the patient [4, 6–8].

NCS

Any change in NCS velocity or distal latency outside the normal range is significant for nerve pathology though nonspecific; segmental slowing suggest a focal compression or trauma while multiple sites of slowing suggest a systematic neuropathy [5].

EMG

Needle Insertion

A brief burst of activity followed by silence is normal. Any increased or decreased insertional activity is the earliest sign of denervation though not specific [5].

Muscle Rest

At rest the muscle is normally electrically silent, but abnormal findings would include fibrillations, sharp waves, or fasciculations [5, 6].

Muscle Contraction

With minimal contraction, the MUAPs will show normal triphasic waveforms with amplitude and duration within their normal range; abnormal findings would include polyphasic waveforms and a decrease in amplitude or duration [5]. Maximal contraction normally shows destruction of the electrical baseline and inability to isolate individual waveforms (full interference pattern) [6]. Abnormal results would show only a partial interference pattern (muscle weakness or noncompliance), isolated action potentials (severe degeneration), or lastly the presence of early interference pattern (end-stage myopathy or neuropathy) [5].

Diagnosis

A diagnosis of carpal tunnel syndrome is obtained if the median sensory NCS across the wrist with a conduction distance of 13–14 cm is abnormal compared to another adjacent nerve in the symptomatic limb [12–15]. If these are normal, then a diagnosis can still be obtained using any of these other methods: comparison of the median sensory or mixed nerve conduction across the wrist

Electrodiagnostic diagnosis of CTS—practice parameters						
#	Abnormal value	CD (cm)	Area	Comparison	CD (cm)	Area
1	Median sensory	14	Wrist	Adjacent nerve	14	Wrist
2a	Median sensory or mixed	8	Wrist	Ulnar sensory	8	Wrist
2b	Median sensory	–	Wrist	Ulnar or radial sensory	–	Wrist
2c	Median sensory or mixed	–	Carpal tunnel	Median sensory or mixed	–	Forearm or digits
3	Median motor	–	Thenar m	Adjacent nerve	–	Same limb

Order of test, *CD* conduction distance, *Area* anatomical area nerve crossing

over a short conduction distance (7–8 cm) with the ulnar sensory nerve conduction across the wrist over the same short conduction distance, or comparison of the median sensory conduction across the wrist with radial or ulnar sensory conduction across the wrist in the same limb, or comparison of the median sensory or mixed nerve conduction through the carpal tunnel to the sensory or mixed NCS of the proximal or distal segments of the median nerve in the same limb [12–15]. Additionally, testing may involve comparing median motor recording from the thenar musculature to one other nerve in the symptomatic limb to include the distal latency as well [12–15]. Optional supplemental testing not included as standard may include comparison of the median motor distal latency in the second lumbrical to the ulnar motor distal latency in the second interossei, median motor terminal latency index, median motor nerve conduction between the wrist and palm, median motor compound muscle action potential amplitude ratio from the wrist to the palm, median sensory action potential amplitude ratio from the wrist to the palm, and 1 cm short incremental segments median sensory across the carpal tunnel [6–9].

While these are the parameters set forth by the AANEM, AAN, and AAPMR, other limits in the literature have been used including distal motor latency to the abductor pollicis brevis greater than 4 ms [16], orthodromic sensory conduction velocity of the long finger to the wrist less than 35 m/s [16], orthodromic median-ulnar latency difference greater than 0.4 ms for the ring finger [16], orthodromic median midpalmer latency of greater than 2.2 ms [17], or median-ulnar latency difference of greater than 0.4 ms [17].

Other areas of compression of the median nerve must be delineated as well. Positive NCS and EMG findings of muscles in the arm and forearm may be indicative of pronator syndrome, AIN syndrome, proximal entrapment, or cervical radiculopathy; [18, 19] these tests can be helpful in ruling out pathology or ruling in additional diagnoses in a double-crush phenomenon [18–20]. In AIN syndrome, electrodiagnostic testing is important to rule out more proximal lesions or tendon ruptures in patients with rheumatoid arthritis or limited wrist motion preventing a tenodesis assessment [19]. Conversely, pronator syndrome is a dynamic process and testing may yield normal results [18]. While electrodiagnostic testing can be helpful in confirming or ruling out a diagnosis, it must be used in conjunction with both the history and the clinical exam.

Other Effects on EMG

While the focus has been on entrapment of the median nerve in the carpal tunnel, one must be aware of other factors which may be causing abnormal electrodiagnostic testing. Hypothyroidism has been shown to have effects on motor action potentials, and 52% of neurologically asymptomatic individuals have abnormal NCS [21, 22]. The median nerve is the most commonly affected nerve in 30% of individuals with changes in F-wave latency of the

median motor, latency of the medial palmer response, and median motor distal latency [21, 22]. It should be noted, however, that symptoms typically resolve when the patient reaches an euthyroid state [23, 24].

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