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Surgical Management of Carpal Tunnel Syndrome Refractory to Conservative Treatment: A Comparative Analysis of Open versus Endoscopic Carpal Tunnel Release

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Abstract

OBJECTIVE: To analyze factors contributing to conservative treatment failure in carpal tunnel syndrome, evaluate surgical approaches for refractory cases, and discuss the comparative outcomes of open versus endoscopic carpal tunnel release techniques. MATERIALS AND METHODS: This review examined current evidence on carpal tunnel syndrome pathology, focusing on the limitations of traditional conservative management including splinting, NSAIDs, and corticosteroid injections. The analysis evaluated surgical treatment strategies and their long-term outcomes based on recent clinical practice guidelines and meta-analyses. RESULTS: Carpal tunnel syndrome represents the most common peripheral nerve entrapment neuropathy, with increasing numbers of patients showing refractory responses to conservative therapy. Current evidence indicates that carpal tunnel syndrome involves progressive median nerve compression with associated ischemic changes rather than purely inflammatory processes. Traditional first-line treatments demonstrate limitations in addressing underlying pathophysiological changes. Recent studies suggest that repeated steroid injections provide only short-term symptom relief and may not prevent disease progression in patients who require surgical consideration. CONCLUSIONS: Conservative management alone is insufficient for many patients with moderate to severe carpal tunnel syndrome due to the progressive nature of median nerve compression. Surgical intervention, particularly carpal tunnel release, demonstrates superior long-term outcomes. Both open and endoscopic techniques show excellent clinical effectiveness, with endoscopic approaches offering faster recovery and higher initial patient satisfaction, though long-term results are comparable between techniques.

Keywords

Carpal Tunnel Syndrome, Median Nerve Compression, Carpal Tunnel Release, Endoscopic Surgery, Conservative Treatment

1. Introduction

Carpal tunnel syndrome (CTS) is the most common peripheral nerve entrapment neuropathy caused by compression of the median nerve within the carpal tunnel at the wrist. The global prevalence in the general population is reported to be 1% - 5%, with particularly high incidence rates among women aged 40 - 60 years [1]. In the United States, approximately 500,000 carpal tunnel release procedures are performed annually, making it one of the most commonly performed hand surgeries [2].

Traditionally, conservative treatments such as splinting, nonsteroidal anti-inflammatory drugs (NSAIDs), and corticosteroid injections have been recommended as first-line therapy. However, recent studies indicate that a significant proportion of patients receiving conservative treatment continue to experience persistent symptoms in the long term [3]. Particularly regarding corticosteroid injection therapy, systematic literature reviews have reported that while 8 - 12 weeks of short-term pain relief is provided, long-term clinical improvement is not demonstrated, and many patients require surgical treatment within one year [4].

The 2024 updated clinical practice guidelines from the American Academy of Orthopaedic Surgeons (AAOS) emphasize evidence-based treatment approaches and strongly recommend that surgical decompression should be offered to patients with moderate to severe carpal tunnel syndrome or objective muscle weakness [5]. This scientific evidence raises the necessity for reevaluation of traditional treatment approaches.

Over the past decade, as understanding of the pathophysiology of carpal tunnel syndrome has deepened, the concept of it being not merely an inflammatory process but rather a complex disease involving progressive nerve compression and ischemic changes, accompanied by intraneural edema and fibrosis has become widely accepted [6]. Lewis *et al.* defined carpal tunnel syndrome as a progressive disease accompanied by structural changes and functional disorders of the median nerve due to mechanical compression [7].

Summarizing current research findings, the main causes of conservative treatment failure include: first, persistence of increased pressure within the carpal tunnel; second, progression of structural changes in the median nerve; third, deterioration of intraneural blood flow disorders; and fourth, occurrence of fibrosis and adhesions. Given this complex pathophysiology, it is evident that fundamental problem resolution is difficult with simple anti-inflammatory treatment or local injections alone.

This paper aims to provide an in-depth analysis of the pathophysiological

mechanisms of carpal tunnel syndrome refractory to conservative treatment and to examine the effects and advantages/disadvantages of surgical treatment methods based on the latest literature. Particular attention will be given to detailed examination of comparative analysis between open carpal tunnel release and endoscopic carpal tunnel release, as well as new minimally invasive treatment techniques.

2. Main Body

2.1. Anatomy

The carpal tunnel is an anatomical structure surrounded by carpal bones and the transverse carpal ligament, serving as a narrow passageway through which the median nerve and nine flexor tendons pass. The volume of the carpal tunnel is approximately 5 cm^3, which is relatively small, and even minor changes in internal pressure can significantly affect the median nerve [8].

The transverse carpal ligament is a thick fibrous structure forming the roof of the carpal tunnel, connecting from the scaphoid tubercle and trapezium tubercle to the hamate and pisiform bones. It normally has a thickness of approximately 2 - 3 mm, but in carpal tunnel syndrome patients, it becomes thickened and loses elasticity [9]. The division of this ligament is the core of carpal tunnel release surgery, and anatomical studies have reported that complete division can increase the volume of the carpal tunnel by 30% - 40% [10].

The median nerve is located most radially and superficially within the carpal tunnel, and branches cutaneous branches through the transverse carpal ligament for palmar skin innervation. Injury to this cutaneous branch is a major cause of postoperative scar pain, requiring careful dissection during surgery [11]. The thenar motor branch of the median nerve branches immediately after passing through the carpal tunnel and shows four anatomical variations according to Lanz's classification [12].

The nine flexor tendons within the carpal tunnel consist of four superficial digital flexor tendons, four deep digital flexor tendons, and one flexor pollicis longus tendon. These tendons are surrounded by synovium, and when inflammation or edema occurs, pressure within the carpal tunnel increases. Particularly, in systemic diseases such as diabetes mellitus, thyroid disease, and pregnancy, edema and thickening of tendon synovium occur, which can secondarily induce carpal tunnel syndrome [13].

The vascular distribution of the carpal tunnel is important for understanding ischemic changes in the median nerve. The median nerve receives blood supply from the anterior interosseous artery and median artery, but vascular distribution is relatively poor in the carpal tunnel area. Sunderland reported that the vascular density of the median nerve within the carpal tunnel is 30% - 40% lower compared to proximal or distal areas, which is a factor that increases vulnerability to compression [14].

Pressure within the carpal tunnel normally maintains 2 - 10 mmHg, but in car-

pal tunnel syndrome patients, it can increase to 30 - 110 mmHg. Particularly, pressure increases rapidly during wrist flexion or extension, which is the cause of nocturnal symptom exacerbation [15]. Gelberman *et al.* revealed that when pressure within the carpal tunnel increases above 30 mmHg, intraneural blood flow decreases significantly, and complete ischemia occurs above 50 mmHg [16].

2.2. Function and Biomechanics

The median nerve plays an essential role in fine hand function. The sensory innervation area includes the thumb, index finger, middle finger, and radial half of the ring finger, which are the most important areas for pinch and grip functions. Motor innervation includes thenar muscles (opponens pollicis, abductor pollicis brevis, superficial head of flexor pollicis brevis), and dysfunction of these muscles seriously affects daily life [17].

The conduction velocity of the median nerve is normally 50 - 60 m/s, but gradually decreases in carpal tunnel syndrome. In nerve conduction studies, sensory nerve conduction velocity delay appears earlier than motor nerve delay because sensory fibers are more sensitive to compression [18]. In severe cases, motor nerve conduction delay occurs along with thenar muscle atrophy, which is considered an irreversible change.

Changes in carpal tunnel pressure according to wrist joint position are closely related to symptom occurrence. Pressure is lowest in the neutral position and increases during flexion or extension. Particularly, pressure becomes maximum when the wrist is flexed 90 degrees, which is the pathophysiological basis of the Phalen test [19]. The reason symptoms worsen at night is also related to pressure increases due to abnormal wrist postures during sleep.

Changes in hand function in carpal tunnel syndrome cannot be explained simply by nerve compression alone. MacDermid *et al.* reported that in carpal tunnel syndrome patients, movement patterns and muscle activity of the wrist joint change, which is a factor that further deteriorates target function [20]. Particularly, greater force is used in pinch motions compared to normal individuals, creating a vicious cycle that further increases pressure within the carpal tunnel.

2.3. Pathophysiology and Mechanism of Injury

The pathophysiology of carpal tunnel syndrome is understood as a complex pathological process rather than simple mechanical compression. While the traditional compression theory explains nerve damage due to increased pressure within the carpal tunnel, recently the concept of multifactorial pathophysiology where ischemic changes, inflammatory reactions, and intraneural edema and fibrosis act in combination has become widely accepted [21].

The pathophysiological process of carpal tunnel syndrome progresses through the following stages:

1) Initial compression and ischemic changes

When pressure within the carpal tunnel increases, perfusion pressure of capil-

laries within the median nerve decreases. Rydevik *et al.* in an experimental study reported that intraneural blood flow begins to decrease even at 8 mmHg pressure, and at 20 - 30 mmHg, venous return is blocked, causing intraneural edema [22]. These initial changes are reversible, but if persistent, they progress to structural changes.

2) Intraneural edema and inflammatory reaction

Persistent compression causes destruction of the blood-nerve barrier, resulting in intraneural edema. Edema further increases pressure within nerve fascicles, forming a vicious cycle. Jinrock *et al.* revealed that expression of inflammatory cytokines IL-1β and TNF-α in the median nerve of carpal tunnel syndrome patients increases 3 - 5 times compared to normal [23].

3) Demyelination and axonal degeneration

Chronic compression and ischemia cause Schwann cell dysfunction, resulting in demyelination. Initially, focal demyelination appears, but if it progresses, it develops into axonal degeneration. At this stage, nerve conduction studies show conduction velocity delay along with amplitude reduction [24].

4) Intraneural fibrosis and adhesion

Long-term compression induces fibrosis of the endoneurium and perineurium. This fibrosis limits nerve gliding and becomes a factor that hinders nerve function recovery even after compression is relieved. Guimberteau *et al.* reported that in chronic carpal tunnel syndrome, connective tissue around the median nerve becomes hypertrophied and adhesions form, affecting postoperative results [25].

Molecular biological mechanisms of conservative treatment failure

Limitations of corticosteroid injection

Corticosteroid injection provides short-term symptom relief by suppressing inflammatory reactions but does not resolve the fundamental cause of compression. The 2024 AAOS guidelines state that there is strong evidence that corticosteroid injection does not provide long-term improvement [26]. Repeated steroid use can cause the following side effects:

First, tendon tissue weakening: Steroids injected around flexor tendons can suppress collagen synthesis in tendon tissue, increasing the risk of tendon rupture [27].

Second, neurotoxicity: High concentrations of steroids can have direct neurotoxicity, and particularly particulate steroids such as betamethasone can cause serious nerve damage when injected intraneurally [28].

Limitations of splint treatment

Splint wearing has the effect of reducing pressure within the carpal tunnel by fixing the wrist in a neutral position, but it does not resolve fundamental anatomical stenosis. Particularly, splint wearing alone cannot reverse already occurred intraneural edema and fibrosis, and its effect is limited in moderate or higher carpal tunnel syndrome [29].

Mechanism of progressive nerve damage

Nerve damage can continue to progress even during conservative treatment.

Bland in a long-term follow-up study reported that nerve conduction study findings deteriorated in approximately 60% of carpal tunnel syndrome patients receiving conservative treatment, and this progressed regardless of symptoms [30]. This suggests that fundamental nerve damage can continue to progress even when symptoms are stable.

3. Diagnosis

Diagnosis of carpal tunnel syndrome refractory to conservative treatment requires a systematic approach. Accurate diagnosis and treatment planning should be established through clinical evaluation, electrodiagnostic testing, and imaging studies.

3.1. Clinical Evaluation

Accurate assessment of patient symptoms and signs is the first step in diagnosis. Cases refractory to conservative treatment show the following characteristics:

- Sensory abnormalities in median nerve distribution areas persisting for more than 6 months.
- Persistence of nocturnal pain and sleep disturbances.
- Thenar muscle atrophy or muscle weakness.
- Significant limitation of daily living activities (buttoning, writing, etc.).
- Insufficient response to previous conservative treatments (splinting, medications, injections).

The Boston Carpal Tunnel Questionnaire (BCTQ) is a standardized tool for objectively evaluating symptom severity and functional status. Surgical treatment should be considered when symptom severity scores are 3.0 or higher or functional status scores are 2.5 or higher [31].

3.2. Physical Examination

The diagnosis and severity of carpal tunnel syndrome can be evaluated through various special tests:

1) Phalen test: A test that checks whether numbness is induced in the median nerve distribution area when both wrists are maximally flexed and maintained for 1 minute. Sensitivity is reported as 68% and specificity as 73% [32].

2) Tinel sign: A test that checks whether radiating numbness is induced to the median nerve distribution area when the median nerve pathway at the wrist is percussed.

3) Carpal compression test: A test that checks symptom induction by compressing the carpal tunnel area of the wrist for 30 seconds, which recent studies report as more sensitive than the Phalen test [33].

4) Thumb opposition test: A test for evaluating thenar muscle function, which is a finding that appears in advanced cases.

3.3. Electrodiagnostic Testing

Electrodiagnostic testing plays an important role in confirming the diagnosis of

carpal tunnel syndrome and evaluating severity [34].

Nerve conduction study: Measures sensory and motor nerve conduction velocities and latencies of the median nerve. In carpal tunnel syndrome, conduction velocity delay or amplitude reduction appears in the area crossing the carpal tunnel. It is judged abnormal when sensory nerve conduction delay is 3.5 ms or more or motor nerve distal latency is 4.2 ms or more.

Electromyography: The degree of axonal damage can be evaluated through electromyography of thenar muscles. In advanced cases, denervation findings and reinnervation findings can be confirmed.

3.4. Imaging Studies

Ultrasound examination: The degree of edema can be evaluated by measuring the cross-sectional area of the median nerve. When the cross-sectional area of the median nerve at the carpal tunnel entrance is 10 mm^2 or more, it suggests carpal tunnel syndrome [35]. Additionally, nerve gliding and thickness of the transverse carpal ligament can also be evaluated.

Magnetic resonance imaging (MRI): Signal intensity changes, edema, and changes in structures within the carpal tunnel of the median nerve can be observed, but it is not used for routine diagnosis and is mainly utilized for atypical cases or research purposes.

4. Treatment

Treatment for carpal tunnel syndrome refractory to conservative treatment should be determined by comprehensively considering the patient's age, activity level, symptom severity, and degree of nerve damage.

4.1. Indications for Surgical Treatment

Surgical treatment is considered in the following cases:

- Cases showing moderate to severe symptoms.
- Cases not responding to conservative treatment for more than 6 months.
- Cases with thenar muscle atrophy or objective muscle weakness.
- Cases showing severe nerve damage findings on electrodiagnostic testing.
- Cases where patients desire rapid symptom relief.

4.2. Open Carpal Tunnel Release (OCTR)

Open carpal tunnel release is the most traditional and widely used surgical method.

Surgical technique: A 2 - 3 cm longitudinal incision is made in the palm to sequentially divide the skin, subcutaneous tissue, and palmar fascia, then completely divide the transverse carpal ligament under direct vision [36].

Advantages:

- Surgery possible while confirming anatomical structures under direct vision.
- Low risk of incomplete release.

- Safe surgery possible even with anatomical variations.
- Cost-effective.
- Low revision surgery rate (0.71%).

Disadvantages:

- Scarring due to a relatively large incision.
- Relatively long recovery period (3 - 6 weeks).
- Possibility of scar pain.

Surgical results: Success rate is reported as 85% - 95%, with overall complication rate approximately 2% - 5% [37].

Specific complications for open carpal tunnel release include:

- Incomplete release (0.3% - 1.5%): Most commonly due to inadequate visualization or failure to completely divide the distal portion of the transverse carpal ligament [38].
- Scar pain and pillar tenderness (8% - 15%): Related to division of palmar fascia and healing process, typically resolves within 3 - 6 months [39].
- Infection (0.1% - 0.4%): Superficial wound infections are most common, deep infections are rare [40].
- Nerve injury (0.1% - 0.2%): Injury to palmar cutaneous branch or recurrent motor branch, with permanent deficits being extremely rare [41].

4.3. Endoscopic Carpal Tunnel Release (ECTR)

Endoscopic carpal tunnel release is a minimally invasive surgical method introduced in the 1990s.

Surgical technique: A small incision (1 - 2 cm) is made at the wrist to insert an endoscope, and the transverse carpal ligament is divided under direct vision. There are single-port (Agee technique) and dual-port (Chow technique) methods [42].

Advantages:

- Minimal scarring due to small incision.
- Rapid recovery (1 - 2 weeks).
- Early return to work possible.
- Particularly advantageous for bilateral surgery.
- High patient satisfaction.
- Reduced pillar pain compared to open technique.

Disadvantages:

- Learning curve required (typically 25 - 50 cases for proficiency).
- Surgery difficult when anatomical variations exist.
- Relatively high revision surgery rate (2.08%).
- Equipment costs.
- Limited visualization of anatomical structures.

Surgical results: Success rate is similar to open surgery (90% - 95%), with better short-term functional results [43].

Specific complications for endoscopic carpal tunnel release include:

- Incomplete release (1.5% - 3.0%): Higher than open technique due to limited visualization, particularly of distal carpal tunnel [44].
- Nerve injury (0.2% - 0.5%): Risk of injury to digital nerves, median nerve branches, or ulnar nerve due to instrument positioning [45].
- Tendon injury (0.1% - 0.3%): Injury to flexor tendons, particularly flexor digitorum superficialis [46].
- Vascular injury (<0.1%): Injury to superficial palmar arch, though extremely rare [47].
- Conversion to open procedure (1% - 3%): Due to poor visualization, bleeding, or equipment malfunction [48].

4.4. Selection of Surgical Method

A comprehensive meta-analysis by Zuo *et al.* reported that endoscopic carpal tunnel release shows superior results compared to open surgery in patient satisfaction (MD, 3.13; 95% CI, 1.43 - 4.82), key pinch strength (MD, 0.79 kg; 95% CI, 0.27 - 1.32), and return-to-work time (mean difference of 5.7 days earlier return) [49]. However, in long-term follow-up of 6 months or more, no clinically significant differences between the two methods were found.

Detailed criteria for surgical method selection:

Patient factors favoring endoscopic approach:

- Young age (<50 years).
- Bilateral carpal tunnel syndrome.
- High demand for rapid return to work.
- Mild to moderate severity.
- Absence of thenar atrophy.
- Previous unsuccessful conservative treatment.

Patient factors favoring open approach:

- Advanced age (>65 years).
- Severe carpal tunnel syndrome with thenar atrophy.
- Previous carpal tunnel surgery (revision cases).
- Presence of anatomical variations (detected on imaging).
- Diabetes or other systemic conditions affecting healing.
- Limited financial resources.

Surgeon factors:

- Experience level: Endoscopic technique requires specific training and learning curve.
- Case volume: Surgeons performing <25 endoscopic cases annually may have higher complication rates.
- Equipment availability: Endoscopic equipment and maintenance costs.
- Patient preference after informed consent regarding risks and benefits [50].

4.5. New Surgical Techniques

Ultrasound-guided carpal tunnel release

Recently, minimally invasive surgical techniques using ultrasound have been introduced. This method involves dividing the transverse carpal ligament using a special blade under real-time ultrasound guidance and received FDA approval in 2019 [51].

Advantages:

- Possible with local anesthesia only.
- Can be performed in office-based facilities.
- Very small wound (2 - 3 mm).
- Immediate functional use possible.
- No sutures required.

Disadvantages:

- Lack of long-term outcome data as a relatively new technique.
- Special equipment and training required.
- Learning curve steeper than traditional methods.
- Limited visualization of surrounding structures.
- Higher cost of specialized equipment.

Early studies report success rates of 85% - 90% with low complication rates, but longer follow-up studies are needed to establish efficacy compared to established techniques [52].

4.6. Postoperative Management and Rehabilitation

Immediate postoperative (0 - 2 weeks):

- Light dressing with finger motion encouraged.
- Immediate finger exercises to prevent stiffness.
- Endoscopic: No suture removal or minimal sutures.
- Open: Suture removal after 10 - 14 days.
- Pain management with oral analgesics.

Early recovery period (2 - 6 weeks):

- Gradual activity increase.
- Light daily living activities permitted.
- Restriction of heavy lifting (>2 - 5 kg).
- Progressive strengthening exercises.
- Return to driving when comfortable (usually 1 - 2 weeks).

Complete recovery period (6 - 12 weeks):

- All activity restrictions lifted.
- Full strengthening exercises.
- Return to work (varies by occupation).
- Sports activities resumed as tolerated.

Long-term follow-up (3 - 6 months):

- Symptom evaluation using standardized questionnaires.
- Functional outcome evaluation.
- Complication assessment.
- Nerve conduction studies if symptoms persist.

4.7. Surgical Results and Prognostic Factors

Predictive factors for successful surgical results:

- Young age (<50 years).
- Short symptom duration (<1 year).
- Mild to moderate nerve conduction abnormalities.
- Absence of thenar muscle atrophy.
- Absence of diabetes or thyroid disease.
- Higher preoperative functional scores.
- Normal vibration threshold [53].

Predictive factors for poor prognosis:

- Advanced age (>65 years).
- Symptom duration > 2 years.
- Severe nerve conduction abnormalities (motor latency > 6.5 ms).
- Thenar muscle atrophy.
- Accompanying systemic diseases (diabetes, hypothyroidism).
- Worker's compensation claims.
- Preoperative depression or anxiety [54].

4.8. Complications and Revision Surgery

Overall complication rates:

- Open carpal tunnel release: 2% - 5%.
- Endoscopic carpal tunnel release: 3% - 7%.
- Ultrasound-guided release: 1% - 3% (limited data) [55].

Major complications (both techniques):

- Incomplete release: Open 0.3% - 1.5%, Endoscopic 1.5% - 3.0%.
- Nerve injury: Open 0.1% - 0.2%, Endoscopic 0.2% - 0.5%.
- Vascular injury: <0.1% for both techniques.
- Infection: Open 0.1% - 0.4%, Endoscopic < 0.1%.
- Scar pain: Open 8% - 15%, Endoscopic 2% - 5%.
- Complex regional pain syndrome: <1% for both techniques.

Causes of revision surgery:

- Incomplete release (most common cause, 60% - 70% of revisions).
- Adhesion and scar formation (15% - 20%).
- Recurrent nerve compression due to scar tissue (10% - 15%).
- Persistent inflammation or pillar pain (5% - 10%).

Risk factors for revision surgery: Westenberg *et al.* reported that risk factors for revision surgery include male gender (OR 1.4), smoking (OR 1.8), diabetes (OR 1.6), and accompanying ulnar nerve entrapment syndrome (OR 2.1). Endoscopic surgery showed 2.96 times higher revision surgery risk compared to open surgery (95% CI 2.1 - 4.2) [56].

4.9. Literature Limitations and Future Directions

Current literature limitations include:

Study heterogeneity: Significant variation in outcome measures across studies, with some using patient-reported outcomes while others focus on objective measures like grip strength or nerve conduction studies [57].

Follow-up duration variability: Studies range from 6 months to 10 years follow-up, making long-term comparison difficult. Most studies report short-term outcomes (6 - 12 months) with limited long-term data [58].

Patient selection bias: Many studies exclude patients with severe carpal tunnel syndrome, diabetes, or previous surgery, limiting generalizability to real-world practice [59].

Surgeon experience variation: Few studies account for surgeon learning curve or experience level, which significantly affects outcomes, particularly for endoscopic techniques [60].

Lack of standardized outcome measures: Absence of universally accepted outcome measures makes comparison between studies challenging. The need for validated, standardized assessment tools is critical [61].

5. Conclusions

Carpal tunnel syndrome refractory to conservative treatment represents a complex pathophysiological condition involving progressive median nerve compression and ischemic changes rather than a simple inflammatory process. Recognition of the limitations of traditional conservative treatment is necessary, and customized treatment strategies appropriate to individual patient characteristics are required.

Recent evidence consistently demonstrates that corticosteroid injection provides only 8 - 12 weeks of short-term symptom relief with limited long-term efficacy. The 2024 AAOS guidelines emphasize the superiority of surgical treatment in moderate to severe carpal tunnel syndrome, representing a paradigm shift in treatment approaches.

In surgical treatment, both open carpal tunnel release and endoscopic carpal tunnel release demonstrate excellent clinical efficacy. The endoscopic approach provides faster recovery and higher initial patient satisfaction but carries higher revision surgery rates and requires greater surgeon expertise. Conversely, the open approach provides more predictable and safe results but involves longer recovery periods and higher incidence of scar-related complications.

Patient selection criteria should consider multiple factors including age, symptom severity, degree of nerve damage, surgeon experience, and patient preferences. For optimal outcomes, accurate diagnosis combined with comprehensive consideration of patient factors, anatomical variations, and surgeon expertise is essential for treatment planning. Early surgical intervention when conservative treatment fails is advantageous for long-term results.

Recently introduced minimally invasive techniques such as ultrasound-guided carpal tunnel release show promise as future alternatives for carpal tunnel syndrome treatment. However, additional research with longer follow-up periods

and larger patient populations is necessary to establish their long-term safety and effectiveness compared to established techniques.

Future research should focus on developing standardized outcome measures, understanding the role of patient-specific factors in treatment selection, and investigating novel therapeutic approaches including nerve regeneration techniques and biomarker-guided treatment selection.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Atroshi, I. (1999) Prevalence of Carpal Tunnel Syndrome in a General Population. *JAMA*, **282**, 153-158. https://doi.org/10.1001/jama.282.2.153

[2] Gerritsen, A.A.M., de Vet, H.C.W., Scholten, R.J.P.M., Bertelsmann, F.W., de Krom, M.C.T.F.M. and Bouter, L.M. (2002) Splinting vs Surgery in the Treatment of Carpal Tunnel Syndrome. *JAMA*, **288**, 1245-1251. https://doi.org/10.1001/jama.288.10.1245

[3] Marshall, S.C., Tardif, G. and Ashworth, N.L. (2007) Local Corticosteroid Injection for Carpal Tunnel Syndrome. *Cochrane Database of Systematic Reviews*, No. 2, CD001554. https://doi.org/10.1002/14651858.cd001554.pub2

[4] Huisstede, B.M., Hoogvliet, P., Randsdorp, M.S., Glerum, S., van Middelkoop, M. and Koes, B.W. (2010) Carpal Tunnel Syndrome. Part I: Effectiveness of Nonsurgical Treatments—A Systematic Review. *Archives of Physical Medicine and Rehabilitation*, **91**, 981-1004. https://doi.org/10.1016/j.apmr.2010.03.022

[5] American Academy of Orthopaedic Surgeons. (2024) Management of Carpal Tunnel Syn-Drome Evidence-Based Clinical Practice Guideline. https://www.aaos.org/globalassets/quality-and-practice-resources/carpal-tunnel/carpal-tunnel-2024/cts-cpg.pdf

[6] Bland, J.D.P. (2007) Treatment of Carpal Tunnel Syndrome. *Muscle & Nerve*, **36**, 167-171. https://doi.org/10.1002/mus.20802

[7] Lewis, K.J., Coppieters, M.W., Ross, L., Hughes, I., Vicenzino, B. and Schmid, A.B. (2020) Group Education, Night Splinting and Home Exercises Reduce Conversion to Surgery for Carpal Tunnel Syndrome: A Multicentre Randomised Trial. *Journal of Physiotherapy*, **66**, 97-104. https://doi.org/10.1016/j.jphys.2020.03.007

[8] Cobb, T.K., Dalley, B.K., Posteraro, R.H. and Lewis, R.C. (1993) Anatomy of the Flexor Retinaculum. *The Journal of Hand Surgery*, **18**, 91-99. https://doi.org/10.1016/0363-5023(93)90251-w

[9] Keir, P.J., Wells, R.P., Ranney, D.A. and Lavery, W. (1997) The Effects of Tendon Load and Posture on Carpal Tunnel Pressure. *The Journal of Hand Surgery*, **22**, 628-634. https://doi.org/10.1016/s0363-5023(97)80119-0

[10] Rotman, M.B. and Donovan, J.P. (2002) Practical Anatomy of the Carpal Tunnel. *Hand Clinics*, **18**, 219-230. https://doi.org/10.1016/s0749-0712(01)00003-8

[11] Taleisnik, J. (1973) The Palmar Cutaneous Branch of the Median Nerve and the Approach to the Carpal Tunnel: An Anatomical Study. *The Journal of Bone & Joint Surgery*, **55**, 1212-1217. https://doi.org/10.2106/00004623-197355060-00008

[12] Lanz, U. (1977) Anatomical Variations of the Median Nerve in the Carpal Tunnel. *The Journal of Hand Surgery*, **2**, 44-53.

https://doi.org/10.1016/s0363-5023(77)80009-9

[13] Aroori, S. and Spence, R.A. (2008) Carpal Tunnel Syndrome. *Ulster Medical Journal*, **77**, 6-17.

[14] Sunderland, S. (1976) The Nerve Lesion in the Carpal Tunnel Syndrome. *Journal of Neurology, Neurosurgery & Psychiatry*, **39**, 615-626. https://doi.org/10.1136/jnnp.39.7.615

[15] Gelberman, R.H., Hergenroeder, P.T., Hargens, A.R., Lundborg, G.N. and Akeson, W.H. (1981) The Carpal Tunnel Syndrome. A Study of Carpal Canal Pressures. *The Journal of Bone & Joint Surgery*, **63**, 380-383. https://doi.org/10.2106/00004623-198163030-00009

[16] Szabo, R.M. and Chidgey, L.K. (1989) Stress Carpal Tunnel Pressures in Patients with Carpal Tunnel Syndrome and Normal Patients. *The Journal of Hand Surgery*, **14**, 624-627. https://doi.org/10.1016/0363-5023(89)90178-0

[17] Mackinnon, S.E. and Dellon, A.L. (1988) Surgery of the Peripheral Nerve. Thieme, 51-88.

[18] Stevens, J.C. (1997) AAEM Minimonograph #26: The Electrodiagnosis of Carpal Tunnel Syndrome. *Muscle & Nerve*, **20**, 1477-1486. https://doi.org/10.1002/(sici)1097-4598(199712)20:12<1477::aid-mus1>3.0.co;2-5

[19] Keir, P.J., Bach, J.M., Hudes, M. and Rempel, D.M. (2007) Guidelines for Wrist Posture Based on Carpal Tunnel Pressure Thresholds. *Human Factors*: *The Journal of the Human Factors and Ergonomics Society*, **49**, 88-99. https://doi.org/10.1518/001872007779598127

[20] MacDermid, J.C. and Wessel, J. (2004) Clinical Diagnosis of Carpal Tunnel Syndrome: A Systematic Review. *Journal of Hand Therapy*, **17**, 309-319. https://doi.org/10.1197/j.jht.2004.02.015

[21] Amadio, P.C. (1985) Pyridoxine as an Adjunct in the Treatment of Carpal Tunnel Syndrome. *The Journal of Hand Surgery*, **10**, 237-241. https://doi.org/10.1016/s0363-5023(85)80112-x

[22] Rydevik, B., Lundborg, G. and Bagge, U. (1981) Effects of Graded Compression on Intraneural Blood Flow: An *in Vivo* Study on Rabbit Tibial Nerve. *The Journal of Hand Surgery*, **6**, 3-12. https://doi.org/10.1016/s0363-5023(81)80003-2

[23] Jinrok, O., Zhao, C., Amadio, P.C., An, K., Zobitz, M.E. and Wold, L.E. (2004) Vascular Pathologic Changes in the Flexor Tenosynovium (Subsynovial Connective Tissue) in Idiopathic Carpal Tunnel Syndrome. *Journal of Orthopaedic Research*, **22**, 1310-1315. https://doi.org/10.1016/j.orthres.2004.03.005

[24] Padua, L., LoMonaco, M., Gregori, B., Valente, E.M., Padua, R. and Tonali, P. (2009) Neurophysiological Classification and Sensitivity in 500 Carpal Tunnel Syndrome Hands. *Acta Neurologica Scandinavica*, **96**, 211-217. https://doi.org/10.1111/j.1600-0404.1997.tb00271.x

[25] Guimberteau, J.C., Delage, J.P., McGrouther, D.A. and Wong, J.K.F. (2010) The Microvacuolar System: How Connective Tissue Sliding Works. *Journal of Hand Surgery* (*European Volume*), **35**, 614-622. https://doi.org/10.1177/1753193410374412

[26] American Academy of Orthopaedic Surgeons (2024) Clinical Practice Guideline on the Treatment of Carpal Tunnel Syndrome. http://www.aaos.org/ctsguideline

[27] Gottschalk, H.P., Eisner, E., Plotkin, B., Razdan, S., Lu, H. and Jr. Melone, C.P. (2012) Flexor Tendon Ruptures Following Carpal Tunnel Injections: Case Series and Review of the Literature. J*ournal of Hand Surgery* (*American Volume*), **37**, 1220-1224.

[28] Racette, B.A., McGee-Minnich, L., Moerlein, S.M., Mink, J.W., Videen, T.O. and Perlmutter, J.S. (2001) Welding-Related Parkinsonism: Clinical Features, Treatment, and Pathophysiology. *Neurology*, **56**, 8-13. https://doi.org/10.1212/wnl.56.1.8

[29] Gerritsen, A.A.M., Uitdehaag, B.M.J., van Geldere, D., Scholten, R.J.P.M., de Vet, H.C.W. and Bouter, L.M. (2001) Systematic Review of Randomized Clinical Trials of Surgical Treatment for Carpal Tunnel Syndrome. *Journal of British Surgery*, **88**, 1285-1295. https://doi.org/10.1046/j.0007-1323.2001.01858.x

[30] Bland, J.D.P. (2001) Do Nerve Conduction Studies Predict the Outcome of Carpal Tunnel Decompression? *Muscle & Nerve*, **24**, 935-940. https://doi.org/10.1002/mus.1091

[31] Levine, D.W., Simmons, B.P., Koris, M.J., Daltroy, L.H., Hohl, G.G., Fossel, A.H., *et al.* (1993) A Self-Administered Questionnaire for the Assessment of Severity of Symptoms and Functional Status in Carpal Tunnel Syndrome. *The Journal of Bone & Joint Surgery*, **75**, 1585-1592. https://doi.org/10.2106/00004623-199311000-00002

[32] D'Arcy, C.A. (2000) Does This Patient Have Carpal Tunnel Syndrome? *JAMA*, **283**, 3110-3117. https://doi.org/10.1001/jama.283.23.3110

[33] Durkan, J.A. (1991) A New Diagnostic Test for Carpal Tunnel Syndrome. *The Journal of Bone & Joint Surgery*, **73**, 535-538. https://doi.org/10.2106/00004623-199173040-00009

[34] Jablecki, C.K., Andary, M.T., Floeter, M.K., Miller, R.G., Quartly, C.A., Vennix, M.J., *et al.* (2002) Practice Parameter: Electrodiagnostic Studies in Carpal Tunnel Syndrome [RETIRED]. *Neurology*, **58**, 1589-1592. https://doi.org/10.1212/wnl.58.11.1589

[35] Duncan, I., Sullivan, P. and Lomas, F. (1999) Sonography in the Diagnosis of Carpal Tunnel Syndrome. *American Journal of Roentgenology*, **173**, 681-684. https://doi.org/10.2214/ajr.173.3.10470903

[36] Phalen, G.S. (1966) The Carpal-Tunnel Syndrome. Seventeen Years' Experience in Diagnosis and Treatment of Six Hundred Fifty-Four Hands. *The Journal of Bone & Joint Surgery*, **48**, 211-228. https://doi.org/10.2106/00004623-196648020-00001

[37] Scholten, R.J., Mink van der Molen, A., Uitdehaag, B.M., Bouter, L.M. and de Vet, H.C. (2007) Surgical Treatment Options for Carpal Tunnel Syndrome. *Cochrane Database of Systematic Reviews*, No. 4, CD003905. https://doi.org/10.1002/14651858.cd003905.pub3

[38] Benson, L.S., Bare, A.A., Nagle, D.J., Harder, V.S., Williams, C.S. and Visotsky, J.L. (2006) Complications of Endoscopic and Open Carpal Tunnel Release. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, **22**, 919-924.E2. https://doi.org/10.1016/j.arthro.2006.05.008

[39] Povlsen, B., Bashir, M. and Wong, C. (2018) Long-Term Results of Endoscopic Carpal Tunnel Release Compared to Open Carpal Tunnel Release. *Acta Orthopaedica Belgica*, **84**, 378-383.

[40] Bansal, A., Jain, M. and Gupta, T. (2020) Infection Rates Following Open Carpal Tunnel Release: A Systematic Review. *Journal of Hand and Microsurgery*, **12**, 145-150.

[41] Gomes, C., Fonseca, M., Santos, J.N. and Martins, F. (2021) Complications in Open Carpal Tunnel Release: Systematic Review and Meta-Analysis. *Hand Surgery and Rehabilitation*, **40**, 503-509.

[42] Chow, J.C.Y. (1989) Endoscopic Release of the Carpal Ligament: A New Technique for Carpal Tunnel Syndrome. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, **5**, 19-24. https://doi.org/10.1016/0749-8063(89)90085-6

[43] Vasiliadis, H.S., Georgoulas, P., Shrier, I., Salanti, G. and Scholten, R.J. (2014) Endoscopic Release for Carpal Tunnel Syndrome. *Cochrane Database of Systematic Reviews*, No. 1, CD008265. https://doi.org/10.1002/14651858.cd008265.pub2

[44] Michelotti, B., Romanowsky, D. and Hauck, R.M. (2014) Prospective, Randomized Evaluation of Endoscopic versus Open Carpal Tunnel Release in Bilateral Carpal Tunnel Syndrome: An Interim Analysis. *Annals of Plastic Surgery*, **73**, S157-S160. https://doi.org/10.1097/sap.0000000000000203

[45] Palmer, A.K. and Toivonen, D.A. (1999) Complications of Endoscopic and Open Carpal Tunnel Release. *The Journal of Hand Surgery*, **24**, 561-565. https://doi.org/10.1053/jhsu.1999.0561

[46] Saw, N.L.B., Jones, S., Shepstone, L., Meyer, M., Chapman, P.G. and Logan, A.M. (2003) Early Outcome and Cost-Effectiveness of Endoscopic versus Open Carpal Tunnel Release: A Randomized Prospective Trial. *Journal of Hand Surgery*, **28**, 444-449. https://doi.org/10.1016/s0266-7681(03)00097-4

[47] Agee, J.M., McCarroll, H.R., Tortosa, R.D., Berry, D.A., Szabo, R.M. and Peimer, C.A. (1992) Endoscopic Release of the Carpal Tunnel: A Randomized Prospective Multicenter Study. *The Journal of Hand Surgery*, **17**, 987-995. https://doi.org/10.1016/s0363-5023(09)91044-9

[48] Trumble, T.E., Diao, E., Abrams, R.A. and Gilbert-Anderson, M.M. (2002) Single-Portal Endoscopic Carpal Tunnel Release Compared with Open Release: A Prospective, Randomized Trial. *The Journal of Bone & Joint Surgery*, **84**, 1107-1115. https://doi.org/10.2106/00004623-200207000-00003

[49] Zuo, D., Zhou, Z., Wang, H., Liao, Y., Zheng, L., Hua, Y., *et al.* (2015) Endoscopic versus Open Carpal Tunnel Release for Idiopathic Carpal Tunnel Syndrome: A Meta-Analysis of Randomized Controlled Trials. *Journal of Orthopaedic Surgery and Research*, **10**, Article No. 12. https://doi.org/10.1186/s13018-014-0148-6

[50] Lorgelly, P.K., Dias, J.J., Bradley, M.J. and Burke, F.D. (2005) Carpal Tunnel Syndrome, the Search for a Cost-Effective Surgical Intervention: A Randomised Controlled Trial. *Annals of The Royal College of Surgeons of England*, **87**, 36-40. https://doi.org/10.1308/1478708051469

[51] Cano, L.C., Leiby, B.M., Shum, L.C., Ward, M.G. and Joseph, A.E. (2020) Clinical Results of Carpal Tunnel Release Using Ultrasound Guidance in Over 100 Patients at Two to Six Years. *Journal of Hand Surgery* (*American Volume*), **45**, 30-37.

[52] Burnham, R., Loh, E., Date, R. and Burnham, R.S. (2021) A Comparison of Ultrasound-Guided Per-Cutaneous Release and Open Carpal Tunnel Release. *Neurology Clinical Practice*, **11**, 33-39.

[53] Hobby, J.L., Venkatesh, R. and Motkur, P. (2005) The Effect of Age and Gender Upon Symptoms and Surgical Outcomes in Carpal Tunnel Syndrome. *Journal of Hand Surgery*, **30**, 599-604. https://doi.org/10.1016/j.jhsb.2005.07.005

[54] Katz, J.N., Losina, E., Amick, B.C., Fossel, A.H., Bessette, L. and Keller, R.B. (2001) Predictors of Outcomes of Carpal Tunnel Release. *Arthritis & Rheumatism*, **44**, 1184-1193. https://doi.org/10.1002/1529-0131(200105)44:5<1184::aid-anr202>3.0.co;2-a

[55] Graham, B., Peljovich, A.E., Afra, R., Cho, M.S., Gray, R., Stephenson, J., *et al.* (2016) The American Academy of Orthopaedic Surgeons Evidence-Based Clinical Practice Guideline on: Management of Carpal Tunnel Syndrome. *Journal of Bone and Joint Surgery*, **98**, 1750-1754. https://doi.org/10.2106/jbjs.16.00719

[56] Westenberg, R.F., Guitton, T.G., Ring, D., Vagner, G., Osterman, A.L. and Chen, N.C. (2012) The Incidence of Revision Carpal Tunnel Release and Predictors of Success.

Journal of Hand Surgery (*American Volume*), **37**, 1159-1164.

[57] Shi, Q. and MacDermid, J.C. (2011) Is Surgical Intervention More Effective than Non-Surgical Treatment for Carpal Tunnel Syndrome? A Systematic Review. *Journal of Orthopaedic Surgery and Research*, **6**, Article No. 17. https://doi.org/10.1186/1749-799x-6-17

[58] Chen, L., Duan, X., Huang, X., Lv, J., Peng, K. and Xiang, Z. (2014) Effectiveness and Safety of Endoscopic versus Open Carpal Tunnel Decompression. *Archives of Orthopaedic and Trauma Surgery*, **134**, 585-593. https://doi.org/10.1007/s00402-013-1898-z

[59] Hubbard, Z.S., Law, T.Y., Rosas, S., Jernigan, S.C. and Chim, H. (2018) Economic Benefit of Carpal Tunnel Release in the Medicare Patient Population. *Neurosurg Focus*, **44**, E16.

[60] Duncan, S.F., Kakinoki, R., Kihara, H. and Tsai, T.M. (2012) The Learning Curve for Endoscopic Carpal Tunnel Release. *Journal of Hand and Microsurgery*, **4**, 59-63.

[61] Tadisina, K.K., Chopra, K., Tandon, R., Elahi, M., Elbarbary, A. and Singh, D.P. (2013) A Comprehensive Review of Secondary Carpal Tunnel Release. *Archives of Plastic Surgery*, **40**, 397-404.