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Role of Ultrasound in Diagnosis of Carpal Tunnel Syndrome: Review Article

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ABSTRACT

Background: Carpal tunnel syndrome (CTS) is the most prevalent peripheral entrapment neuropathy, affecting 3.8% of the population, particularly middle-aged women. It results from compression of the median nerve in the carpal tunnel due to mechanical, vascular, or ischemic factors. Traditional diagnosis relies on clinical evaluation and electrodiagnostic studies, but these can be invasive and uncomfortable. Recent advancements in ultrasound (US) technology provide a non-invasive, dynamic, and cost-effective imaging modality for CTS evaluation, enabling structural and functional assessment of the median nerve and surrounding tissues.

Objective: This review aimed to provide an in-depth analysis of the role of ultrasound in the diagnosis of CTS, highlighting anatomical, epidemiological, and pathophysiological features. It further explored static, dynamic, and elastographic ultrasound techniques, comparing their diagnostic performance and clinical utility with conventional methods.

Methods: A thorough literature review was performed utilizing PubMed, Scopus, and Web of Science databases, employing the search terms: Carpal tunnel syndrome, ultrasound, median nerve, elastography, speckle tracking, and nerve entrapment. The selection criteria included studies published in English between 2000 and 2024 that presented original research or comprehensive reviews related to the use of ultrasound in the evaluation of carpal tunnel syndrome. Articles exclusively addressing surgical outcomes or employing alternative imaging techniques were systematically excluded.

Conclusion: Ultrasound is a valuable diagnostic tool for CTS, offering real-time, high-resolution imaging and quantitative assessment. Techniques such as cross-sectional area analysis, elastography, and speckle tracking that enhance diagnostic accuracy. Future research should standardize thresholds, refine elastographic tools, and integrate 4D imaging for improved evaluation and monitoring.

Keywords: Carpal tunnel syndrome, Median nerve, Cross-sectional area, Ultrasound, Speckle tracking, Elastography.

INTRODUCTION

Carpal tunnel syndrome (CTS) represents the most prevalent form of peripheral compressive neuropathy responsible for approximately 90% of such conditions. It encompasses a spectrum of motor, sensory, and autonomic disturbances, often presenting clinically with intrinsic hand muscle weakness, diminished grip strength, pain, paresthesia, and impaired thermoregulatory function in the wrist and hand. CTS affects an estimated 3.8% of the general population, contributing significantly to functional disability, occupational absenteeism, and an annual economic impact exceeding $2 billion [1].

Pain, and tingling as well as numbness, in the affected hand are classic symptoms of CTS, which are a frequent medical ailment. When the median nerve in the wrist is compressed, it leads to symptoms known as CTS, which is characterized by a loss of strength or numbness in the afflicted area. CTS affects at least 3.8% of those who have hand discomfort, numbness, or tingling [2].

Conventionally, the diagnosis of CTS is primarily based on clinical history and physical examination, with electrodiagnostic studies frequently employed to confirm the diagnosis. While these studies demonstrate a sensitivity of approximately 85% and a specificity of 95% for CTS detection. They are invasive in nature and may cause significant discomfort for patients. In recent years, advancements in ultrasound (US) technology have enhanced both image resolution and cost-effectiveness, fostering wider utilization of US in the assessment of nerve entrapment syndromes and prompting a substantial increase in related scientific publications [3]. Therefore, the goal of this review was to provide an in-depth analysis of the role of ultrasound in the diagnosis of CTS, highlighting anatomical, epidemiological, and pathophysiological features. It further explored static, dynamic, and elastographic ultrasound techniques, comparing their diagnostic performance and clinical utility with conventional methods.

Anatomical consideration: CTS symptoms vary due to anatomical differences in nerves and structures. A bifid median nerve appears in 1–3.3% of cases, often with a persistent median artery. Variations in the thenar motor branch include extraligamentous (46%), subligamentous (31%), and transligamentous (23%) types. The palmar cutaneous branch may follow different paths, occasionally crossing the transverse ligament. Rarely, the ulnar nerve runs within the tunnel. Wrist movements alter tunnel size and pressure, influenced by the transverse carpal ligament's anatomy and position [4].

Epidemiology and risk factors of CTS: CTS is the most common peripheral nerve entrapment condition, affecting 3.8% of people with hand discomfort, numbness, and tingling. The incidence rate for CTS is higher in women (9.2%) relative to men (6%) and is

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most common in individuals aged 40-60. The occurrence is especially high in regions like the UK, with reports ranging from 7%-16%. Work-related musculoskeletal disorders, especially in industries like fish processing, significantly contribute to CTS cases [5].

While CTS is often idiopathic, several risk factors contribute to its development. These include extrinsic factors (e.g., wrist flexion and exposure to vibration) and intrinsic factors (e.g., tumors or fractures). Medical risk factors such as obesity, pregnancy, diabetes, and hypothyroidism also increase susceptibility. Diabetic patients, particularly those with neuropathy, are at a higher risk of developing CTS, with incidence rates rising significantly in these individuals [6].

Pathophysiology and stages of CTS: CTS is the most common peripheral nerve entrapment condition, causing numbness or weakness in the affected area. It affects around 3.8% of individuals experiencing hand pain, with a higher prevalence among women (9.2%) compared to men (6%). CTS is especially common among adults aged 40-60 years and is more prevalent in the United Kingdom (7%-16%) compared to the United States (5%). Occupations with repetitive hand movements, such as fish processing, report even higher CTS rates, underlining the need for effective management strategies [7].

Several risk factors contribute to CTS, including prolonged wrist flexion or extension, repetitive use of flexor muscles, and vibration exposure. Medical risk factors are categorized into extrinsic (e.g., pregnancy and obesity), intrinsic (e.g., nerve tumors and fractures), and neuropathic (e.g., diabetes and alcoholism) factors. Diabetes significantly increases CTS risk, with higher incidence rates in diabetic patients (30%) compared to non-diabetic individuals (14%). Additionally, environmental factors like pregnancy and menopause also contribute to the increased prevalence of CTS [5].

Ultrasound evaluation and diagnosis of CTS: Medical exams and electrophysiological testing are used to diagnose idiopathic CTS, which is the most common cause of related symptoms. In the United States, 276 new CTS cases are reported annually. Women have a higher incidence rate (9.2%) compared to men (6%). CTS affects individuals of all ages but is more prevalent among the middle-aged and elderly. Compared to the U.S. (5%), CTS rates are higher in the United Kingdom and other European countries, ranging between 7% and 16%. A primary etiological factor in CTS is the compression of the median nerve within the confines of the carpal tunnel, typically resulting from mechanical stress, elevated intracarpal pressure, or compromised vascular perfusion [8]. The carpal tunnel pressure, typically between 2–10 mmHg, increases significantly with wrist movement—more than tenfold during extension and eightfold during flexion. CTS typically presents with pain and paresthesia distributed along the course of the median nerve, involving the palmar aspects of the thumb, index finger, middle finger, and the radial half of the ring finger. In contrast, sensory innervation of the little finger and the ulnar half of the ring finger is mediated by the ulnar nerve [9].

Ultrasound is increasingly used in diagnosing CTS due to its ability to capture high-resolution, dynamic images. It provides a multi-layered view of tissues without ionizing radiation and can be conducted using portable devices. Technological advances, including high-frequency miniature transducers, have improved imaging quality. These enhancements allow regular ultrasound evaluation of the wrist, hand, and carpal tunnel. The method is also cost-effective, supports monitoring over time, and can assess the effectiveness of treatments [10].

Table (1): Comparison of Ultrasound vs nerve conduction studies (NCS) and Electromyography in diagnosing CTS [8].

Parameter	Ultrasound	NCS & Electromyography
Pooled Sensitivity	0.80 (95% CI: 0.73–0.88)	0.89 (95% CI: 0.84–0.95)
Pooled Specificity	0.90 (95% CI: 0.83–0.96)	0.77 (95% CI: 0.64–0.90)
Patient Comfort	High (non-invasive, painless)	Low (can be painful)
Cost	Lower	Higher
Time Required	~30–90 seconds	~30 minutes
Ability to Visualize Anatomy	Yes (direct visualization of nerve and surrounding structures)	No
False Negatives	Varies (potentially higher in some studies)	Typically 10–15% (up to 20% reported)
Preferred by Patients	Yes	Less preferred
Severity Grading	Not reliable	Reliable (based on DML, DSL, SCV, etc.)
Utility in Atypical Cases	Limited	High (better for polyneuropathy, radiculopathy, etc.)
Observer Dependence	High (results vary by operator skill)	Less dependent

NCS: Nerve Conduction Studies, CI: Confidence Interval, DML: Distal Motor Latency, DSL: Distal Sensory Latency, SCV: Sensory Conduction Velocity.

To image nerves effectively, a linear probe with a frequency of 12–14 MHz and resolution below 0.3 mm is used. For imaging deeper nerves or in overweight patients, a convex probe is preferred. Gelous agar spacers enhance nerve visualization by improving probe contact and aligning the nerve with the ultrasound beam. This is particularly useful for small nerves in the wrist [11].

During sonographic exams for CTS, patients' forearms are rested on a flat surface with wrists relaxed and fingers slightly bent. The median nerve, often compressed by surrounding tissues, appears swollen proximally and sometimes distally while shrinking at the compression site. This creates an hourglass shape. The cross-sectional area (CSA) of the median nerve, especially in the proximal carpal tunnel, is the primary ultrasound marker for CTS diagnosis. Identifying the nerve's CSA requires tracing the epineurium perpendicularly to its long axis [12].

The CSA values for diagnosing CTS vary between 9 and 14 mm². Sensitivity ranges from 57% to 94% and specificity from 57% to 98%. Meta-analysis reported ultrasound sensitivity and specificity at 76% and 86%, respectively, with an overall diagnostic accuracy of 82.2%. Factors like race, age, sex, and anatomical differences influence CSA values. A more recent diagnostic approach involves assessing the difference in CSA of the median nerve between the carpal tunnel and the level of the pronator quadratus muscle, commonly referred to as delta CSA. Alternatively, comparing the CSA at the wrist to that at the forearm has also proven useful; a wrist-to-forearm CSA ratio of 1.4 or greater has been reported to yield 100% sensitivity in identifying carpal tunnel syndrome [13].

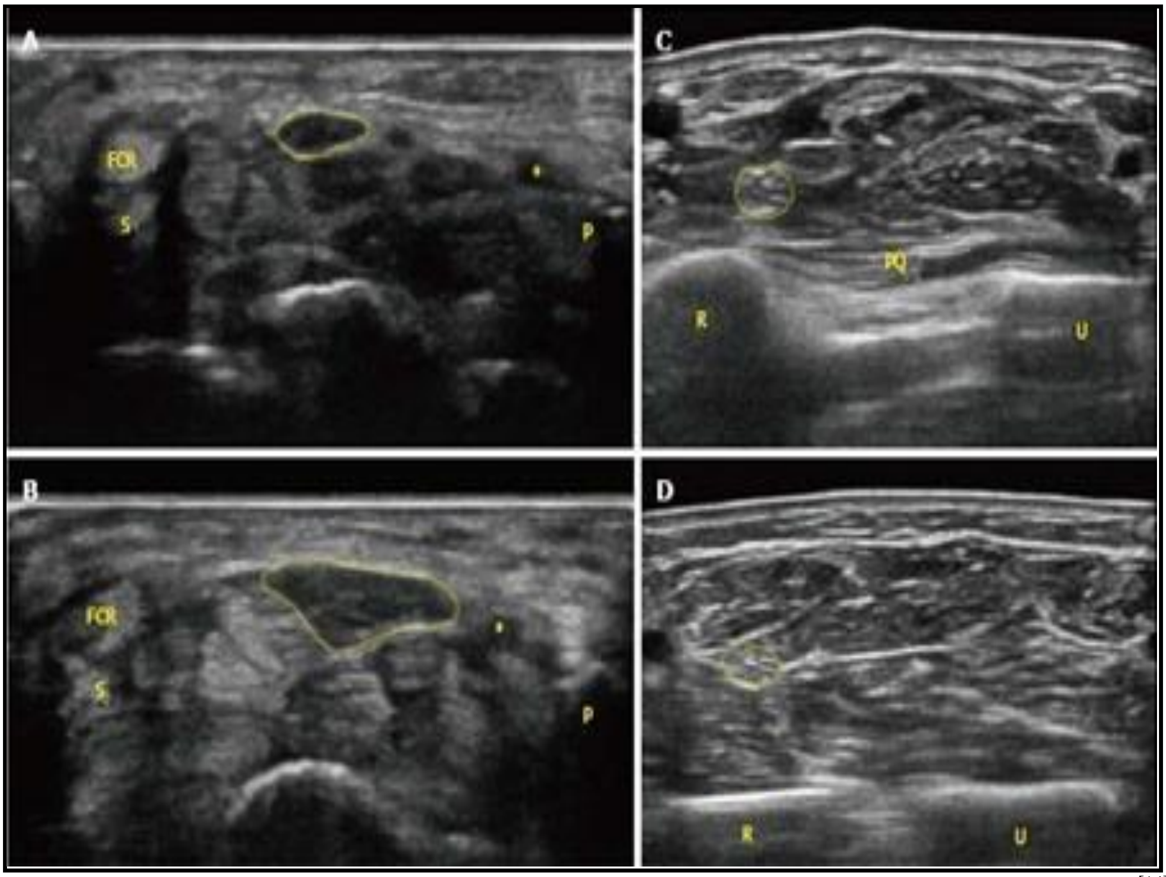

Figure (1): Carpal tunnel syndrome: transverse pictures in a seventy-nine years old case [14].

Static Cross-Sectional Ultrasound in the evaluation of CTS: In the 1990s, static ultrasound imaging became a reliable method for detecting various pathologies related to CTS, including thickening of the flexor tendons and flexor retinaculum, synovial proliferation, and swelling of the median nerve in the carpal tunnel. Ultrasound also demonstrated restricted movement of the median nerve with different wrist and finger positions in CTS patients. Cross-sectional imaging revealed the median nerve's honeycomb structure, surrounded by the hyperechoic epineurium, which allows for detailed observation [15].

The cross-sectional area of the median nerve serves as a fundamental ultrasonographic marker in the diagnosis of CTS. In response to compression, the nerve typically exhibits a reduction in volume at the site of entrapment, accompanied by proximal—and occasionally distal—swelling. Visualization of the median nerve is generally more accessible at the proximal portion of the carpal tunnel. However, its delineation becomes more challenging at the middle or distal segments owing to its deeper anatomical position

The cross-sectional area of the median nerve at the proximal carpal tunnel is the most frequently reported ultrasound parameter for diagnosing CTS. Studies have shown that measuring the median nerve's cross-sectional area at the wrist has level A evidence supporting its use in CTS diagnosis. However, the reported cutoff value for the cross-sectional area varies widely, from 9 to 14 mm², and diagnostic sensitivity and specificity range from 57–94% and 57–98%, respectively [18].

Optimal visualization of the median nerve along its course from the proximal to the distal carpal tunnel necessitates the use of a high-resolution ultrasound system coupled with expert sonographic technique. Several anatomical and technical factors—such as the natural curvature of the palmar surface, skin thickness, subcutaneous adipose tissue, and the nerve's and the overlying flexor retinaculum. In cases of CTS, the nerve frequently assumes an hourglass configuration, characterized by pronounced enlargement at both tunnel extremities [16].

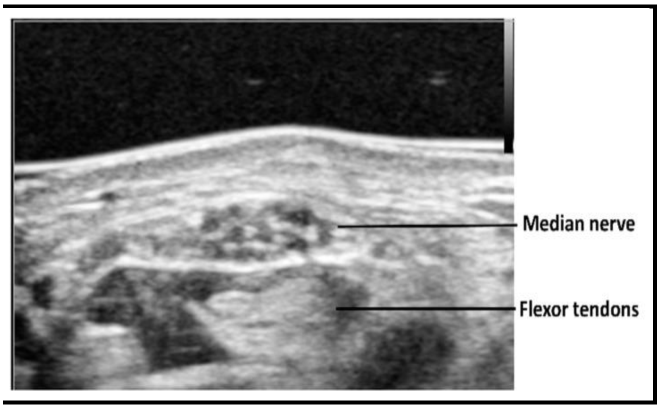

Figure (2): A typical ultrasound image of median nerve at proximal carpal tunnel [17].

relatively deep position—can hinder image clarity, particularly in the mid to distal tunnel segments. To enhance acoustic transmission and improve image quality, the application of an acoustic coupler between the transducer and the skin is recommended, as it facilitates better contact and superior delineation of anatomical structures [19].

The wrist-to-forearm CSA ratio serves as a valuable adjunctive measure for identifying focal median nerve enlargement. This approach includes evaluating the CSA at the wrist and at a site 12 cm up the forearm. A ratio surpassing 1.4 has demonstrated excellent diagnostic performance, achieving complete sensitivity in CTS detection. This metric is particularly beneficial in unilateral CTS, where the unaffected limb can act as a reference standard for comparative assessment [20].

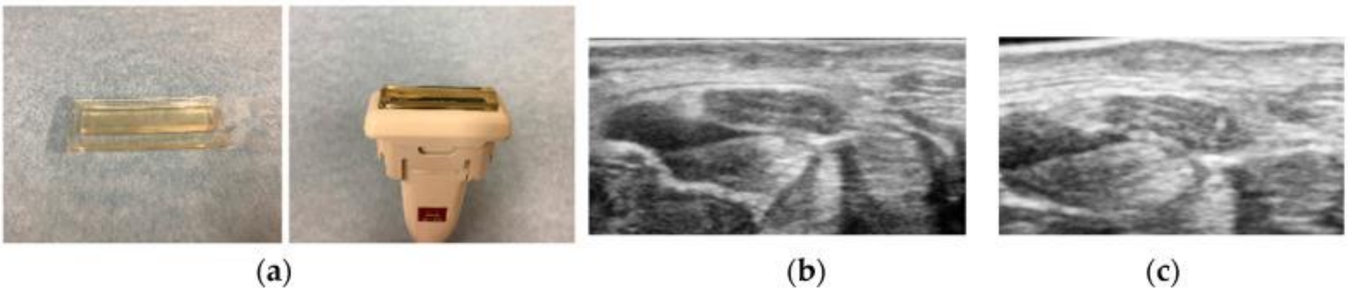

Figure (3): Use of acoustic coupler for the uneven skin surface. (a) Acoustic coupler, (b) An example image of median nerve without acoustic coupler, (c) An example image of median nerve with acoustic coupler. Fascicular pattern can be visualized with the acoustic coupler [17].

Dynamic Ultrasound for CTS assessment:

Within the carpal tunnel, the subsynovial connective tissue (SSCT) functions to interconnect the flexor tendons and anchors them to the median nerve. It helps reduce friction during tendon movement and maintains blood flow.

In idiopathic CTS patients, the SSCT shows collagen degeneration, fibrosis, edema, vascular thickening, and thrombus formation, but no inflammation. These alterations diminish the viscoelastic properties of the tissue and may influence the dynamics and configuration of the median nerve during tendon motion. Recently, mechanical stress on the median nerve during finger and wrist movements has emerged as a potential contributing factor to CTS [21].

To examine median nerve morphology during tendon motion in CTS patients, cross-sectional dynamic ultrasound analysis was used. The transducer is placed at the proximal carpal tunnel, and the subject performs finger flexion and extension while images are recorded. Evaluation includes parameters such as nerve cross-sectional area, perimeter, aspect ratio, and circularity. Circularity is defined mathematically and is used to evaluate shape complexity. Measurements are compared between CTS patients and healthy subjects during both flexion and extension movements **[17]**.

In both positions, CTS patients showed significant differences in nerve area, circumference, and circularity compared to healthy subjects. During finger flexion, healthy subjects showed decreased aspect ratio and increased circularity, indicating flattening of the nerve.

Conversely, CTS patients showed increased aspect ratio and decreased circularity, suggesting the nerve becomes more circular. These findings indicate distinct deformation patterns between healthy and CTS-affected nerves during finger movements **[22]**.

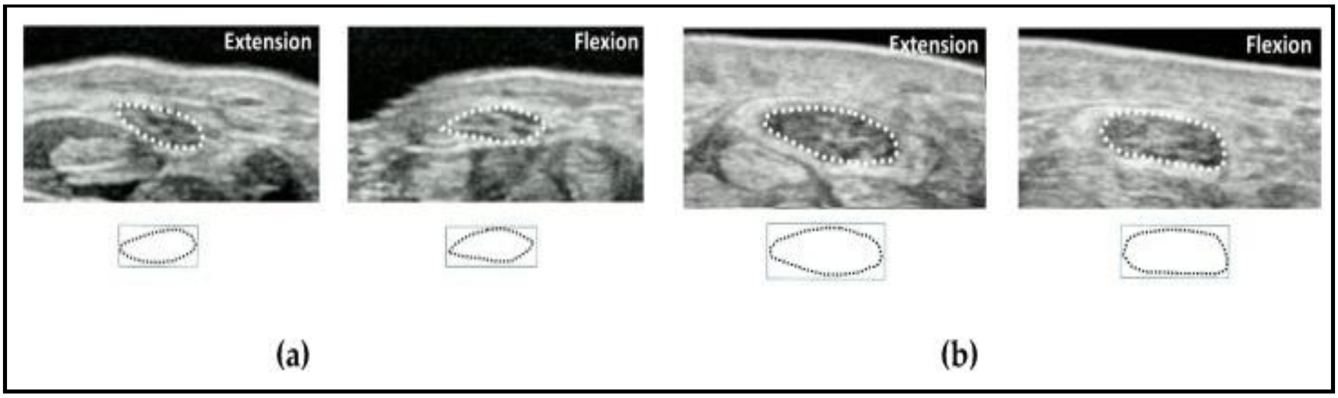

Figure (4): An example image of the median nerve shape in finger extension and flexion positions. (a) Healthy subjects, (b) carpal tunnel syndrome (CTS)patients [17].

These observations indicate that, in healthy individuals, the median nerve undergoes morphological deformation in response to tendon displacement during finger movement. Alterations in its cross-sectional area are interpreted as indicative of the nerve's longitudinal motion. Conversely, in patients with CTS, the extent of such morphological adaptations in response to finger movement is markedly reduced. Dynamic ultrasound serves as a valuable tool in detecting these pathological alterations in median nerve mobility and flexibility associated with CTS [17].

Ultrasound Elastography for CTS Assessment: Ultrasound elastography is a non-invasive technique used to assess tissue stiffness, primarily through two modalities: Strain imaging and shear wave imaging. Strain imaging quantifies tissue deformation resulting from externally applied compression, whereas shear wave imaging evaluates displacement occurring parallel to the direction of induced stress. In strain imaging, deformation is calculated by comparing radiofrequency data acquired before and after compression. In contrast, shear wave imaging applies dynamic mechanical stress to estimate tissue elasticity based on the propagation velocity of shear waves through the tissue. These methods are straightforward in uniform tissues like liver or breast but complex in structures like the carpal tunnel due to varied tissue properties and directional differences in ultrasound wave.

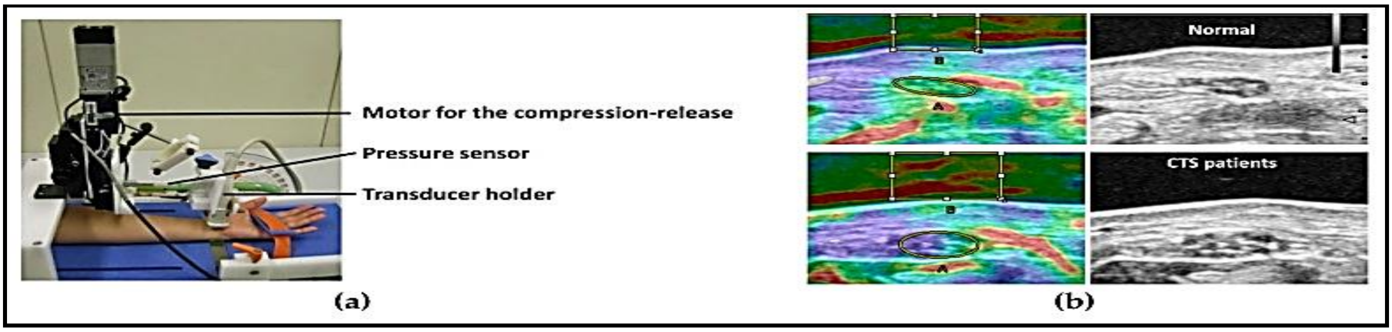

Figure (5): Pressure-monitor ultrasound system for the quantitative assessment of median nerve strain. (a) Pressure-monitor ultrasound system, (b) elastographic images of CTS patients and normal controls. Upper row shows the image of a normal subject. Lower row shows the image of a CTS patient [17].

Shear wave elastography investigations have demonstrated notably reduced shear wave velocity and elevated shear modulus in individuals with CTS compared to healthy controls. This technique quantifies tissue stiffness by measuring the velocity of shear waves, which is intrinsically linked to tissue elasticity. In one study, the shear modulus in CTS patients was reported as 66.7 kPa, whereas controls exhibited a value of 32.0 kPa; a diagnostic cutoff of 40.4 kPa yielded an accuracy of 91.7%. Moreover, shear wave elastography has shown promise in approximating carpal tunnel pressure by evaluating changes in tendon shear wave velocity in cadaveric models, where a linear relationship between shear wave speed and pressure was observed [26].

Both strain imaging and shear wave imaging present inherent limitations. Their diagnostic accuracy can be affected by the quality of the push beam and the reliability of displacement estimation, posing challenges in evaluating tissues located beneath rigid anatomical structures. Strain imaging is sensitive to applied force, requiring consistent pressure by the operator. Shear wave imaging may be inaccurate for deeper structures. It is advised not to compare measurements across different systems, and threshold values should be system- and transducer-specific in clinical practice [27].

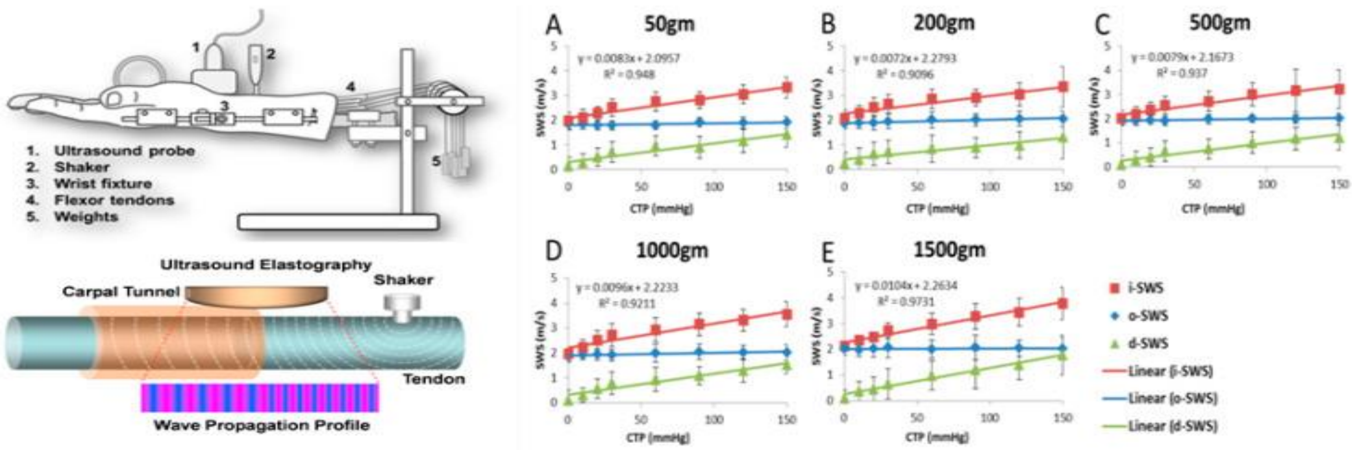

Figure (6): Shear wave elastography for the estimation of carpal tunnel pressure. Left top and bottom figures show the experimental setting and ultrasound elastography measure of third digit FDS tendon. (A–E) demonstrate the wave speed of the tendon within and outside carpal tunnel region. Reprinted from [28].

Chronic nerve compression is known to induce intra-neural edema, which is subsequently followed by peri-neural thickening and structural alterations of nerve fibers, including Wallerian degeneration. Clinically, such conditions often manifest as nerve swelling. However, ultrasound elastography has enabled the quantitative assessment of tissue elasticity alterations. The stiffness metrics derived from elastographic imaging are regarded as clinical indicators that correlate with underlying histopathological changes in the median nerve and adjacent soft tissue structures [29].

Speckle tracking for CTS Assessment: Speckle tracking is an ultrasound-based technique that utilizes pattern recognition algorithms to analyze speckle distributions within sonographic images.

A reference speckle pattern is established in the initial frame, and the corresponding region with the highest pattern similarity is located in subsequent frames. This approach facilitates frame-by-frame quantification of tissue displacement, including both velocity and directional vectors. Through reconstruction of speckle motion and deformation, dynamic analysis of tissue and fluid movement becomes possible. The clinical applicability of this technique has been well established, particularly in the field of cardiac imaging [17].

This technique was adapted to assess shear stress within the flexor tendon and the adjacent subsynovial connective tissue (SSCT) during finger motion within the carpal tunnel. In both healthy individuals and patients with CTS, the ultrasound transducer was aligned longitudinally with the direction of tendon gliding at the proximal portion of the carpal tunnel. A long-axis view of the flexor tendon was captured throughout the finger flexion-extension cycle, defined as one complete sequence of extension–flexion–extension. Tracking markers were placed on both the tendon and the SSCT, specifically at the tendon margins, allowing measurement of displacement distances along the longitudinal axis [30].

The shear index was determined using the formula: [(tendon displacement − SSCT displacement) / tendon displacement] × 100 (%). Findings revealed a notably higher shear index in individuals with CTS (47.8%) compared to healthy controls (36.3%), suggesting elevated shear stress in CTS.

Given the reduced viscoelasticity of the SSCT observed in CTS patients, the assessment of tendon and SSCT shear indices via speckle tracking offers a non-invasive method for evaluating fibrotic changes within the carpal tunnel. This may help correlates physiological changes with treatment outcomes like stretching or steroid injections [31].

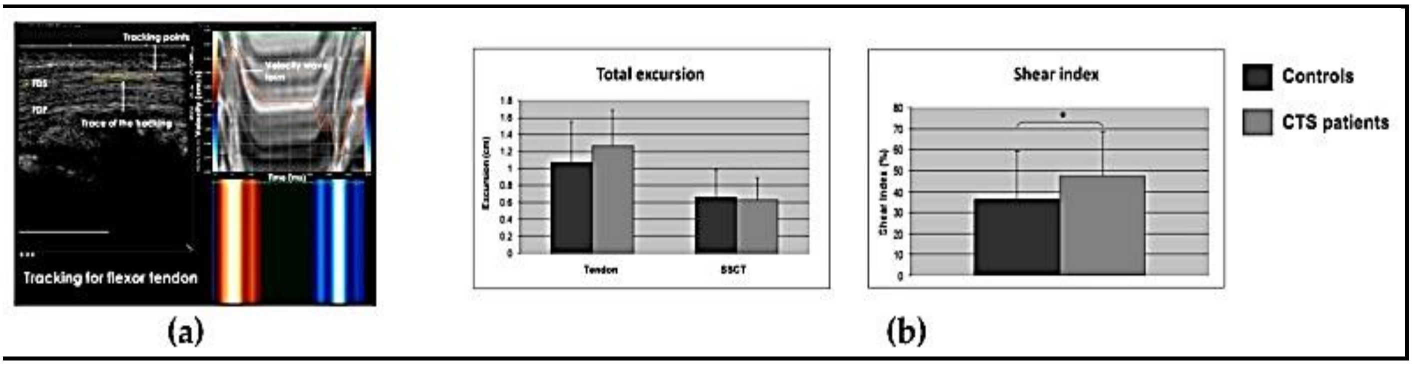

Figure (7): Speckle tracking ultrasound for the assessment of CTS. (a) An example image of speckle tracking, (b) tendon and subsynovial connective tissue excursions, and shear index [17].

Speckle tracking offers a distinct advantage over Doppler imaging by enabling the assessment of tissue kinematics independent of the insonation angle relative to the ultrasound transducer. This technique holds promise in distinguishing shear stress variations between the flexor tendon and its surrounding structures in patients with CTS compared to healthy individuals. Nonetheless, accurate tracking of the flexor tendon—given its complex three-dimensional motion—necessitates precise transducer alignment along the tendon's gliding axis. Despite its potential, several technical limitations remain before speckle tracking can be fully integrated into routine CTS evaluation, particularly in the absence of high-resolution, real-time, 3D dynamic (4D) imaging capabilities in clinical settings [17].

CONCLUSION

Ultrasound is a valuable diagnostic tool for CTS, offering real-time, high-resolution imaging and quantitative assessment. Techniques such as cross-sectional area analysis, elastography, and speckle tracking enhance diagnostic accuracy. Future research should standardize thresholds, refine elastographic tools, and integrate 4D imaging for improved evaluation and monitoring.

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