Sonographic Diagnosis of Carpal Tunnel Syndrome

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KEYWORDS

• Carpal tunnel syndrome • Sonography • Diagnostic ultrasound • Median nerve • Hand surgery

KEY POINTS

- Ultrasonographic diagnosis of carpal tunnel syndrome is mainly based on the assessment of the nerve cross-sectional area.
- Diagnostic ultrasound provides the ability to rule out secondary causes of nerve compression. However, a reliable assessment of the disease severity is not possible.
- Electrodiagnostic testing is based on the nerve's functional parameters. It therefore also allows estimation of the severity of the disease. It cannot be used to differentiate between causes of compression.
- Both diagnostic methods complement each other. In case of limitation to only one diagnostic method, the disadvantages of the specific technique become particularly noticeable postoperatively, especially when patients complain of persistent symptoms.
- Postoperative sonography does not provide functional parameters and therefore no clear comparison to preoperative measurements, while NCS does not provide information on the cause of persistent complaints.

Video content accompanies this article at http://www.hand.theclinics.com.

INTRODUCTION

Carpal tunnel syndrome (CTS) is the most common compression neuropathy in humans and occurs idiopathically in 50% of cases. Patients aged between 40 and 60 years and women are significantly more often affected, in about 50% of cases, the disease occurs bilaterally.[1–5] The causes of the disease remain unclear. There is probably a multifactorial etiology. Possible causes include anatomic changes,[6–9] general disorders, increased strain, and also repetitive activities.[10,11] Secondary compression of the median nerve by flexor tendon synovitis also appears to have pathologic value.[12–15]

The diagnosis of CTS is based on typical clinical symptoms. Additional examinations are only used to confirm the clinical suspicion and complement each other.[16] Clinical symptoms usually consist of nocturnal or early morning tingling paresthesias in the distal supply area of the median nerve, from which the palmar cutaneous branch is typically excluded. Load-related and movement-related complaints are also possible and are usually associated with a flexed (Phalen's test) or extended position (reverse Phalen's test) of the wrist, in which the cross-sectional area of the carpal canal is additionally reduced. Advanced stages show a reduction of peripheral sensitivity and atrophy of the thenar prominence (**Fig. 1**).

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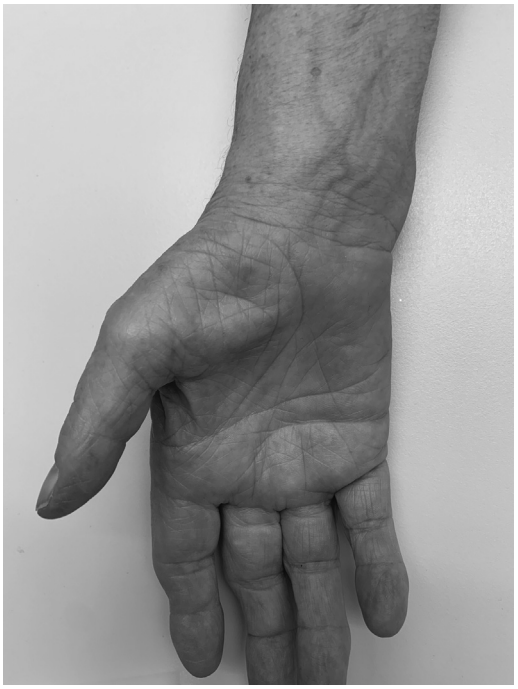

Fig. 1. Advanced carpal tunnel syndrome with atrophy of the thenar muscles.

In addition to confirming the clinical diagnosis, the additional apparative diagnostics also allow the assessment of the severity of the disease and the reliable differentiation from other, usually proximally localized compressions of the median nerve, which can clinically mimic CTS. However, legal aspects also play an important role, even if they usually only come into play in the event of postoperative complications or a lack of regeneration after decompression of the nerve.

Electrodiagnostic testing still represents the gold standard in confirmatory diagnostics. It provides information about the severity of the lesion (demyelinating vs axonal) and, when used correctly, can exclude other diseases that mimic CTS (eg, polyneuropathy). In cases of persistent postoperative symptoms, it helps decisively in objectifying a worsening of findings. The determination of the distal motor latency of the median nerve (in comparison to the ulnar nerve) as well as the comparative determination of the sensory nerve conduction velocity of the median nerve to the middle finger and the ulnar nerve to the small finger are routinely performed. The sensitivity and specificity of this method are 89% and 98%, respectively.[17] Specific conduction techniques can increase the sensitivity and specificity to 97.5% each.[18]

ESSENTIALS OF SONOGRAPHIC DIAGNOSTICS

Nerve compression results in a characteristic cascade of pathophysiologic changes consisting of endoneural edema, demyelination, axon degeneration, inflammation, fibrosis, resprouting of axons, and remyelination.[19] Many of these processes occur at the microcellular level and can only be objectified indirectly. However, some of these changes can be visualized quantitatively and semiquantitatively using appropriate imaging techniques.

Semiquantitative Criteria of Nerve Compression

Microvascular nerve perfusion

A typical hallmark of compression-related neuronal changes is alteration in the nerves microvascular blood supply, which have also been described for CTS.[20–31] In recent years, they have received attention in the sonographic diagnosis of CTS as a semiquantitative criterion of nerve compression (**Fig. 2**).

Nerve Mobility

Compressed nerve structures change their mobility, which can be objectified in both long-axis and short-axis views (Videos 1 and 2). These changes can be dynamically visualized with sonography and evaluated as a semiquantitative feature of compression of the median nerve in the carpal tunnel (Videos 3 and 4).[32–38] They are also relevant to the postoperative assessment,[39] where they can distinguish well between local (persistent) constrictions and adhesions.

Nerve Environment

Changes in the nerve environment can also have an influence on compression. The lower the elasticity of the environment, the less the nerve can yield to external influences. Ultrasound devices nowadays offer the possibility of elastography to measure this tissue elasticity and can thus semiquantitatively determine the compression effect on the nerve in terms of a color-coded mapping.[40–46]

Echogenicity

Another sonographic criterion for nerve compression is the change in the nerve echotexture.[47,48] Usually, a healthy nerve has a honeycomb-like echotexture resulting from the separation of the hypoechoic fascicles by the hyperechoic perineurium.[48] In case of mechanical compression, an edematous thickening of the hypoechoic fascicles occurs with a simultaneous suppression of the perifascicular parts, which causes transformation

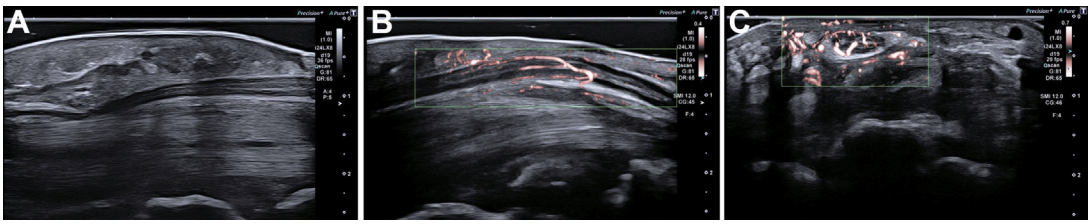

Fig. 2. (*A*) Short-segment compression of the median nerve in the carpal tunnel (long-axis view, B-mode). (*B*) Perineural and epineural hypervascularity of the median nerve at the site of compression (long-axis view, superb microvascular imaging). (*C*) Perineural and epineural hypervascularity of the median nerve at the site of compression (short-axis view, superb microvascular imaging).

of the typical honeycomb structure of the nerve into a predominantly hypoechoic pattern (Fig. 3).

Quantitative Criteria of Nerve Compression

Nerve thickness

Because of its possibility of quantitative assessment, thickening of the perineurium and endoneurium and thus of the entire nerve is probably the most relevant criterion of nerve compression on ultrasonography.[19,49–51] Also referred to as pseudoneuroma, it is located prestenotically[19] and can be localized and quantified by imaging techniques such as MRI[52] or sonography.[53] Their extent correlates with the presence of axonal damage.[49]

SONOGRAPHY OF CTS—NOW AND THEN

The sonographic diagnosis of CTS originated from comparative MR examinations between healthy subjects and electrophysiologically verified patients. Mezgarzadeh and colleagues were able to demonstrate typical changes consisting of swelling of the nerve proximal to the carpal tunnel, a flattening in the distal carpal tunnel, and an increased palmar flexion of the transverse carpal ligament.[52,54] They were applied to ultrasonography a few years later[53] and supplemented (Box 1).[55]

Preliminary studies focused on the extent of the prestenotic swelling, called pseudoneuroma, which in most publications was assumed to be located at the carpal tunnel entrance. Comparative studies between the pathologically increased CSA in patients with electrophysiologically verified CTS and the CSA of healthy subjects were intended to establish a reference value for the diagnosis of CTS. Comparisons between nerve CSA at the carpal tunnel entrance, which was considered to be located at the pisiform bone, and electrophysiologic parameters were used to determine the severity of the disease, but could hardly meet the expectations, since the cut-offs between 6.5 mm^2 and 15 mm^2 showed a high variability and therefore only a moderate correlation between sonographic and electrophysiologic findings.

The reasons for the poor correlation between nerve conduction studies (NCS) and a single sonographic cut-off value are partly proven and partly speculative:

1. Many of the existing studies are subject to a bias, as electrodiagnostic testing is considered to be the diagnostic gold standard. The patient population filtered in this way also contains false-positive and excludes false-negative cases that might have been negative or positive

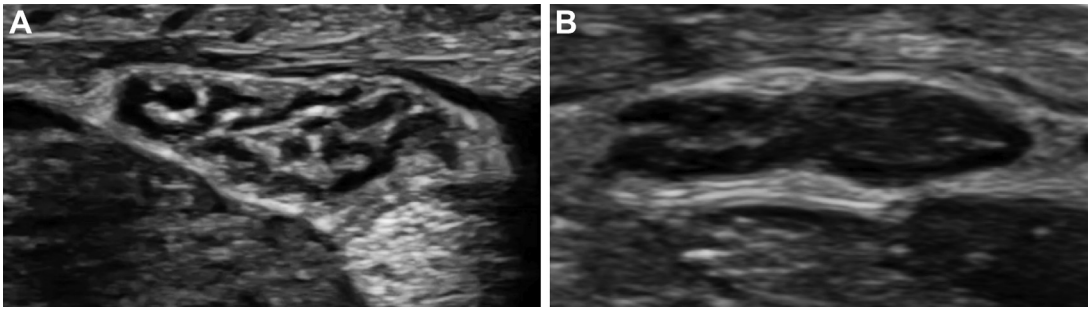

Fig. 3. (*A*) Median nerve (short-axis view, B-mode). Normal honeycomb-like echotexture and echogenicity. (*B*) Median nerve (short-axis view, B-mode). Compression-related hypoechoic alteration of echogenicity and hyperechoic rim (perineurium).

Box 1
Sonographic criteria of carpal tunnel syndrome

Sonographic Criteria | Buchberger et al. 1991

- Swelling of the median nerve at the entrance of the carpal tunnel
- Flattening of the median nerve in the distal carpal tunnel
- Increased palmar flexion of the transverse carpal ligament

Extended Sonographic Criteria | Buchberger et al. 1992, Beekman et al. 2003

- Significant increase in cross-sectional area at the level of the pisiform bone and, to a lesser extent, at the level of the hamate
- Significant increase in cross-sectional area at the level of the pisiform bone compared to the cross-sectional area at the level of the distal radius (swelling ratio)
- Significant increase in flattening ratio at the level of the hook of the hamate
- Significant palmar bowing of the flexor retinaculum

in ultrasound diagnostics. The diagnostic potential of sonography is thereby attenuated. Studies investigating patients with clinical symptoms of CTS and negative NCS seem to better reflect the potential of sonography.[56–61] The same could be assumed for studies using the postoperative outcome as a parameter for the presence of CTS.

2. Apart from methodological differences in study design, different compression levels within the carpal tunnel must be taken into account. Although many studies target the pseudoneuroma at the carpal tunnel inlet, a more proximal or distal compression of the nerve is also possible, as a positive Tinel's sign may be located not only at the carpal tunnel entrance but also in the distal forearm or at the carpal tunnel outlet.
3. The distance between the greatest extent of the nerve swelling and the exact location of the compression, and whether that distance represents a constant, is unclear. It must be assumed that individual factors such as gender,[62,63] origin (**Table 1**), and age[64–67] also play a substantial role. In the same way that age-specific normal values are used in electrodiagnostic testing, the potential to form a pseudoneuroma could also correlate with the patient's age or even with secondary disorders.[68]

Fowler and colleagues performed a meta-analysis comparing the sensitivities and specificities according to different reference standards. Depending on the reference standard used (clinical diagnosis, NCS, and composite), the sensitivities and specificities ranged between 77.3%, 80.2%, and 77.6%, and 92.8%, 78.7%, and 86.85%, respectively.[69] In 2008, Hobson-Webb et al. proposed the use of a wrist-to-forearm ratio, reflecting a comparison of the prestenotic swelling at the level of the wrist and a proximal reference value at the level of the forearm.[70] This method has become widely accepted and has also been used with other locations for reference values (**Table 2**).[71–73] From the authors' point of view, this procedure is recommended to be used in addition to a single cut-off value, especially if there are borderline findings in CSA at the level of the pseudoneuroma. The use of a ratio can increase the sensitivity to values between 93.5% and 99% with a specificity of up to 100%.[71,74] Furthermore, this strategy allows the identification of other pathologies such as multifocal acquired demyelinating sensory and motor neuropathy (MADSAM) (**Fig. 4**).

TECHNICAL ASPECTS AND ULTRASOUND EXAMINATION

Sonographic examination of the median nerve is usually performed on a seated patient. The wrist is placed in a neutral position on a flat surface with the digits semiextended.[75] Sometimes it can be helpful to support the wrist to bring it into a slight hyperextension. Passive traction on the slightly flexed digits can then be applied to check the mobility of the median nerve, which is an important diagnostic criterion, especially in the postoperative situation.

A linear array ultrasound probe with a sonic frequency of 15 to 18 MHz or higher is recommended (**Fig. 5**). In contrast to smaller hockey-stick transducers, it allows the entire width of the carpal tunnel to be visualized, providing a good overview of additional masses or other pathologies. Hockey-stick transducers can be helpful in assessing cubital tunnel syndrome as the winding course of the ulnar nerve at the level of the ulnar condyle can be visualized without any gaps. In contrast, the hockey-stick transducer is usually too small when it comes to visualization of the carpal tunnel in its entire width.

Assessment of the Cut-off Value

The median nerve can be easily located and measured at the carpal tunnel entrance using the specified anatomic landmarks, the pisiform bone,

Table 1
Nerve cross-sectional values of the median nerve in relation to the patient's origin (Schelle 2015)

Author	CSA (mm^2) Mean ± SD	CSA (mm^2) Upper Threshold	Population
Boehm et al. 2014	8.5 ± 1.8	10.3	Europe (Germany, Hungary)
Burg et al. 2014	8.3 ± 1.9	10.2	Europe (The Netherlands)
Tagliafico et al. 2013	8.2 ± 2.3	10.5	Europe (Italy)
Zaidman et al. 2009	9.7 ± 1.9	11.6	North America (USA)
Burg et al. 2014	7.0 ± 1.1	8.1	Asia (India)
Wanitwattanarumlug et al. 2012	6.8 ± 0.9	7.7	Asia (Thailand)
Kim et al. 2014	7.9 ± 1.3	9.2	Asia (Korea)
Azami et al. 2014	8.5 ± 0.8	9.3	Asia (Iran)

and the scaphoid tubercle. For this purpose, the 2 carpal bones are adjusted in short-axis-view and the nerve CSA is measured by direct tracing using the device software (**Fig. 6**). The hyperechoic rim of the nerve should be excluded from the measurement. One reason for this is that the echogenicity of the nerve fascicles is reduced and therefore can be better demarcated from the hyperechoic perineurium than the perineurium from the also hyperechoic connective tissue. Second, the compression-induced swelling seems to affect the nerve fascicles rather than the perineurium.[76] Especially in cases of a thin perineurium, differentiation of the hypoechoic nerve can be difficult, as the flexor tendons run obliquely relative to the surface and therefore are subject to the artifact of anisotropy, which causes them to appear hypoechoic as well. If this is the case, it might be helpful to tilt the transducer slightly to distal (Video 5) or to trace the nerve proximally

Table 2
Selected diagnostic parameters of carpal tunnel syndrome

Level I Evidence Studies		
$CSA_{Wrist\ Level}$ (cut-off) $\geq$ 0.085 cm^2	Sensitivity 97% | Specificity 98%	Mohammadi et al. 2010
$CSA_{Wrist\ Level}$ (cut-off) $\geq$ 0.10 cm^2	Sensitivity 82% | Specificity 87%	Ziswiler et al. 2005
$CSA_{Wrist\text{-}to\text{-}Forearm\ Ratio} \geq 1.4$	Sensitivity 100%	Hobson-Webb et al. 2008
$CSA_{Wrist\ Level}$ + $CSA_{Wrist\text{-}to\text{-}Forearm\ Ratio} \geq 1.4$		Billakota et al. 2017
Meta-Analyses		
28 Studies | 3995 Extremities	Sensitivity 87% | Specificity 83% for $CSA_{Wrist\ Level} \geq$ 0.09 cm^2	Tai et al. 2012
13 Studies	Sensitivity 84% | Specificity 74% (pooled) for $CSA_{Wrist\ Level} \geq$ 9.5–10.5 mm^2	Descata et al. 2012
Bifid Median Nerve (Level II Evidence Studies)		
$CSA_{Wrist\ Level}$ (cut-off) $\geq$ 0.12 cm^2	Sensitivity 85% | Specificity 47%	Klauser et al. 2001
$CSA_{Wrist\ Level} - CSA_{Forearm} \geq$ 4 mm^2	Sensitivity 93% | Specificity 95%	

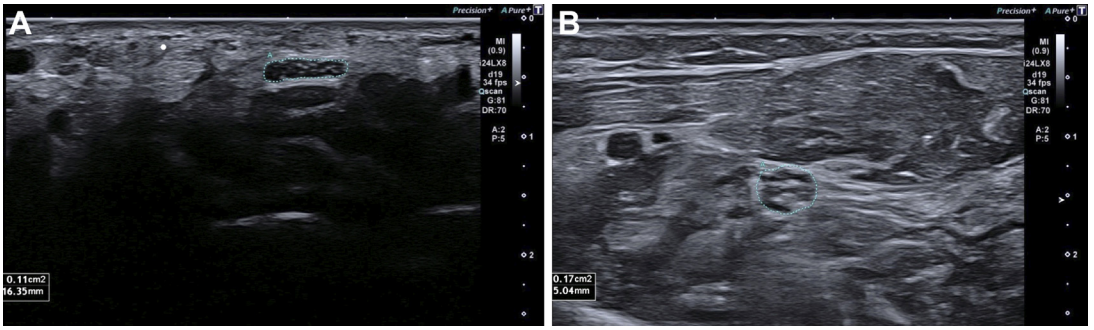

Fig. 4. (*A*) and (*B*) Median nerve (short-axis view, B-mode) showing slight increase in nerve CSA at the carpal tunnel entrance (11 mm^2) and fascicular hypertrophy at forearm level (17mm^2) indicating multifocal acquired demyelinating sensory and motor neuropathy (MADSAM).

by short-axis sliding up to the point where the honeycomb echotexture becomes visible again. A higher reliability to identify the pseudoneuroma at its proper localization is given if the nerve is visualized in long-axis view. The full extent of compression is then typically seen as an hourglass-shaped constriction under the flexorum retinaculum with the pseudoneuroma located proximal to it (**Fig. 7**). The CSA can then be measured individually after rotating the transducer by 90°. This technique gives a complete overview of the entire course of the median nerve throughout the carpal tunnel and even ensures the localization of a pseudoneuroma in the distal part of the carpal tunnel or at the carpal tunnel outlet (**Fig. 8**). If necessary, the median nerve can also be traced in the long-axis view (Video 6). If ultrasound assessment reveals a high division of the nerve or a bifid median nerve, the CSA can also be determined. In these cases, the nerve cross-sectional areas of both nerve portions are simply added together (**Fig. 9**).[77]

Fig. 5. High-frequency matrix transducers for use in nerve sonography. Although sound frequencies between 15 and 24 MHz provide an optimal balance between resolution and penetration depth, higher frequencies (eg, 33 MHz) can increase resolution and diagnostic accuracy in the imaging of superficial sensory cutaneous nerves or pediatric patients.

Determining a Reference Value

The relationship of cut-off value to a reference is calculated using either a swelling ratio or a flattening ratio (**Fig. 10**). To determine the swelling ratio, the measurement of a proximal reference value is required, which is also obtained in the short-axis view. Starting from the cut-off value at the level of the pseudoneuroma, the desired proximal reference point can be reached by short-axis sliding (Video 7) and the CSA can be determined by direct tracing as well (**Fig. 11**). Determining the change in relationship between proximal reference value and pseudoneuroma (swelling ratio) leads to an increase in the sensitivity of sonographic diagnosis of CTS.[73]

Diagnosis of CTS can be alternatively (or supplementary) made by determining a flattening ratio.[73,74,78–82] In contrast to the swelling ratio, the pseudoneuroma is here related to the distal flattening of the nerve. In the authors' view, this procedure is more difficult to reproduce as the median nerve is increasingly subject to the artifact of anisotropy in its distal course and is more difficult to define in cross-section. This is further aggravated by the fact that the median nerve may have already divided at this level. All in all, however, the supplementary measurement of the CSA at the level of the carpal tunnel outlet seems to provide a further increase in sensitivity.[80,82] Olde Dubbelink and colleagues describe a completely different approach in which the nerve cross-sectional area is related to the circumference of the wrist.[83]

RATING SONOGRAPHIC DIAGNOSTICS

Exclusion Diagnostics

With high-resolution ultrasound, the diagnosis of CTS has been improved by a very valuable procedure. Using a sonographic ratio between prestenotic swelling and ipsilateral comparative

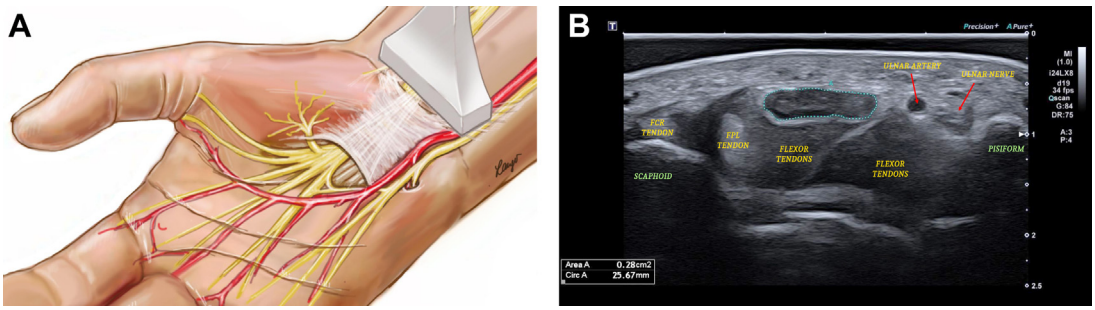

Fig. 6. (*A*) Placement of the transducer at the carpal tunnel entrance to determine the CSA of the pseudoneuroma. (*B*) Median nerve (short-axis view, B-mode) at the carpal tunnel entrance defined by the bony landmarks of the scaphoid and pisiform bones. Hypoechoic appearance of the flexor tendons due to the artifact of anisotropy.

value or a flattening ratio, ultrasound provides a reliable exclusion diagnosis of the disease without the need for additional NCS. At the same time, however, sonography is a useful complementary procedure to electrodiagnostic testing.[84] Especially in cases where typical symptoms and clinical parameters of CTS are present and cannot be confirmed by NCS, ultrasonography can help to establish the diagnosis.[56–61] If both NCS and sonography are negative, steroid infiltration may be considered as an additional diagnostic tool. Its ultrasound-guided application has additional advantages over a blind, landmark-associated approach (**Fig. 12**).[85,86]

Disease Severity

In CTS (and other compression neuropathies), preoperative assessment of disease severity provides an individual impression of the necessity and urgency of surgical treatment and draws an imaginary picture of the existing nerve damage. In contrast to NCS, in which the signal is recorded over a defined segment including the localization of the compression, the shape and the amount of the pseudoneuroma relevant for sonographic diagnosis varies from individual to individual. Furthermore, its localization is not precisely defined anatomically. A direct comparison of both methods is therefore only possible to a limited extent. Electrodiagnostic parameters such as distal motor latency, nerve conduction velocity, and others allow sufficient quantification of the disease. Although a correlation between nerve cross-sectional area and electrodiagnostic parameters has been clearly demonstrated,[87] the correlation coefficients of most comparative studies are only moderate. Therefore, statements about disease severity after sonographic diagnosis alone are not possible or should be regarded with caution.[84,88,89] In the assessment of disease severity, ultrasonography is therefore only a complementary additional diagnostic tool to NCS, which at best allows orienting statements on disease severity and, with regard to postoperative nerve regeneration and sufficiency of nerve decompression, does not reach the accuracy of NCS.

Causes of Nerve Compression

In addition to the possibility of a reliable exclusion diagnosis, ultrasound examination has further advantages for patients and therapists, as important

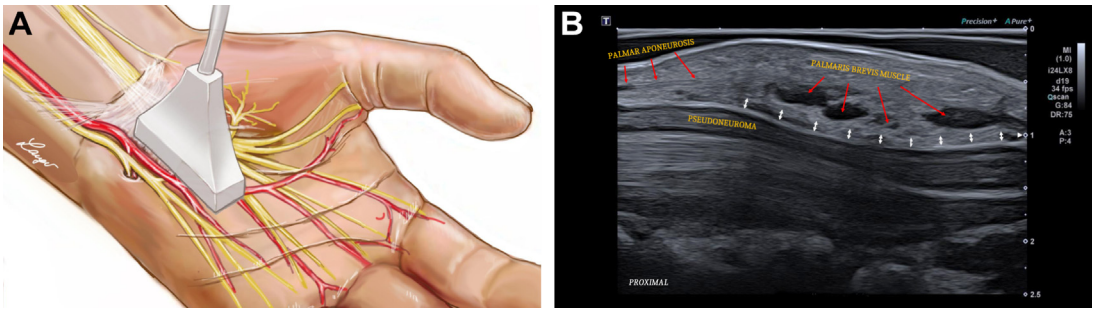

Fig. 7. (*A*) Positioning of the transducer along the median nerve for proper localization of the pseudoneuroma. (*B*) Median nerve (long-axis view, B-mode) at the level of the carpal tunnel for proper localization of the pseudoneuroma, just proximal to the flexor retinaculum (*white arrows*).

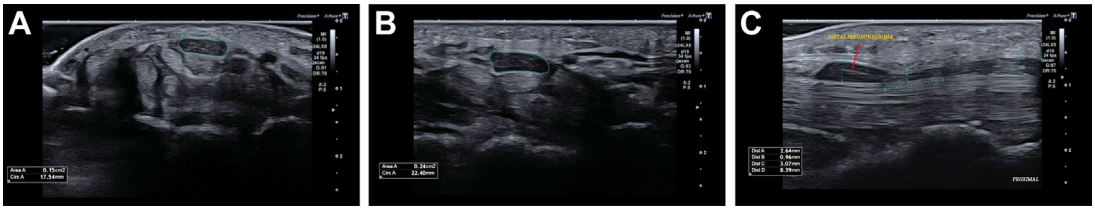

Fig. 8. (*A*) Median nerve (short-axis view, B-mode) at the carpal tunnel entrance. Extensive synovitis of the flexor tendons with increase in nerve cross-sectional area to 15 mm^2. (*B*) Median nerve (short-axis view, B-mode) at the carpal tunnel outlet. In addition to the pseudoneuroma at the carpal tunnel entrance, a distal pseudoneuroma with a nerve cross-sectional area of 24 mm^2 can be identified. (*C*) Median nerve (long-axis view, B-mode) at the middle and distal aspects of the carpal tunnel. The long-axis view provides additional information on the pseudoneuroma at the carpal tunnel outlet.

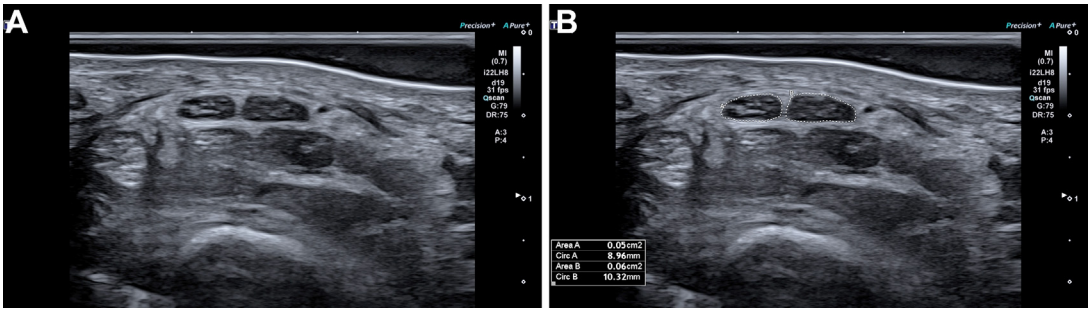

Fig. 9. (*A*) Bifid median nerve (short-axis view, B-mode) at the carpal tunnel entrance. (*B*). Bifid median nerve (short-axis view, B-mode) at the carpal tunnel entrance. Separate direct tracing of the 2 nerve segments.

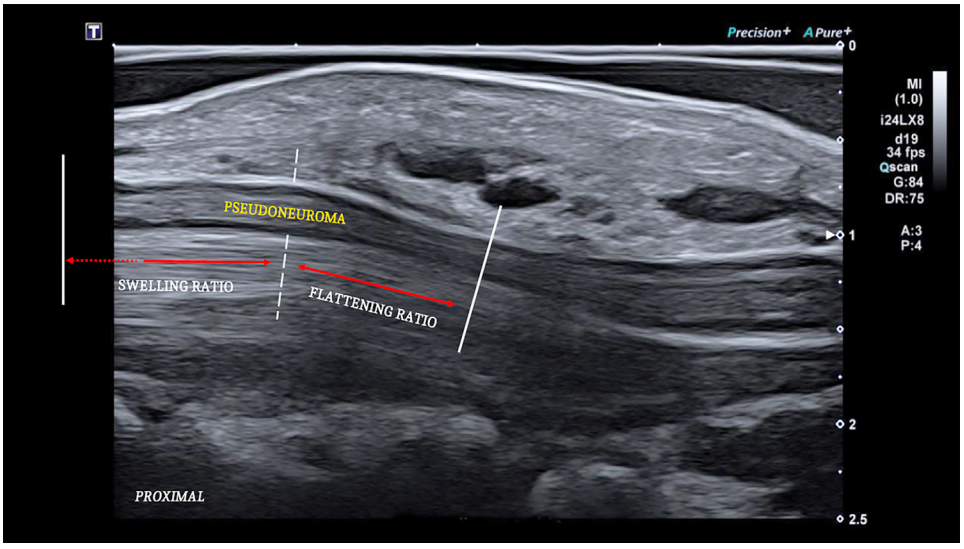

Fig. 10. Median nerve (long-axis view, B-mode). Pseudoneuroma, swelling ratio, and flattening ratio.

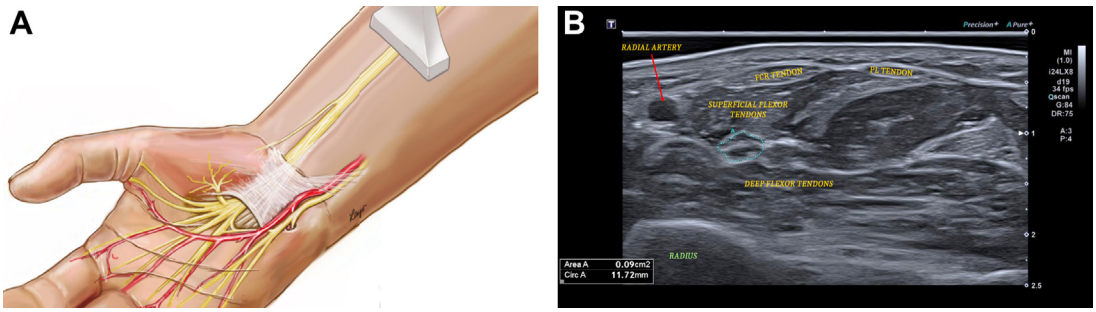

Fig. 11. (*A*) Transducer positioning approximately 12 cm proximal to the distal wrist crease to determine the reference value according to Hobson-Webb et al. (see also **Table 2**). (*B*). Median nerve (short-axis view, B-mode). Transducer positioning approximately 12 cm proximal to the distal wrist crease and measurement of the nerve cross-sectional area by direct tracing.

additional information can be obtained. Atypical findings and causes of compression such as marked synovitis,[90] hypertrophic or aberrant muscle fibers,[91] nerve subluxations,[92] intraneural space-occupying lesions,[93] a high division of the median nerve, variant branches and isolated compressions of the thenar motor branch (**Fig. 13**),[94] a bifid median nerve with a median artery (**Fig. 14**),[77,95–104] trifid nerves[105] but also compressing wrist ganglion cysts (**Fig. 15**) or crystal deposition diseases (**Fig. 16**), nerve[106] and tendon sheath tumors (**Fig. 17**) can be identified and will guide the surgical approach. Dynamic assessments facilitate the diagnosis of dynamic compressions as they occur in postoperative adhesions (Video 8)[107,108] but also in muscle variants (**Fig. 18**) (Videos 9 and 10),[91,109] and anomalous tendon slips[110] and may be induced by certain activities.[111] In addition, sonography allows for sonographically guided infiltrations and therapies with a proven lower complication rate than a blind approach.[85,86]

Postoperative Diagnostics

A quantitative assessment is not only of preoperative interest. Quantitative parameters are also of prognostic relevance in the event of no improvement in postoperative findings. The direct comparison between the preoperative and postoperative

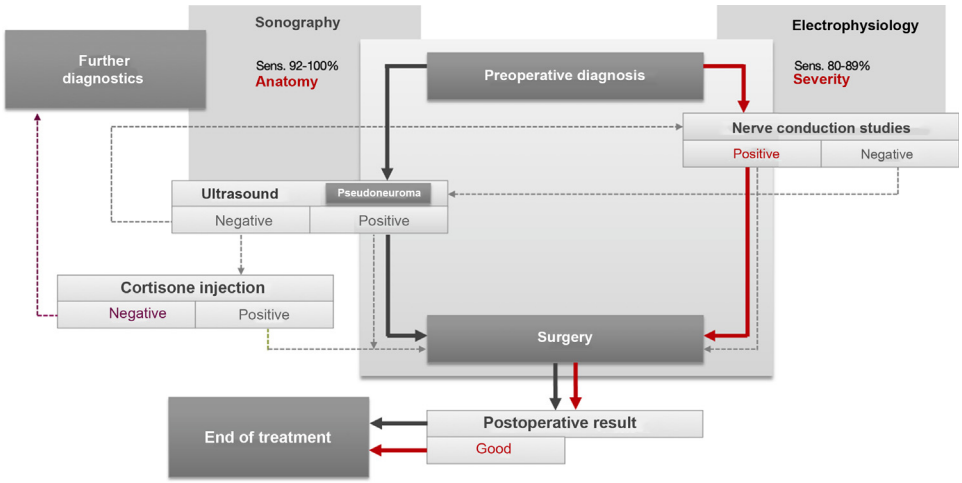

Fig. 12. Comparison between sonography and electroneurography—Preoperative workflow. While electrodiagnostic testing can diagnose carpal tunnel syndrome with a sensitivity of 80% to 89%, the sensitivity of sonography is about 92% to 100%. Electrodiagnostic testing basically allows statements to be made about the severity of the disease (*right*), whereas sonography focuses primarily on quantitative and semiquantitative parameters (*left*). In the case of negative findings in either electrophysiology or sonography, both examination modalities can complement each other. In the case of negative findings on both sides, diagnostic steroid infiltration can help to confirm the diagnosis, which is also possible under sonographic guidance.

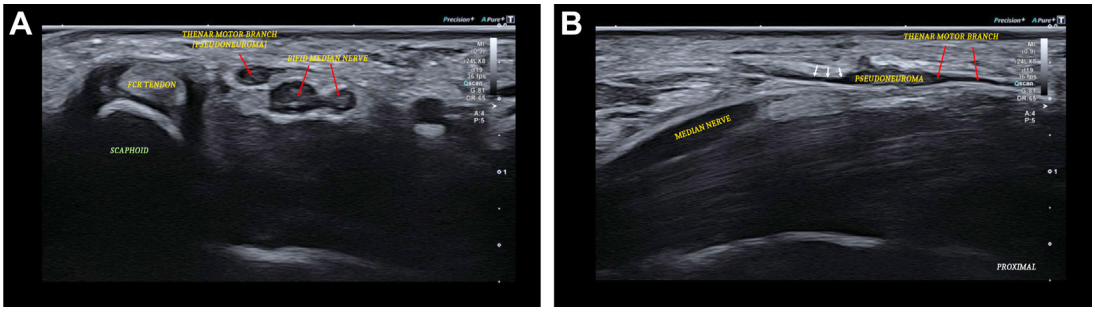

Fig. 13. (*A*) Bifid median nerve (short-axis view, B-mode) at the carpal tunnel entrance. Anatomic variant and isolated compression and pseudoneuroma of the thenar motor branch along its path throughout the flexor retinaculum. (*B*). Thenar motor branch of the median nerve (long-axis view, B-mode) along its path throughout the flexor retinaculum with isolated compression (*white arrows*) and visible pseudoneuroma formation.

situation requires parameters that correlate as closely as possible with the severity of the disease preoperatively and with the improvement in findings postoperatively. Unfortunately, scientific interest has been predominantly focused on preoperative diagnostics, which is why a limited number of studies, at best, have addressed sonography of CTS in preoperative and postoperative comparisons.[112–123]

In addition to the previously mentioned limited correlation of quantitative values of preoperative sonography and NCS, the sonographic quantification of the disease also appears to be limited postoperatively.[114,116,119,124] Although clinical improvement is associated with regression of the CSA,[113,115,119,120] this turns out to be much slower in direct comparison to normalization of electrodiagnostic values.[117–119,121] Temporarily, there is even an increase in nerve CSA at the level of the carpal tunnel outlet postoperatively.[120] Even the wrist-to-forearm ratio seems to have no further benefit here,[122] and it may even be possible that residual swelling must be assumed in the long term.[117,121]

From the authors' point of view, several postoperative situations have to be covered, which can basically be classified into 3 main scenarios, each of them requiring an individually adapted additional diagnostic approach:

- The probably most frequent situation is the one in which subjectively no postoperative improvement of findings occurs even after a considerable waiting period. In the case of severe CTS, this is quite common, but occasionally causes operatively treated patients to question the success of the surgery. In this

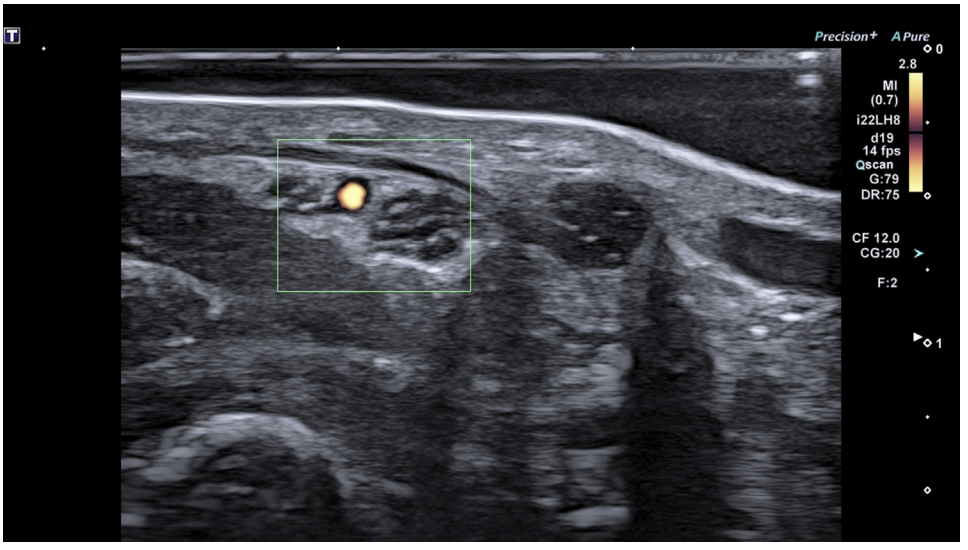

Fig. 14. Bifid median nerve with median artery (short-axis view, B-mode).

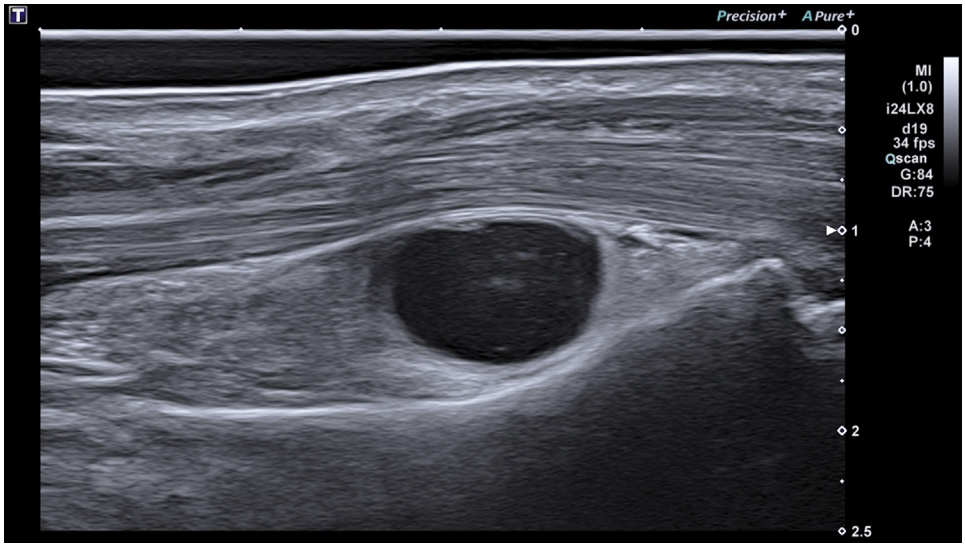

Fig. 15. Large palmar wrist ganglion cyst in the pronator quadratus muscle with compression of the median nerve (long-axis view, B-mode).

case, improvement in short-term follow-up is most accurately demonstrated by NCS, which is only possible if preoperative baseline values exist. Although electrophysiologic parameters do not linearly correlate with the extent of clinical improvement,[125] NCS still allow a more reliable and accurate monitoring in short-term follow-up compared to sonography. In contrast, normalization of the sonographically determined CSA appears to occur much more slowly,[117–120,122] indicating that sonography is less suitable for an early postoperative follow-up assessment.

- The situation is different, in patients who tend to complain of an increase in symptoms postoperatively. In this case, incomplete decompression (unrelieved CTS)[126,127] or even a nerve injury must be assumed, which are easy to differentiate sonographically. While in the case of a nerve injury, a discontinuity of the nerve structure or partial disruption of the perineurium can be visualized (**Fig. 19**), persistent compression usually results in a

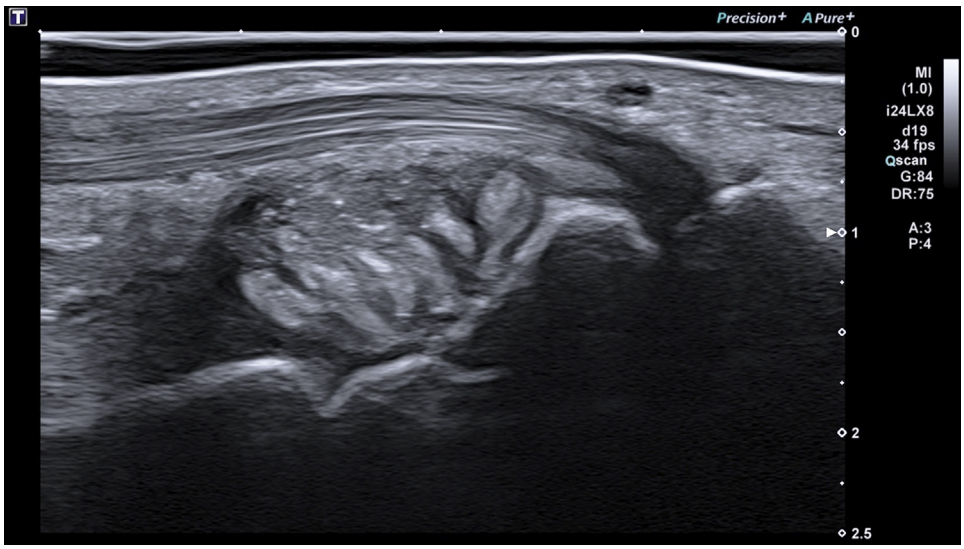

Fig. 16. Extensive infiltrations of the palmar wrist capsule in a patient with a crystalline deposition disease. Kinking and compression of the median nerve (long-axis view, B-mode).

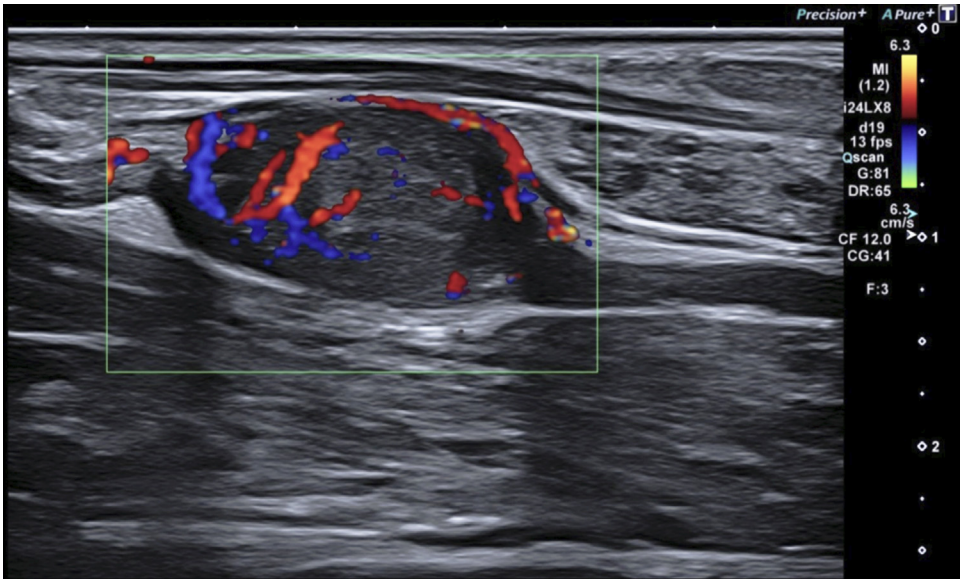

Fig. 17. Median nerve proximal to the carpal tunnel inlet (long-axis view, Doppler-mode). Nerve sheath tumor (Schwannoma) with typical hypervascularity.

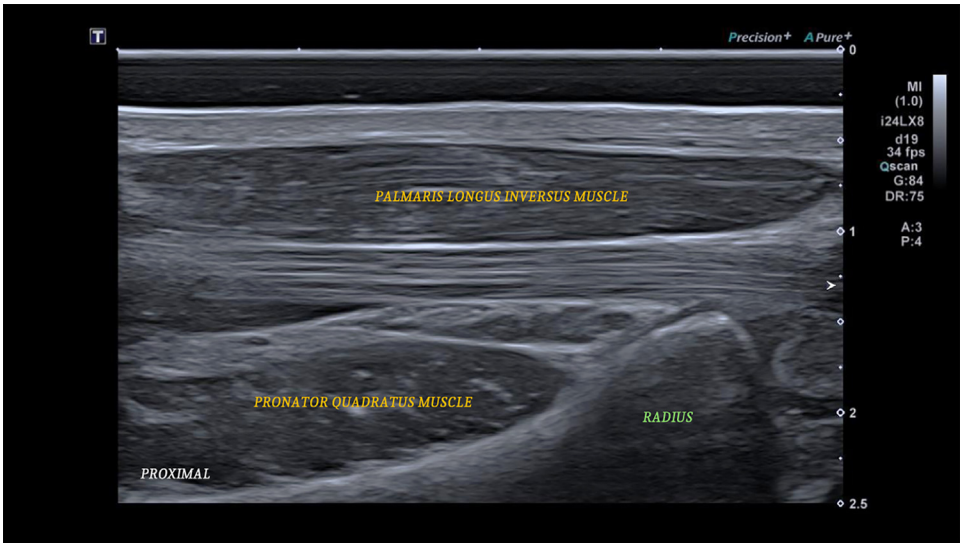

Fig. 18. Palmaris longus inversus muscle with dynamic compression of the median nerve at the distal forearm/carpal tunnel inlet (long-axis view, B-mode).

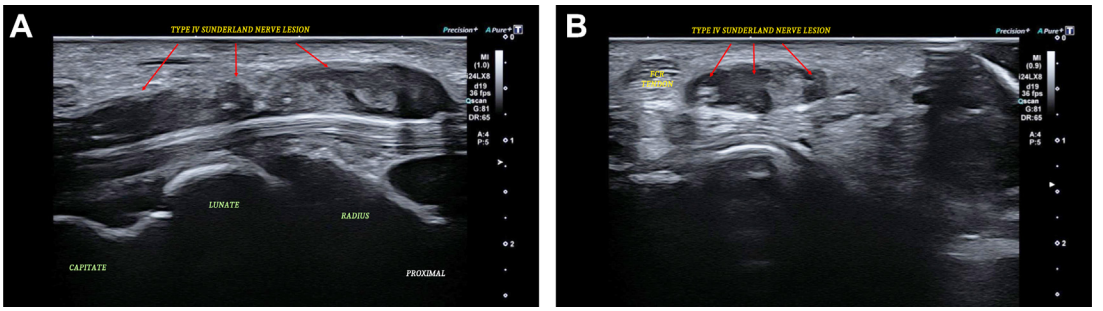

Fig. 19. (*A*) Median nerve (long-axis view, B-mode). Type IV Sunderland nerve lesion with neuroma in continuity after endoscopic carpal tunnel release. (*B*) Median nerve (short-axis view, B-mode). Type IV Sunderland nerve lesion with neuroma in continuity after endoscopic carpal tunnel release.

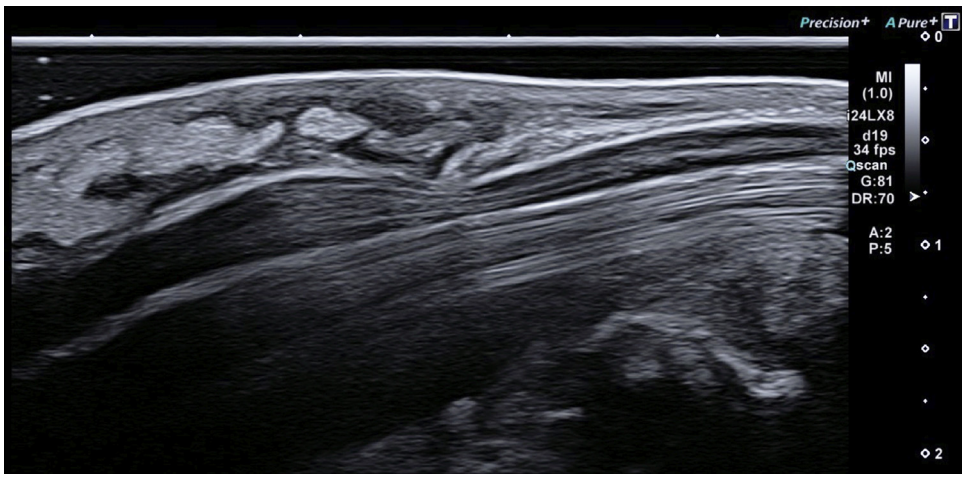

Fig. 20. Median nerve at the carpal tunnel (long-axis view, B-mode). Persistent short-segment compression of the median nerve after surgical treatment of carpal tunnel syndrome.

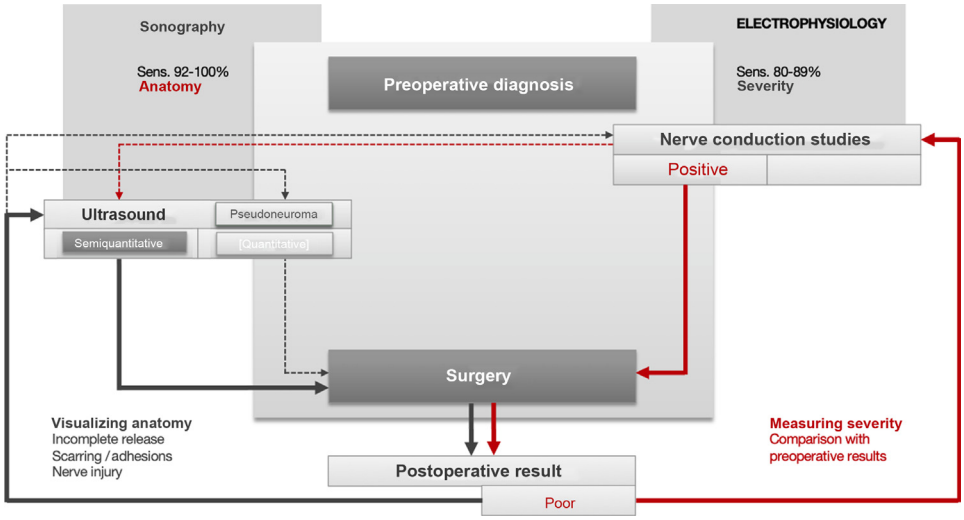

Fig. 21. Comparison between sonography and electrophysiology—postoperative workflow. The value of postoperative ultrasound lies in the visualization of the anatomy. While preoperative ultrasound diagnostics focus on the CSA of the median nerve, in the postoperative setting mainly semiquantitative sonographic parameters such as mobility and scarring are of interest. NCS, on the other side, provide a direct comparison of preoperative and postoperative nerve function if preoperative baseline values have been obtained. Depending on the specific postoperative situation, both diagnostic modalities have their specific indications and can complement each other.

short-segment stenosis, which can best be localized in the long-axis view (Fig. 20). Because of the overall decompression of the nerve, an increase of the pseudoneuroma is recognizable,[108] which can be quantified in the short-axis view. In contrast, NCS are less relevant in the first 14 to 21 days and have only supplementary value in the long term. The same applies to symptoms of a CTS after previous surgical treatment of a radius fracture, which are a primary indication for ultrasound diagnostics, especially since the severity of CTS plays a secondary role in this specific situation. Pre-existing symptoms and those exacerbated by the surgical procedure can be diagnosed based on the pseudoneuroma. Irritation of the nerve by the access trauma should also be taken into account. It is usually the result of an incorrectly performed Henry approach in which the radius is not approached radial to the FCR tendon but ulnarly between the FCR tendon and the median nerve. In these cases, adhesions of the median nerve are frequently observed along the surgical approach, which can be visualized in short-axis view proximal to the carpal tunnel inlet. Dynamic assessment with active flexion of the digits usually confirms adhesions of the nerve to the muscle fibers of the long finger flexors. Lacerations of the median nerve are also visible as loss of continuity. Lesions of the palmar branch of the median nerve can be visualized as a loss of continuity in the early course, later by visualizing a hypoechoic neuroma.

- The third situation describes cases in which the symptoms of median nerve compression improve initially but reappear after a certain period. They are referred to as recurrent CTS. Whether a complete normalization of the nerve CSA or the swelling ratio can be expected and when it will occur remains unclear. It rather must be assumed that the median nerve is subject to a certain memory effect with persistent residual swelling.[121] Ultrasound diagnostics in this situation is therefore focused on the semiquantitative parameters mentioned above, primarily on changes in gliding behavior and postoperative scarring.[107,108] This should be done in correlation with electrodiagnostic testing which, in some degree, allows a differentiation between persistent and residual changes. The value of postoperative ultrasound lies in the visualization of the anatomy and the conclusions that can be drawn from it.[107,128] It focuses primarily on the semiquantitative sonographic parameters of nerve compression such as mobility,[129,130] postoperative adhesions, and scarring.[107,108] Postoperative ultrasound is mainly based on the causes of persistent complaints rather than quantifying the CSA, which was focused on preoperatively.[131] Nerve lesions as well as persistent strictures can be visualized[126,127,131–133] and clearly localized, especially in the long-axis view. Imaging of postoperative subluxations[92] and compressive hematoma formations is also straightforward. In recurrent disease, the primary focus is to dynamically exclude postoperative scarring, which results in a reduction of nerve gliding (Fig. 21).[134]

CLINICS CARE POINTS

- Electrodiagnostic testing still represents the gold standard in confirmatory diagnostics of carpal tunnel syndrome. It allows sufficient quantification of the disease and the reliable differentiation from other compressions of the median nerve.
- US provides a reliable exclusion diagnosis of the disease without the need for additional NCS and is a useful complementary procedure to electrodiagnostic testing.
- In cases where typical symptoms of CTS are present and cannot be confirmed by NCS, ultrasonography can help to establish the diagnosis.
- In addition to the possibility of a reliable exclusion diagnosis, ultrasound examination has further advantages, as important additional information can be obtained.
- Ultrasonografic diagnosis of carpal tunnel syndrome is based on changes in nerve perfusion, nerve mobility, nerve environment, echogenicity, and nerve thickness.
- Preoperative sonographic examination mainly focuses on the pathologically increased CSA of the median nerve proximal to the compression site (pseudoneuroma).
- In the assessment of disease severity, ultrasonography is only a complementary additional diagnostic tool to NCS, which at best allows orienting statements on disease severity and, with regard to postoperative nerve regeneration, does not reach the accuracy of NCS. Statements about disease severity after sonographic diagnosis alone should be regarded with caution.

- Determining the change in relationship between a reference value and pseudoneuroma (swelling ratio / flattening ratio) leads to an increase in the sensitivity of sonographic diagnosis of CTS.
- The use of a ratio between a proximal or distal reference value in addition to a single cut-off value can increase the sensitivity to values between 93.5% and 99% and a specifici

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.hcl.2021.08.003.

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