Ultrasonography of the peripheral nervous system

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Summary With improvements in ultrasound (US) imaging equipment and refinements in scanning technique, an increasing number of peripheral nerves and related pathologic conditions can be identified. Modern US imaging supports the clinical examination and electrophysiologic testing in setting the diagnosis, and enhances this information by illuminating the morphological aspects and etiology of peripheral nerve pathology. US can readily be used for detection of nerve abnormalities caused by trauma, tumors, inflammation and a variety of nonneoplastic conditions, including compressive neuropathies. Well recognized advantages of the method such as the possibility of a dynamic examination, assessing long nerves segments in a short time, bedside-availability, non-invasivity and low cost, make US the ideal imaging tool in peripheral nerve disease.

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Introduction

Diseases of the peripheral nerves are common in neurological practice. They are important differential diagnoses of nerve root lesions, and also of many musculoskeletal disorders in the fields of orthopaedy and rheumatology. The traditional diagnostics of peripheral nerve lesions is based on the clinical and electrophysiologic findings. These methods reflect the functional status of the nerves and inform about the presence of nerve damage, its acuity, character (axonal / demyelinating) and regeneration processes. However, they do not inform about the morphological status of the nerves and their surroundings, especially in relation to the etiology of the disease. Ultrasonography visualizes these changes, so that it completes the information on nerve function and thus enhances the diagnostic information and contributes to the therapeutic decision. The contribution of the method in peripheral nerve diagnosis is comparable to diagnostic imaging (CT and MRI) in stroke or multiple sclerosis.

The first reports on nerve ultrasonography (NUS) were published already in the mid 1980s [1] detecting gross pathologic changes, e.g. nerve tumors. But only the substantial improvement of ultrasound technology at the turn of the millennium enabled an accurate diagnostic visualization of the peripheral nerves. The following article gives an overview of the technical requirements, the examination technique and current applications of NUS in the diagnosis of peripheral nerve disease.

Technical requirements, equipment settings, and examination technique

For sonography of the peripheral nerves a high image quality and resolution are critical. For an optimal resolution a high-end ultrasound unit equipped with a high-resolution broadband linear-array probe (e.g. 5–17 MHz) and corresponding soft-tissue software are necessary. In the case of a 15 MHz transmission frequency, an axial resolution of up to 250 μm is achieved. Depending on the type of probe and

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focusing, the highest resolution is achieved at a depth of approximately 0.5–1.5 cm from the skin [2]. The scanning frequency used is depending on the examined nerve and the clinical question. For superficial nerves (e.g. median nerve in the carpal tunnel or ulnar nerve at the elbow) the maximum frequency (up to 18 MHz) can be applied. Due to the limitation of the penetration depth of high frequencies, in deeper lying nerves or nerve segments (e.g. median nerve at the proximal forearm or sciatic nerve), lower frequencies (down to 5 MHz) are required. With low ultrasound frequencies, the resolution is worse and the differentiability of the nerves in the surrounding tissue as well as of their internal structure becomes difficult. Good ultrasonic devices allow up to a depth of about 2.5 cm also an assessment of subtle changes.

In addition to a high physical resolution, the soft-tissue contrast in particular, is decisive for optimal visualization of the peripheral nerves. Special software, e.g. "compound-imaging", "high-resolution-imaging", is very helpful in this process. Additional tools, e.g. extended field of view imaging, which create a panorama image from numerous individual images, can improve image documentation.

The application of color coded sonography (color Doppler or power Doppler) allows assessing the vascular situation of the nerves and their surroundings. This is particularly useful in inflammatory conditions, nerve tumors or compressive neuropathies. Color coded sonography is also helpful in localizing nerves that are often accompanied by vessels (e.g. radial nerve at the lateral upper arm accompanied by the profound brachial artery; sural nerve accompanied by a vein). For color Doppler, a small-flow-setting of the ultrasound device is recommended (pulse repetition frequency 500 Hz, band-pass filter 50 Hz). It is important to notice that an exploratory study, even without high-end ultrasound equipment, can detect major changes, such as severe nerve compression or a mass lesion. For the assessment of fine structures or complex changes, such as in post-operative conditions or nerve injuries, however, high-quality equipment is required. In addition to the apparative equipment a good knowledge of the regional topographic anatomy is important. Further, the examiner’s expertise in diseases of the peripheral nervous system and electrophysiological knowledge facilitate the interpretation of NUS.

The typical examination of peripheral nerves begins with transverse sections. The nerve is initially visualized at a site with typical anatomical landmarks (e.g. median nerve in the carpal tunnel, ulnar nerve in the sulcus). After image optimization, the nerve can be followed further continuously in the proximal and distal directions, and in the area of suspected pathology. The site of underlying pathology is normally located in transverse sections, for a more precise information longitudinal scans and the examination of vascularization with color coded sonography are performed.

What nerves can be examined?

In normal-weight people, all major nerves of the extremities, e.g. the median, ulnar, radial, sciatic, tibial and peroneal nerves, can be visualized in their entire course at the extremities. Even smaller nerves, e.g. the interosseus posterior and the superficial radial nerve, are regularly displayed. The spinal nerves C4-C8 and the supraclavicular brachial plexus can also be visualized, but especially the inferior trunk and the fascicles are not constantly imaged in good quality. The visualization of the infraclavicular and infrarotectoral brachial plexus is restricted by the clavicle and the depth of the structures. Cranial nerves like the vagal and accessory nerves, can be visualized regularly. Particularly in obese patients, the examination of the sciatic nerve in the thigh and tibial nerve at the proximal lower leg is difficult or even impossible. In lean people, however, even small sensory nerves, such as the saphenous, sural and superficial peroneal nerve as well as the lateral femoral cutaneous nerve can be assessed.

Sonography of healthy peripheral nerves

The nerves are cable-like structures that appear on transverse sections as round to oval hyperchoic structures (Fig. 1a). They are surrounded by an echogenic rim representing the epifascicular epineurium and the perineurial fatty tissue. The sonographic echo pattern (echotexture) is called "honeycomb-shaped" [3]. The rounded hypoechoic areas correspond histologically to the nerve fascicles, and the echogenic septa to the interfascicular epineurium. In

![Figure 1](a and b): Normal median nerve (arrows) in the mid of the forearm. Notice the echotexture in the transversal (honeycomb-like) and longitudinal (fascicular) scans. FDS = superficial finger flexor, FDP = deep finger flexor. Arrowheads = fascia between the muscles.
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large nerves a clear cable-like fascicular echotexture can be seen (Fig. 1b). With color coded sonography the epineurial vasa nervorum can be displayed in some nerves (e.g. median nerve at the distal forearm).

Pathological findings

Compressive neuropathies

Nerve sonography is nowadays used in all disease categories of the peripheral nervous system. The compressive neuropathies, and in particular entrapment syndromes, are the most common illnesses. NUS allows examination of the most frequent entrapment sites in the upper extremities, e.g. the carpal tunnel (median nerve), the cubital tunnel and the Guyons canal (ulnar nerve), and the supinator tunnel (interosseus posterior nerve). In the lower extremities, peroneal nerve at the fibular head, tibial nerve in the tarsal tunnel, the interdigital nerves (Morton-Metatarsalgia) and the lateral femoral cutaneous nerve can be examined. The basic diagnostic criterion is the visualization of nerve compression, which appears regardless of anatomic location on longitudinal scans as an abrupt flattening (notching) at the site of nerve compression and a fusiform swelling proximal and distal to it (Fig. 2). The swelling is accompanied, depending on the degree of compression, by a hypoechogenicity and a reduction of visibility or extinction of the typical fascicular echotexture resulting of nerve edema. Correspondingly, the transverse sections show an enlargement of the nerve cross-sectional area of a hypoechoic nerve. The sonographic findings thus reflect the pathomorphological changes in terms of nerve constriction at the site of compression and the pseudoneuroma formation. In addition, NUS allows evaluation of the surrounding structures and finding nerve compression etiology, e.g. compression by a mass lesion. Anatomical variations can be evaluated as well. Thus, NUS helps in planning and timing of further therapy (conservative / operative, e.g. in case of compression by a mass lesion early surgical therapy).

Carpal Tunnel syndrome

Carpal tunnel syndrome (CTS) is the most common peripheral nerve disorder with a lifetime prevalence of about 15%. In typical cases the longitudinal scans show a nerve compression under the flexor retinaculum with the formation of a pseudoneuroma proximally and (often to a lesser extent) distally to the retinaculum. The transversal scans show a nerve enlargement at the site of pseudoneuroma, which is quantified by cross-sectional area measurements at the level of the carpal tunnel inlet (pisiform bone). In seldom cases, an enlargement at the carpal tunnel outlet only can be seen. NUS has a sensitivity (from 73% to 92%) and specificity comparable to electrophysiological methods [4]. Further, NUS represents a complementary method to the electrophysiological evaluation. Even with normal electrophysiology NUS can detect pathological findings, and vice versa. An even more important contribution of NUS is to rule out secondary CTS that includes tenosynovitis of the flexor tendons, ganglia, arthritic changes, amyloid deposits, accessory muscles or median artery thrombosis [5,6]. Furthermore, anatomical variants such as prolonged muscle bellies of the finger flexors reaching into the tunnel, can be detected. More important are nerve variants such as bifid median nerve divided into two strands already in the carpal tunnel or variants of the thenar branch (subligamentary or transligamentary course). Also, vessel variants like a persisting median artery or atypical course of the ulnar artery, can be seen. The detection of such normal variants can be significant especially for the endoscopic surgeon. In every third patient with CTS, sonography found one of the above-mentioned structural abnormalities [6]. Therefore, contrary to the prevailing opinion, CTS cannot be regarded as an idiopathic condition. NUS plays a very important role in postoperatively persisting or recurrent CTS. It allows visualization of surgically treatable causes like incomplete retinaculum transection with persistent nerve compression or surgery complications such as abnormal scarring or iatrogenic nerve injury. Based on personal experience, sonography can reveal a false preoperative diagnosis showing conditions mimicking CTS like nerve tumor [7] or neuritis.

Ulnar neuropathy at the elbow

Ulnar neuropathy in the elbow region (UNE) comprises three entities with their own etiology, and therapy. The cubital tunnel syndrome represents the most common disorder. Its pathological basis is a nerve compression under the aponeurosis between the origins of the ulnar flexor muscle of the wrist (humeroulnar arcade). Correspondingly, ultrasound shows a flattening of the nerve under the arcade with a proximal swelling in the sulcus. Cross-sectional areas greater than 0.1 cm² accompanied by a hypoechogenic appearance and loss of the honeycomb echotexture, are diagnostic for cubital tunnel syndrome. Another entity is caused by a repetitive subluxation or luxation of the nerve out of the sulcus leading to chronic pressure damage. A lacking or loose humeroulnar arcade is postulated as a reason for this. In the case of subluxation, the ulnar nerve is located at the tip of the medial epicondyle at maximum elbow flexion. In the case of luxation, it is dislocated volar to the medial epicondyle. The nerve dislocation is often accompanied by a nerve swelling [2].

Further, space-occupying lesions such as ganglia, lipomas, arthritic changes, accessory muscles, or a dislocation of the medial triceps head ("snapping triceps syndrome")
can be reliably identified. In these cases, the compression is often located proximal to the cubital tunnel, which may result in atypical electrophysiological findings.

The diagnostic value of sonography is comparable with electrophysiological methods, in combination it improves the diagnostic yield. In addition, it provides prognostic information: the extent of swelling in the sulcus correlates negatively with clinical improvement after surgery [8].

**Less common compression syndromes**
Since the less common compression syndromes affect mostly smaller nerves, the sonographic depiction of a direct nerve compression is more difficult. Therefore, the main role of sonography lies in the recognition of neighborhood processes as compression factors. Thus, sonography can detect space-occupying lesions such as ganglia or lipomas affecting the ulnar nerve in Guyon’s Loge, the median nerve at the proximal forearm, the intersosseus posterior nerve in the supinator tunnel, the axillary nerve in the quadrilateral space as well as the suprascapular nerve. In the so-called algeic interosseus-posterior-syndrome an ultrasound-guided infiltration can be performed for diagnostic purposes. In thoracic-outlet-syndrome, sonography can reveal a compression of the spinal nerve C7 or C8 by a cervical rib. In the lower extremities, peroneal nerve at the fibular head and tibial nerve in the tarsal tunnel can be affected by different soft tissue masses (enlarged bursae, ganglia, heterotopic ossification after trauma). Especially the peroneal nerve can be affected by intraneural ganglia emerging from tibiobular joint via the articular branch [9]. In Morton’s metatarsalgia a ‘neuroma-like enlargement’ of the second or third plantar interdigital nerve can be seen. Even in obese patients with meralgia paresthetica, a compression of the lateral femoral cutaneous nerve can be demonstrated and combined with an ultrasound-guided infiltration (personal experience).

**Sonography of peripheral nerve tumors**
The diagnosis of peripheral nerves with ultrasound was described in literature back in the 1980s. This was possible because large nerve tumors could be detected even with older transducers with a low scanning frequency (around 7 MHz). The two most common types of tumors are schwannomas (neurinoma) and neurofibromas. Sonographically, both appear as well-defined, round masses with a hyperechoic rim, which are localized in the course of a peripheral nerve. Schwannomas (Fig. 3) are mostly homogeneously hypoechogenic and lie eccentric to the long nerve axis, in contrast to neurofibromas, which lie central. Neurofibroma’s echogenicity is higher and distributed in the center of the mass (so called target sign) [10]. Schwannomas show often a hypervascularization in color coded examination, in neurofibromas no significant internal perfusion can be seen even in contrast enhanced ultrasound [11]. Plexiform neurofibromas, which occur typically in neurofibromatosis type 1 (von Recklinghausen’s disease), spread over long segments of one or more nerves. The nerves are infiltrated with small nodules which form a dysmorphic mass of heterogeneous echogenicity uplifting the inner nerve architecture (’sack full of worms’) [12]. Perineuriomas are generally less well known. They appear often in young patients and present with painless progressive motor deficits. With NUS they appear as fusiform hypoechogenic structures without vascularization spreading over several centimeters.

A sonographic screening examination for the presence of nerve tumors should be performed in every etiologically unexplained neuropathy. The affected nerve has to be visualized in its entire course of the limb. This investigation is also possible without a high-quality technical equipment.

**Generalized neuropathies (polyneuropathies)**
In generalized neuropathies, ultrasonography is not routinely used yet. In a variety of diseases, however, NUS can demonstrate a generalized enlargement (edema) of the peripheral nerves, e.g. in acromegaly, or diabetes mellitus, which explains the frequent occurrence of entrapment syndromes. A generalized nerve hypertrophy is also found in hereditary neuropathies (e.g. HMSN 1) [13]. In immune-mediated inflammatory neuropathies (e.g. AIDP, CIDP, MMN), a so called hypertrophic remodeling of the peripheral nerves is present. It is characterized by nerve hypertrophy and a variation of individual fascicle thickness changing in the nerve course (personal experience). Focal nerve or fascicle thickening can also be found in painful mononeuropathies with a possibly immunologic etiology. Sonography can also differentiate nerve compression syndromes in polyneuropathies, which is particularly difficult with electrophysiological methods.

**Sonography of traumatic nerve lesions**
Sonography has an important role in the assessment of traumatic neuropathies. For the investigation is a high-quality equipment of great benefit, since it facilitates the presentation of changes in difficult conditions with tissue edema, hematomas, and scars. NUS can assess the continuity and integrity of the nerve, characterize the defect, and identify secondary nerve compression. Thereby, location, extent and type of damage are determined. This allows displaying a complete and partial nerve transection, the distance and condition of the stumps (formation of a neuroma) or a compression of the nerve, for example by scars, ostoosynthetic material, callus formation, bone fragments, hematomas, or foreign bodies [2]. The most frequent
alteration found in nerve trauma is axonal swelling. The nerve and its fascicles show a hypoechoic thickening over several centimeters, in proximal limb lesions sometimes affecting the whole extremity. In severe traumas, axonal swelling persists over several months and diminishes from proximal to distal with the forthcoming reinnervation (personal experience). Sonography allows differentiating major nerve trauma that requires surgical therapy, i.e. a complete and partial nerve neurotmesis. Since the degree of stump dehiscence determines the surgical procedure (neurorrhaphy in the case of a small defect, nerve transplant in the case of greater dehiscence), the distance of the nerve stumps should be measured. In longitudinal scans an amputation neuroma appears as a hypoechoic thickening or a bulbous mass where the nerve ends. In the case of a partial nerve transection, also intact parts of the nerve and its interfascicular epineurium can be seen (Fig. 4). This type of lesion is very difficult to diagnose with clinical and electrophysiological methods especially in the early post-traumatic period (within 3 months). Neuroma-in-continuity is represented by a fusiform hypoechoic thickened nerve with extincted nerve echotexture. Thus, NUS can facilitate the therapeutic decisions and initiate early surgical intervention using the appropriate method (neurorrhaphy, nerve grafting or neurolysis). Postoperative complications such as dehiscence of the nerve sutures or abnormal scarring can be identified, too.

Conclusion

The complete diagnosis of peripheral nerve damage includes not only the evaluation of nerve function with clinical and electrophysiological methods, but also the assessment of nerve morphology with imaging methods. Sonography allows not only to set the diagnosis, but also to reveal the etiology of the condition. Hence, early and appropriate therapeutic measures can be derived. Sonography can be used as the screening imaging tool for all disease categories of the peripheral nervous system.

References