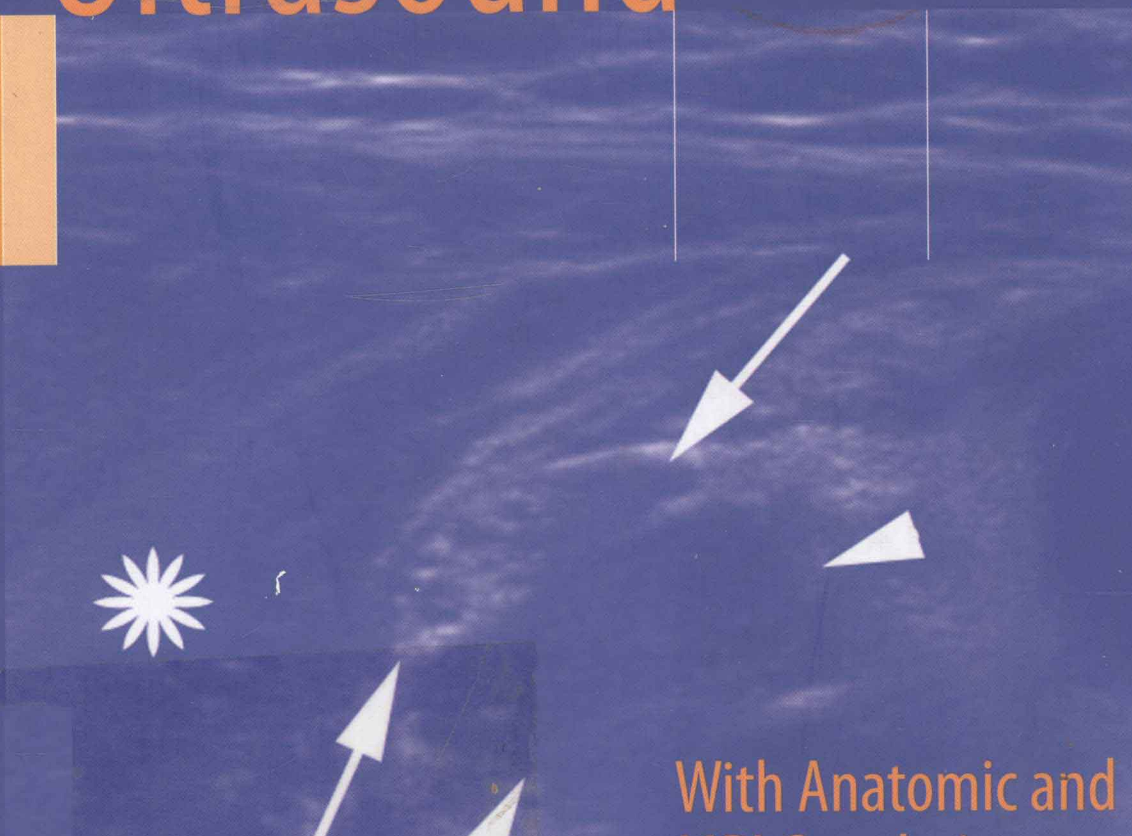
Siegfried Peer
Hannes Gruber
Editors

Atlas of Peripheral Nerve Ultrasound



With Anatomic and MRI Correlation

Springer

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Atlas of Peripheral Nerve Ultrasound

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Preface

The first publication on peripheral nerve ultrasound dates back to 1988 with Bruno Fornage's article *Peripheral nerves of the extremities: Imaging with US* published in Radiology. Afterwards peripheral nerve ultrasound has been performed only by very few specialists around the world. During the last years, we have seen a tremendous increase of publications concerning diagnostic and interventional sonography of the peripheral nervous system, especially the technique of sonography-guided regional anesthesia, and pain therapy is getting widespread acceptance.

Especially the latter applications of sonography ask for a profound knowledge of the local topographic anatomy of peripheral nerves. The local topography often is rather complex. As peripheral nerves are small structures, typical landmarks may help to find them with sonography. The same is true for MRI, which is the second imaging modality for diagnosis of peripheral nerve disease.

For daily clinical practice, a resource, which offers side by side presentation of topographic anatomy with correlative sonograms and MR images, allows for quick recapitulation of typical regional features. This is important to succeed with peripheral nerve diagnosis and intervention. Like our old anatomy teacher always said: "doctors without knowledge of anatomy are like moles, they roam in the dark and their daily task are piles of soil!" To prevent that, we provide you with this book, which is based on our extensive experience in nerve imaging.

Innsbruck, Austria — Siegfried Peer, Hannes Gruber

How to Use This Book

Why an *Atlas of Peripheral Nerve Ultrasound*? Well actually there are two reasons: first, until now a book like that simply did not exist. Second, during congresses, seminars, and workshops, we were often asked by participants "How do you do that," "I simply don't get the results, you achieve, when imaging nerves with ultrasound," and "How can I become more efficient in sonography of the peripheral nerve?" Well, probably the best thing is to attend a dedicated workshop and to volunteer in a department, where peripheral nerve ultrasound is done, but what, if in your area a possibility like that simply does not exist? In addition people attending workshops still tell us "once I am at home things do not turn out that easy, when I am confronted with an individual patient!" This is the most important reason why we decided to provide you with this atlas.

What this atlas is not: it is not an attempt to show you sonography of *all* peripheral nerves and especially not how to perform peripheral nerve intervention. This atlas covers the nerves which allow for diagnostic ultrasound, and this is a huge difference. While you may, for example, perform ultrasound-guided intervention of the third occipital nerve, this nerve is hardly affected by pathological changes, which may be diagnosed with ultrasound, and therefore it is not covered in this atlas. Peripheral nerve intervention may often be achieved based on landmark techniques, without visualizing the nerve itself – think of infiltration of lumbar spinal nerve roots! So if you are interested in interventional procedures, please refer to other textbooks, like the *Atlas of Ultrasound Guided Procedures in Interventional Pain Management* by Samer Narouze et al., which is highly recommendable.

What this atlas should be: an up-to-date source on diagnostic strategies for identification and diagnosis of peripheral nerves with ultrasound. The format of this atlas relies on our concept of "landmark-based imaging" of peripheral nerves: nerves are complex structures and travel a long way before reaching their end organ. Along a nerve's course, there may be segments, where it is very difficult to identify because of a complicated local anatomical situation. In the case of coexisting hematoma or edema, identification may sometimes be nearly impossible. But the good news is: for every nerve certain regions exist, where the local anatomy is very typical and the nerve is more easily identified due to its intimate relationship with surrounding "landmarks" such as bony ridges, muscles, tendons, and vascular structures. This atlas is organized according to these typical anatomical regions and provides a set of four images for every typical nerve topography: a photograph showing how to place the transducer in order to see the structures in the corresponding ultrasound image, an anatomical cross section, and T1-weighted MR image in the same plane with the ultrasound scan. These images are exclusively oriented in a strictly transverse orientation to make them easier to understand compared with more complex oblique or longitudinal planes. Remember the focus of this atlas is to help you identify the nerve! Once you did that, a more oblique scan plane together with additional longitudinal imaging may sometimes be more suited for diagnostic evaluation of the nerve! We decided to put all the anatomical labeling exclusively on the anatomical cross section and only mark the nerve in the ultrasound and MRI in order to have you visually compare the structures in the images with the anatomical cross section, which asks your brain to work and as we believe enhances visual learning. In addition to this set of four images, on every page – which is dedicated to one nerve in one typical anatomical region – we provided one or two extra images, which may either be an additional longitudinal or panoramic sonogram of a normal nerve or a sonogram of a typical disease process such as compression neuropathy!

We hope this format achieves what it was designed for: to enable you with a "how to find the nerve guide" according to the individual need of your patients.

Acknowledgement

A book like this would not be possible without the help of a lot of people. Apart from the authors several colleagues contributed substantially and shall not go unmentioned.

Our special thanks goes to the Innsbruck Medical University Department of Anatomy, Histology and Embryology (chairwoman Prof. Dr. Helga Fritsch) Section for Clinical and Functional Anatomy for provision of the human corpse and the anatomical cross sections, in particular Gottfried Gstrein and Rupert Gstrein (autopsy assistants, production of cross sections), Romed Hörmann (photography), and Assistant Professor Dr. Karl-Heinz Künzel M.D. (anatomical advice). In this context, we also like to express our appreciation for all the people who donate their body for scientific studies. Without them basic medical education and research, as well as works like this, would not be possible.

Thanks to the Innsbruck Medical University Department of Radiology (chairman Prof. Dr. Werner Jaschke) for provision of all the sonographic and MRI images, the radiology technicians, who helped in the production of MRIs, and in particular Ingrid Messirek (photography).

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Introduction to High-Resolution Sonography of the Peripheral Nervous System: General Considerations and Examination Technique

1

Siegfried Peer

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Sonography of the peripheral nerve is not essentially new. As early as 1988, Bruno Fornage reported on the feasibility of peripheral nerve imaging (Fornage 1988). The progress of nerve sonography in the subsequent years, however, was slow, and this was mainly due to the fact that nerves are small structures and were not easy to approach with the then available technique. The lacking of high-resolution transducers was the main problem and therefore it took until the late 1990s and the first years of the new millennium for sonography of the peripheral nerve to experience a real boost, which still continues. While in the early era of peripheral nerve sonography actually only freaky guys were focusing on the then exotic area of nerve imaging – there were only very few groups worldwide really devoted to nerve sonography, such as the group around Carlo Martinoli and Stefano Bianchi in Genova, Italy, Leo Visser and Roy Beekman in the Netherlands, and our group in Innsbruck, Austria – meanwhile we experience a rising interest in peripheral nerve sonography from radiologists, neurologists, and anesthesiologists alike. This explosion of nerve sonography is also due to the fact that the unexpected technical progress of ultrasound scanners, transducers, and software development is amazing. Again, peripheral nerves are small and topographically complex structures and therefore a certain arsenal of tools is important to achieve constant high quality in diagnostic and interventional nerve ultrasound.

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1.1 Ultrasound Scanner Hardware and Software Requirements

In the following sections, I will provide a two-level recommendation on the technical requirements for nerve sonography: one for the practitioner, who likes to integrate nerve sonography into his toolbox for examining the most common peripheral nerve pathologies, such as compression neuropathies, and one for the dedicated specialist, who is interested in imaging of smaller nerves, more complex pathologies (nerve trauma, inflammatory conditions), or ultrasound-guided intervention in the peripheral nervous system.

1.1.1 Hardware

I will not comment on the type of ultrasound scanner to be used, because there is a competition among the companies and many of them provide a top of the notch machine, which enables for high-end sonographic imaging. The choice of scanner therefore is open to personal preferences in terms of ergonomics and design. One thing to mention, however, is the general availability of fine portable ultrasound systems such as the Philips CX50 (Philips Healthcare) (Fig. 1.1a). While in the past many of these small systems were lacking software for high-resolution imaging or were not working with some high-resolution transducers, this has changed a lot during the last years. There are systems for the more generally

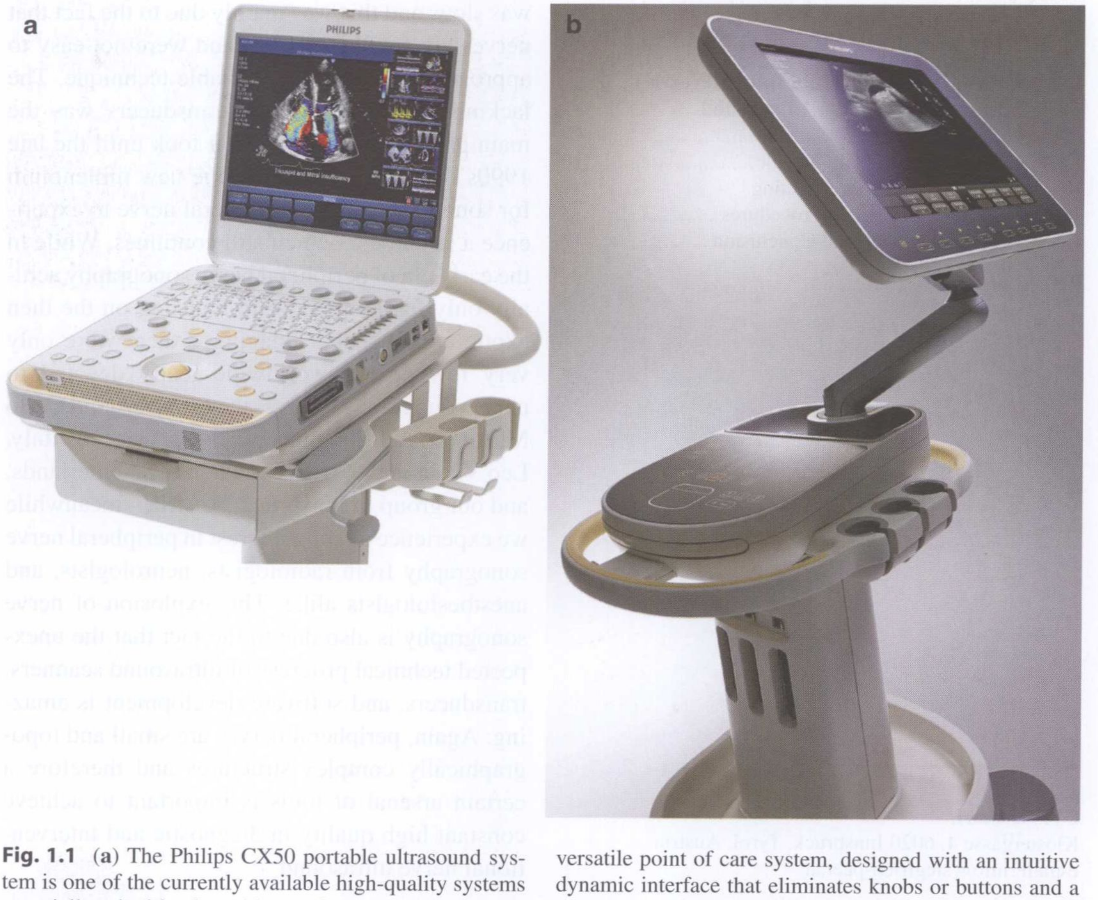

Fig. 1.1 (**a**) The Philips CX50 portable ultrasound system is one of the currently available high-quality systems especially suited for the guidance of nerve blocks and pain treatment. (**b**) The Philips Sparq ultrasound system, a very versatile point of care system, designed with an intuitive dynamic interface that eliminates knobs or buttons and a sealed, easy-to-clean, tempered glass control panel to facilitate disinfecting

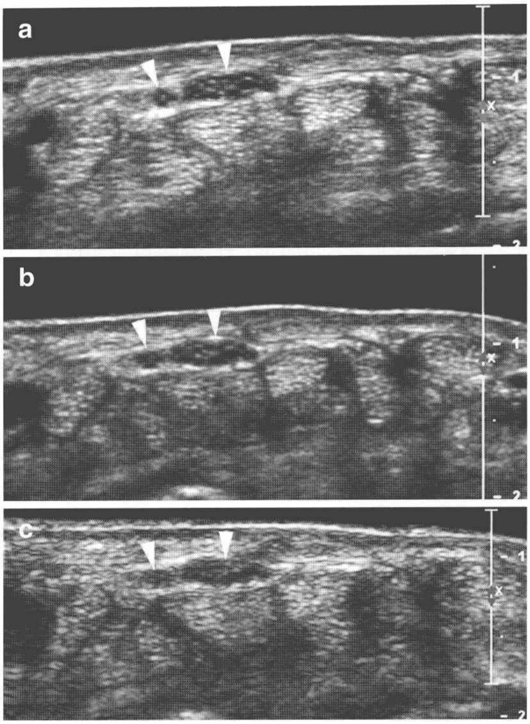

Fig. 1.2 Transverse ultrasound images through bifid median nerve (*arrowheads*) in a healthy volunteer taken with a 17 MHz (**a**), 12 MHz (**b**), and 9 MHz (**c**) transducer (all images taken on a Philips IU22 under the same preset). Note the difference in the discrimination of the fascicular nerve structure. In (**c**) the inner structure of the nerve is barely defined

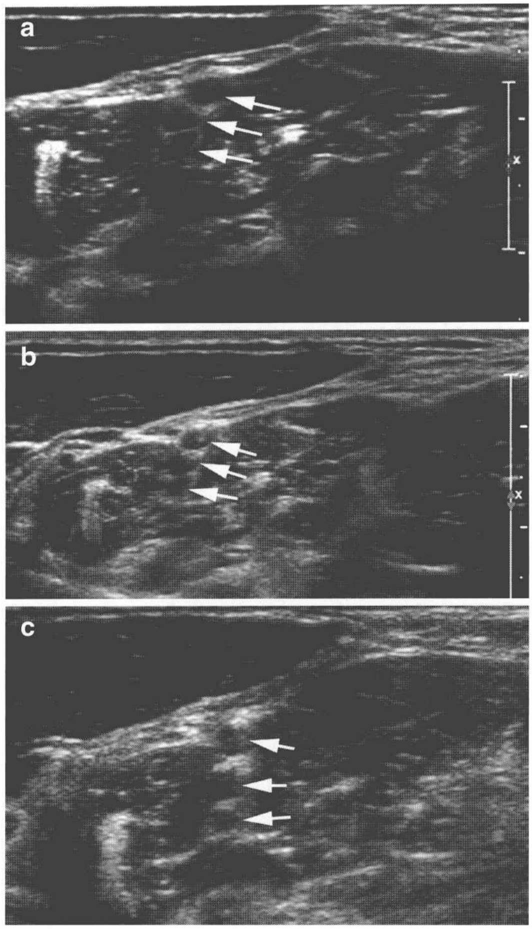

Fig. 1.3 Transverse ultrasound images through the brachial plexus (*arrows* plexus trunks) in a normal volunteer taken with a 17 MHz (**a**), 12 MHz (**b**), and 9 MHz (**c**) transducer (all images taken on a Philips IU22 under the same preset). Note that for deep-lying structures covered by thick soft tissues a 12 MHz or even 9 MHz transducer results in most acceptable image quality

interested user and dedicated systems for the specialist, such as the Philips Sparq (Philips Healthcare) (Fig. 1.1b), which is a small point of care system with a wide array of available transducers from curved arrays for general imaging to a 12 MHz wideband linear transducer especially suited for the anesthesiologist or pain physician performing guided nerve blocks.

Contrast and resolution are the basic physical principles that matter with sonography; therefore, high-resolution transducers are a must for nerve imaging. Currently available transducers for clinical imaging reach frequencies of up to18 MHz which results in an axial resolution of 250–500 μm. Such types of transducers are definitely needed for imaging of small nerves and for evaluation of inner nerve texture – for example, in sonography of nerves after nerve repair. Fine details such as small intraneural neuroma or partial dehiscence of a coaptation may go unnoticed with lower resolution transducers. For imaging of common compression neuropathies, a 12 MHz transducer usually suffices and for deep-lying nerves (e.g., sciatic nerve) or in obese patients a 9 MHz transducer may even be better suited (Figs. 1.2a–c and 1.3a–c). A recommendation on the type of transducer to be used depending on the nerve to be imaged and the clinical scenario is given in Table 1.1.

Table 1.1 Recommendation of transducers based on clinical context, type of nerve, and anatomical location

Transducer	Nerve	Clinical context
L9-3 MHz linear array or similar	Sciatic nerve (proximal), pudendal nerve, obturator nerve	Trauma
L12-5 MHz linear array or similar	Suited for most nerves, especially sciatic nerve (peripheral portion), extremity nerves, brachial plexus, etc.	Suited for almost all clinical scenarios, from compression neuropathy (measurement of nerve diameter and cross section), trauma to tumor imaging and especially suited for intervention
L17-5 MHz linear array or similar	Extremity nerves (median, ulnar, etc.) and peripheral branches of extremity nerves (superficial radial, posterior interosseous nerve, etc.), finger nerves	Compression neuropathy (evaluation of nerve texture, edema, etc.), trauma and postoperative lesions (scarring, partial dehiscence), neuritis
C9-4 MHz or C5-1 MHz curved array		Intervention in the cervical and lumbar spine

In general the smaller and more superficially situated a nerve is, the higher the transducer frequency should be

The future looks bright in terms of new hardware development with matrix arrays and improved crystal technology, but concerning transducer technology there is still a principal trade-off between rising frequency/improved resolution and depth of insonation.

1.1.2 Software

Various software tools are supplied with state-of-the-art ultrasound scanners. All of them attempt to improve image quality by management of the basic signal gained from reflection of sound waves inside the tissue. Generally speaking, these software tools – no matter what their name – improve image quality a lot and without them imaging of peripheral nerves would not have reached its current quality and status.

1.1.2.1 Compound Imaging

Meanwhile real-time image compounding has become a basic feature in state-of-the-art ultrasound scanners. One of the problems with conventional sonography is image degradation by coherent wave interference, known as "speckle." This shows as mottled superimpositions on images especially in regions with rather homogeneous tissue composition. The ultrasound companies use different names for the technique of image compounding, but basically the technique behind fancy names such as Sono-CT® (Philips), ApliPure® (Toshiba), or CrossXBeam® (GE) is somewhat similar: compound imaging averages several ultrasound frames in a single image. By use of the beam-steering software, the region of interest is scanned in different angles (frequencies or strain conditions), thus producing different artifact patterns (Fig. 1.4); averaging the single views results in improved definition of "real" tissue structures with marked reduction of artifacts (Piccoli et al. 2000). Newer developments enable the user to change the compound mode and to switch between modes for more enhancement of the region of interest and a quick overview mode. By reduction of image noise, speckle, dropout, or refractive shadowing, a better definition of tissue interfaces is achieved (Fig. 1.5a, b). Especially in peripheral nerve imaging, the details of a nerve and the discrimination of the epineurial/perineurial tissue are improved, which is why we generally perform nerve sonography with image compounding.

1.1.2.2 Harmonic Imaging

In "normal" B-mode sonography, a broad band of low frequencies is transmitted to the tissue inside the body. The reflected signal – which is detected by the transducer and produces the visible image – resonates off tissue in the body and has then a broad range of signal frequencies compared to the originally transmitted signal. Simply speaking, the sound waves travel into the body and back; therefore, they pass tissue interfaces twice and

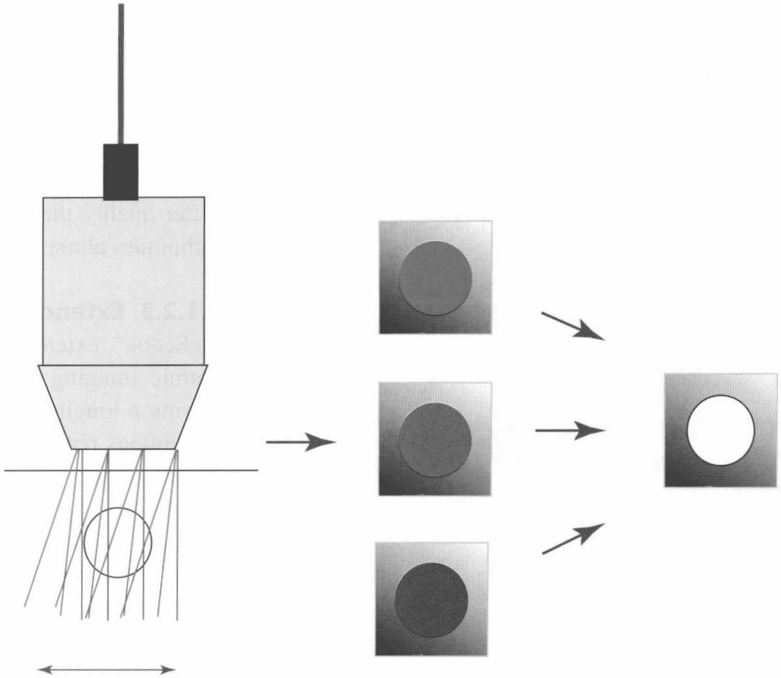

Fig. 1.4 Schematic drawing of compound imaging technique. The target is scanned from different view angles and the individual images from every angle (with different artifact pattern) are combined to one single image

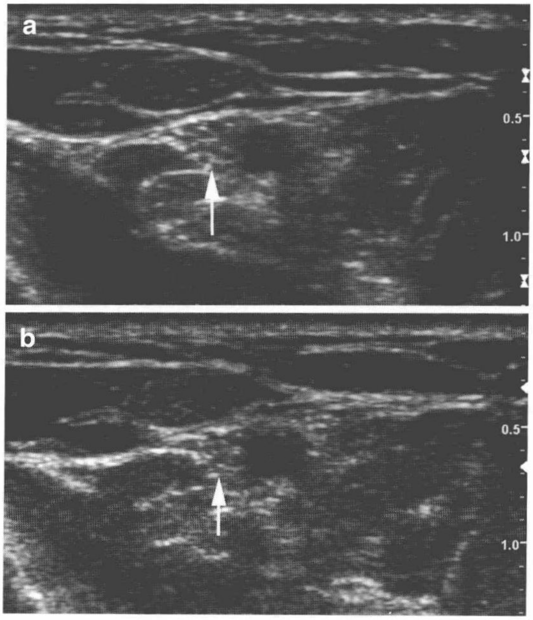

Fig. 1.5 Transverse ultrasound images through a median nerve (*arrow*) of a healthy volunteer taken with a 15 MHz transducer on a GE Logiq9 with (**a**) and without (**b**) image compounding. Note the improved detail in the compound image (distinct echoic inner and outer epineurium)

artifacts increase and sound energy decays exponentially. The physical principle of tissue harmonic imaging is actually quite simple: while travelling through the body, sound waves compress tissue, which results in a fractional increase of tissue density, a change in the sound speed, and distortion of the shape of the initial waveform. The angular components of the latter are the overtones or harmonics. These signals can be selected for imaging and have some advantages: they travel only one way toward the transducer; they are less prone to artifacts and lower in reverberations, which results in improved tissue contrast. As usual there is also a problem with this technique: harmonics are substantially less intense than the fundamental sound waves and therefore signal volume drops markedly. When harmonic imaging is used in a system with a good dynamic range, it results in exceptionally sharp images. This has proven of great benefit in abdominal imaging (Burns et al. 1996), but quite interestingly not so much for soft tissue imaging. The latter is especially true for the imaging of peripheral nerves (Fig. 1.6a, b). According to our experience, using

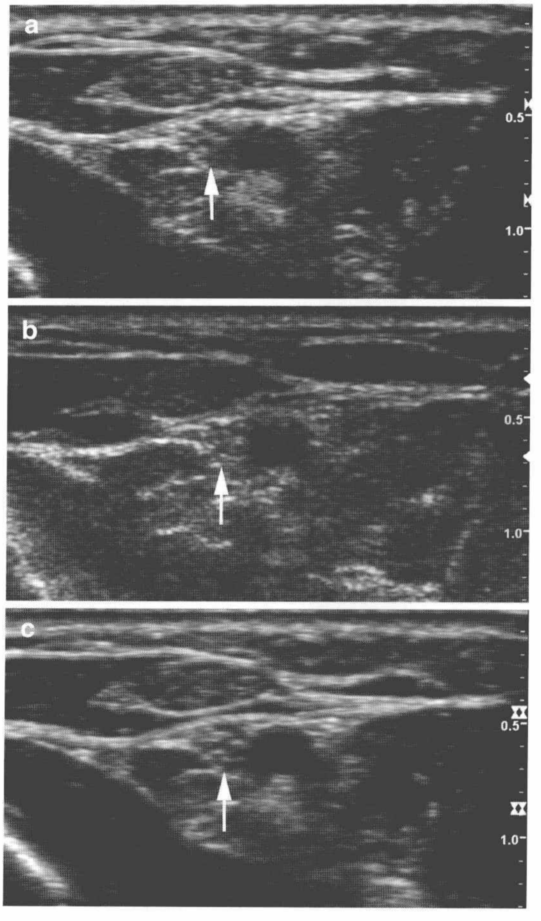

Fig. 1.6 Transverse ultrasound images through median nerve (*arrow*) in a healthy volunteer taken with a 15 MHz transducer on a GE Logiq9 with (**a**) and without (**b**) tissue harmonic imaging. In contrast to the effect of compounding (Fig. 1.5), there is only minimal change in the image quality by the use of harmonic imaging. The addition of image compounding to the harmonic image (**c**) results in the best image quality in this series of images

harmonic imaging does hardly improve image quality in high-resolution nerve scanning but even reduce image intensity. In any case tissue harmonic imaging should not be used without adding image compounding; the combination of both techniques gives in some cases added value, as it results in better quality than application of any of the two techniques alone (Fig. 1.6c)!

1.1.2.3 Extended Field of View Imaging

SieScape®, extended field of view imaging, panoramic imaging: different names for the same. During a longitudinal sweep of the transducer, a continuous registration of reflections takes place and dedicated software is used to build a longitudinal scan along the course of the sweep (Fig. 1.7). While initially only signals at the edge of a transducer were used for image construction, meanwhile special pattern recognition software is applied, which is responsible for the smoothness and resolution of a panoramic image. With application of the latter technique, the user can even easily adjust a sweep by moving back and forth to correct, for example, the loss of a target. The value of the technique lies mainly in the demonstration of complex lesions, documentation of the true extent of a lesion in one single image (Fig. 1.8), and size measurements which is especially appreciated by clinicians because of the better depiction of the local situation.

1.1.2.4 High-Resolution Imaging

Different software is used by the ultrasound providers to further enhance image quality and

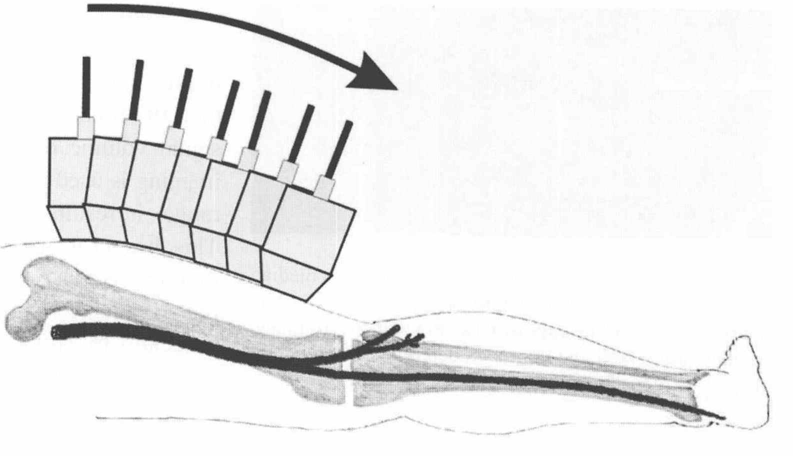

Fig. 1.7 Schematic drawing of extended field of view imaging: during a longitudinal sweep of the transducer along an area of interest, the image is continuously registered and subsequently calculated to one single image along the distance of the sweep

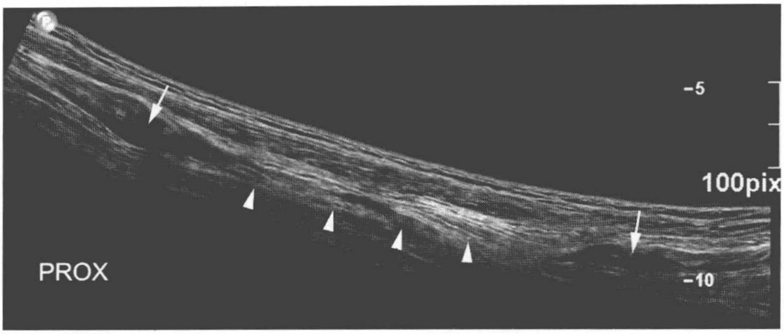

Fig. 1.8 Extended field of view image along the dorsal thigh in a patient with complete rupture of the sciatic nerve in a motor vehicle accident. Both ends of the nerve are thickened (*arrows*) with stump neuroma at the proximal end. Between the stumps there is a gap of almost 20 cm (*arrowheads*)

Fig. 1.9 Transverse ultrasound images through median nerve (*arrow*) in a healthy volunteer taken with a 15 MHz transducer on a GE Logiq9: addition of the company's proprietary image-enhancing software provided on the machine to an image with harmonics and compounding results in further improvement of image with exceptional clarity of tissue interfaces and profound artifact suppression (cf Figs. 1.5 and 1.6)

reduce artifacts. Most of that relies on some kind of pixel analysis, pattern recognition, and other dedicated analyses of the raw data of an ultrasound image. Afterward, a variety of image enhancing processes is used, with the general goal of image quality improvement by reduction of noise, speckles, and artifacts. While some companies have this software in the background as a simple turn "on" or "off" feature, some vendors allow for interactive changes of various settings. For the clinical sonographer, this means to spend some time and work at the scanner and know the "knobology": he has to accustom himself with the type of features that can be chosen on his scanner and to run a series of imaging trials to look for the best setting for the individual region of interest, examination task, and his personal preferences. We generally recommend these features, because they result in sharper tissue interfaces, borders, and margins (Fig. 1.9). Keep in mind that different body regions/imaging tasks and also patients (skinny patients, obese patients) may ask for different settings.

1.2 General Technique of Sonographic Nerve Examination

As it is the case for sonographic examinations in general, nerves must be imaged in two perpendicular planes; however, we recommend starting the exam in a transverse plane. Nerves are tubular structures with hypoechoic fascicular bundles interspersed by echoic connective tissue (Graif et al. 1991; Martinoli et al. 1996). This is why on longitudinal scans nerves are not easily distinguished from close-lying muscle tissue or tendons (Fig. 1.10). On transverse scans, this is much easier achieved, as nerves run along fascial planes embedded in fat and connective tissue – often together with vessels – and the honeycomb appearance of a nerve on a transverse scan is quite characteristic and easily distinguished from other anatomical structures. If there is a problem in distinguishing nerves and tendons on a transverse scan, we recommend tilting of the transducer to look for a signal change caused by anisotropy effects (Fig. 1.11): while tendons show a marked change of their signal from hyper- to hypoechoic, nerves show only a small change of signal with angled insonation. This is due to the fact that tendons have overlapping short fascicular elements, while nerves are long, continuous tubules.

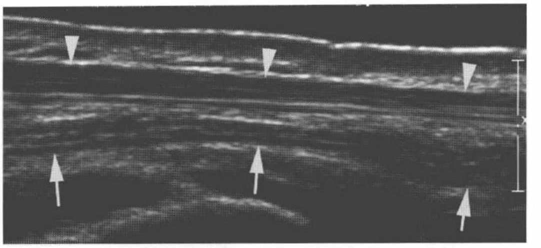

Fig. 1.10 Extended field of view image along the distal wrist with presentation of the ulnar nerve (*arrows*) and flexor tendons (*arrowheads*). Note the rather similar appearance of nerve and tendon on the longitudinal image, thus difficult differentiation

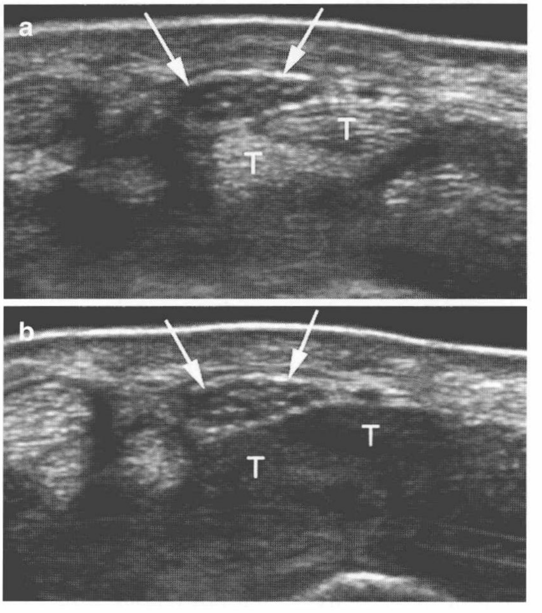

Fig. 1.11 Transverse ultrasound images through the median nerve (*arrows*) in a healthy volunteer taken with a 17 MHz transducer on a Philips IU22 with different transducer tilt position. Note the marked change of flexor tendon (*T*) signal from hyperechoic in (**a**) to hypoechoic in (**b**) but only minimal change of the median nerve

In general the presentation of nerves on high-resolution sonograms is exquisite and nicely correlates with the anatomical ultrastructure (Fig. 1.12) (Walker 2004). On transverse scans, you can experience the nerves' inner fascicular structure. Fascicles are the smallest structure to be discerned by modern sonography and are groups of nerve fibers surrounded by a common outer epi- and perineurial sheath (Silvestri et al. 1995; Maravilla and Bowen 1998). The single nerve fibers composed of axons, myelin sheaths, and Schwann cells are still beyond the resolution of sonographic imaging. An individual amount of fascicles comprises a peripheral nerve, which is surrounded by outer epineurium. How many fascicles combine to a peripheral nerve is variable and depends on the type of nerve (amount of motor and sensory fibers), its location in the body (distance from its origin, type of surrounding tissue), and its size. There is even a longitudinal variation of the amount of fascicles within a nerve, because fascicles repeatedly unite and divide along the course of the nerve, allowing the passage of axons from one fascicle to another. For the clinical sonographer, the fascicles and the epineurial tissue are important features, as changes in these two elements are the hallmark of distinct pathophysiological entities of peripheral nerve disease. Marked swelling of fascicles and loss of inner and outer hyperechoic epineurial borders, for example, may result from venous congestion and edema and are characteristic for

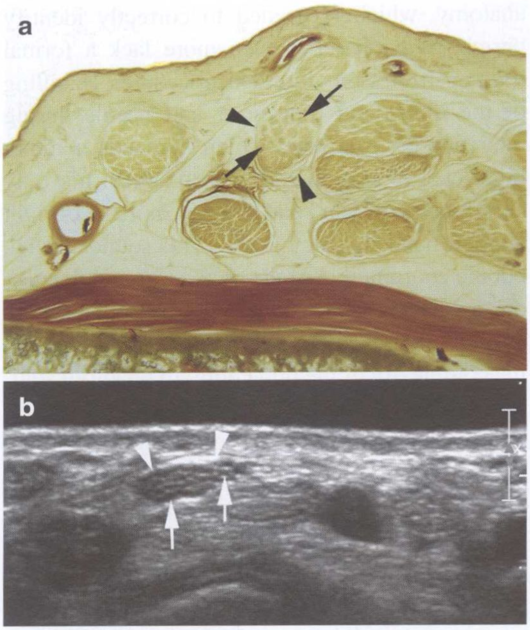

Fig. 1.12 Anatomical plastination specimen through wrist (**a**) with demonstration of median nerve ultrastructure (*arrowheads* outer epineurium, *arrows* fascicular bundle covered by inner epineurium). Corresponding ultrasound image (**b**) with demonstration of the same ultrastructural features

acute or subacute compression neuropathy (Buchberger et al. 1991; Chiou et al. 1998; Dahlin 1991). Thickening of a nerve and enlarged cross section but – in contrast to the aforementioned reaction – with hyperechoic thickening of the outer epineurium can be caused by chronic friction and thus are hallmarks of long-standing chronic neuropathy. So when performing peripheral nerve sonography, attention to the microanatomic texture of a nerve is important.

Especially with traumatic nerve injury, we often strive at the definition of nerve continuity (Bodner et al. 1999; Gruber et al. 2003, 2005; Peer et al. 2002). While the detection of complete transection is quite forward, the examination of injuries with incomplete severance of nerve fascicles or an attempt to define fascicular continuity after suturing has to be done with caution (Peer et al. 2001). The number of fascicles discerned by sonography does not always correspond to the real number of fascicles existing within a nerve. This is probably due to the coalescence of some adjacent fascicles in a single image. Keep also in mind that the number of fascicles seen on sonography decreases with reduced transducer resolution (reduction of frequency)!

Nerves are vascularized structures. Tiny nutrient vessels run along the nerve and penetrate it at frequent intervals along its course, communicating with the longitudinally oriented epineurial, interfascicular, perineurial, and intrafascicular arteries and arterioles. With state-of-the-art high-resolution transducers, these intraneural vessels are sometimes detected with duplex sonography; but up to date, we have only limited experience concerning what is normal and what is abnormal vasculature inside a nerve. There are reports on the presence of nerve hypervascularization in patients with compression neuropathies (Mallouhi et al. 2006; Ghasemi-Esfe et al. 2011), so analyzing a nerve's vascular state is potentially promising.

Nerves have a complex course and travel a long way from their exit at the spine until they reach their end organ. They form into bundles, exchange fibers, give way to small branches, and interconnect with each other. Therefore, imaging a peripheral nerve may be challenging. In many cases, however, the site of potential pathology is clear – as is the case for compression syndromes, which occur in distinct anatomical locations, where a nerve traverses through a narrow tunnel – and the exam is tailored directly to this region. As mentioned, this is the case for entrapment neuropathies, where the neural pathology is well localized, the local situation has typical anatomical features, and the nerve is easily found, measured, and diagnosed. For the evaluation of peripheral nerve trauma, however, the situation is more complex. Based on a neurological exam and/or electrophysiological studies, there may be a diagnosis of paralysis, motor weakness, or a nerve block, but the exact site of nerve compromise and its extent are less obvious in the case of a closed injury (such as traction). In addition hematoma or edema may obscure the local anatomy, by overshadowing or encasement of a nerve. In these cases a direct sonographic approach toward a presumed site of injury may turn out disappointing, even may result in misdiagnosis. For every nerve landmarks along its course, typical topographical relationships to close-lying bone, muscle, tendon, or vascular structures exist, which allow for an easy identification of a nerve at various sites. In clinical practice we therefore