
Introduction to Magnetic Resonance Imaging of the Peripheral Nervous System: General Considerations and Examination Technique

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2.1 General Considerations on Peripheral Nerve MRI

Ever since magnetic resonance imaging (MRI) got introduced in the armamentarium of medical imaging methods, it received highest interest from neuroscience. This method's superb soft tissue contrast allowed for unprecedented imaging of nervous tissue and developed very quickly into a standard method of brain and spine imaging. Over the past few decades, MR scanners became a routine tool and a mass product within affordable cost and thus widely spread. At the same time, rapid technical advances of the method opened the door for even more detailed imaging and complete new applications: to date, scanners with a field strength of 1.5–3T can be considered standard and allow for even more detailed imaging within acceptable imaging time. Cross-sectional imaging of nervous tissue can today be combined with numerous complementary scanning schemes, such as depiction of the vasculature with various MR angiography methods, insight into the biochemistry of nervous tissue and its pathologies with spectroscopy, and observation of nerve tissue function by exploiting tissue perfusion and blood deoxygenation effects with functional MRI. A more recent development in MRI is the ability to assess the Brownian molecular motion of water molecules termed diffusion-weighted imaging (DWI). This method is routinely used for the early depiction of ischemic stroke where hypoxic injury of the neural tissue leads to a shift of free interstitial water into

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swollen neurons (cytotoxic edema), thus reducing the free diffusibility of water molecules which results in a drop of the calculated diffusion coefficient. This imaging method is also used to facilitate the differentiation of dense cellular tumor tissue from inflammatory or infectious changes as well as scar tissue after tumor resection. Even more interestingly, DWI is also capable of assessing the foremost direction of free Brownian molecular motion, thus permitting the visualization of the nerve bundles' course within the spinal cord and cerebral tracts or, in case of injury, their anatomical or functional disruption.

Despite these fascinating capabilities of MRI, its use has so far mainly been focused on central nervous system diseases. The reasons for this are particularly numerous and diverse:

- Microsurgical procedures were not developed to the point to warrant a precise anatomical depiction of nerve injury.
- Electrophysiological studies were considered adequate to ascertain the clinical diagnosis.
- The distribution of mainly low- to midfield scanners with the at that time existing coil technology and scanning hardware and software did not allow for a reliable depiction of peripheral nerve structures.

MRI of the peripheral nervous system was mainly performed to rule out compression of neural bundles from surrounding structures, e.g., depiction of soft tissue tumors, hematomas, or cysts, as well as anatomical variants such as hypertrophic muscles and ligamentous restriction or impingement due to scarring upon a peripheral nerve: in most of these cases, it was sufficient to assess the course of the nerve in question without the need to precisely depict the nerve itself. Only in few instances as in the carpal tunnel syndrome, an effort was made to assess the diameter and the degree of flattening of the median nerve under the retinaculum. Also, the degree of edema with swelling and hyperintensity in T2-weighted images of the nerve proximal to its entry into the carpal canal was evaluated in these cases (Mesgarzadeh et al. 1989; Campagna et al. 2009) (Fig. 2.1). More often, the CTS syndrome being clinically clear and proven by electrophysiologic examinations, MRI was merely ordered to rule

out tumorous or inflammatory reasons of nerve impingement.

Another indication for performing an MRI examination is the depiction, classification, and follow-up of primary neural tumors (Fig. 2.2). Especially in cases of hereditary neurofibromatosis where multiple peripheral nerve tumors need to be observed, MRI offers a variety of advantages: modern scanners allow for multiple scan regions within one examination so that eventual central nervous tumors as well as peripheral schwannomas and plexiform neurofibromas in various parts of the body can be evaluated and reliably monitored using a repetitive standard imaging technique and documentation. Comparison of the actual images with technically identical images of prior exams allows early to pinpoint tumors with tendency of proliferation and rule out eventual malignant transformation (Wasa et al. 2010). These repetitive and sometimes “whole-body exams” with MRI do not endanger the patient with lifelong accumulating ionizing radiation.

In cases of suspected solitary neural tumors, MRI might help in ascertaining its presence or absence as in patients with neuroma formation after limb amputation or in patients with Morton's neuroma. Although ultrasound plays a predominant role in demonstrating the neural origin of such a tumor, MRI is of great value for the surgeon providing a clear anatomical picture of the tumor and its surrounding structures in multiple planes. Thus, MRI greatly facilitates resection planning (Figs. 2.3, 2.4).

In posttraumatic nerve damage, MR is capable to reveal or rule out nerve root avulsion from the spinal cord. In more distally located nerve damage as in peripheral nerve traction injury, there are at times only subtle signal changes to be detected in the compromised section along the course of the nerve: overstretching of nerve fibers leads to edematous changes with subsequent swelling of the nerve. These changes can be observed by MRI by comparing the diameter of the injured nerve with the contralateral nerve or the portion of the same nerve proximal and distal to the site of injury and visualizing its water content by using heavily T2-weighted sequences with spectral fat suppression. These changes in

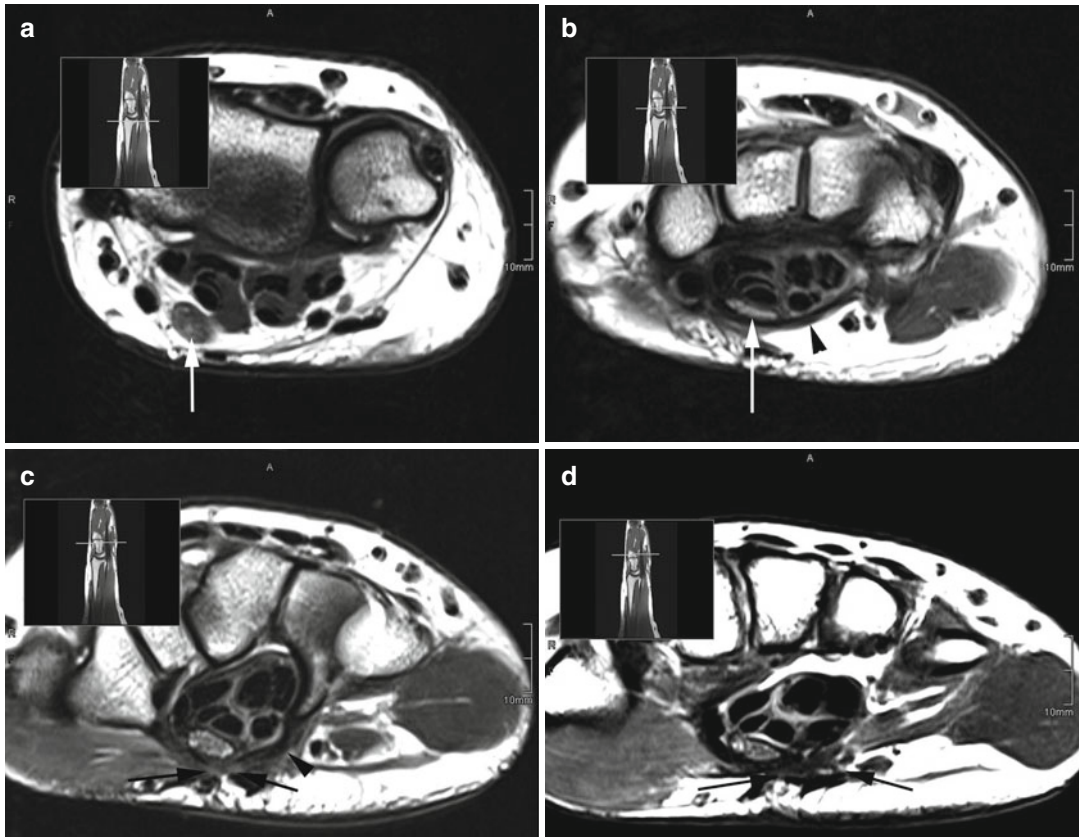


Fig. 2.1 Recurrent carpal tunnel syndrome (CTS) after insufficient dissection of the transverse carpal ligament. Axial T2-weighted images: (a) median nerve (arrow) at the level of the wrist joint before entering the carpal tunnel; the nerve is massively enlarged with increased signal intensity on T2 (higher than the signal of the adjacent musculature) indicating edematous changes of the nerve. (b) Marked flattening of the median nerve (arrow) at the entrance into the carpal tunnel due to the narrowed space between the flexor tendons and the portion of the transverse ligament left intact (arrowhead). (c) Dissected

portion of the transverse ligament at the level of the carpal tunnel (arrows). Note the bowing of the ligament near its insertion at the hamate bone indicating its laxity (arrowhead). The median nerve is decompressed, albeit showing edematous changes with fluid collections in the epineural spaces surrounding the individual nerve fibers. (d) Typical and normal fibrotic changes after surgery in the subcutaneous fatty tissue of the palm of the hand (arrows). The edematous reaction of the median nerve due to the entrapment more proximally extends as far as its bifurcation

T2 values of the injured nerve and their time course have been shown to correlate with the observed functional deficits in an animal model of peripheral nerve traction injury (Shen et al. 2010). Clinically, this method is mainly used to assess injuries to the brachial or lumbosacral plexus: the individual nerve roots subsequently conjoin to form distinct nerve trunks. All of these possess a sufficiently large diameter to make them readily visible on MR images. These scans

should always include coronal T2-weighted images with depiction of both sides of the plexus, so that the signal behavior of the affected area can be compared to the healthy contralateral side of a patient. Furthermore, MR is very sensitive to demonstrate collateral damages, like muscular edema or tears, bone fractures, hematomas, or diffuse edematous changes to the perineural fat indicating the site and severity of a sheer trauma.

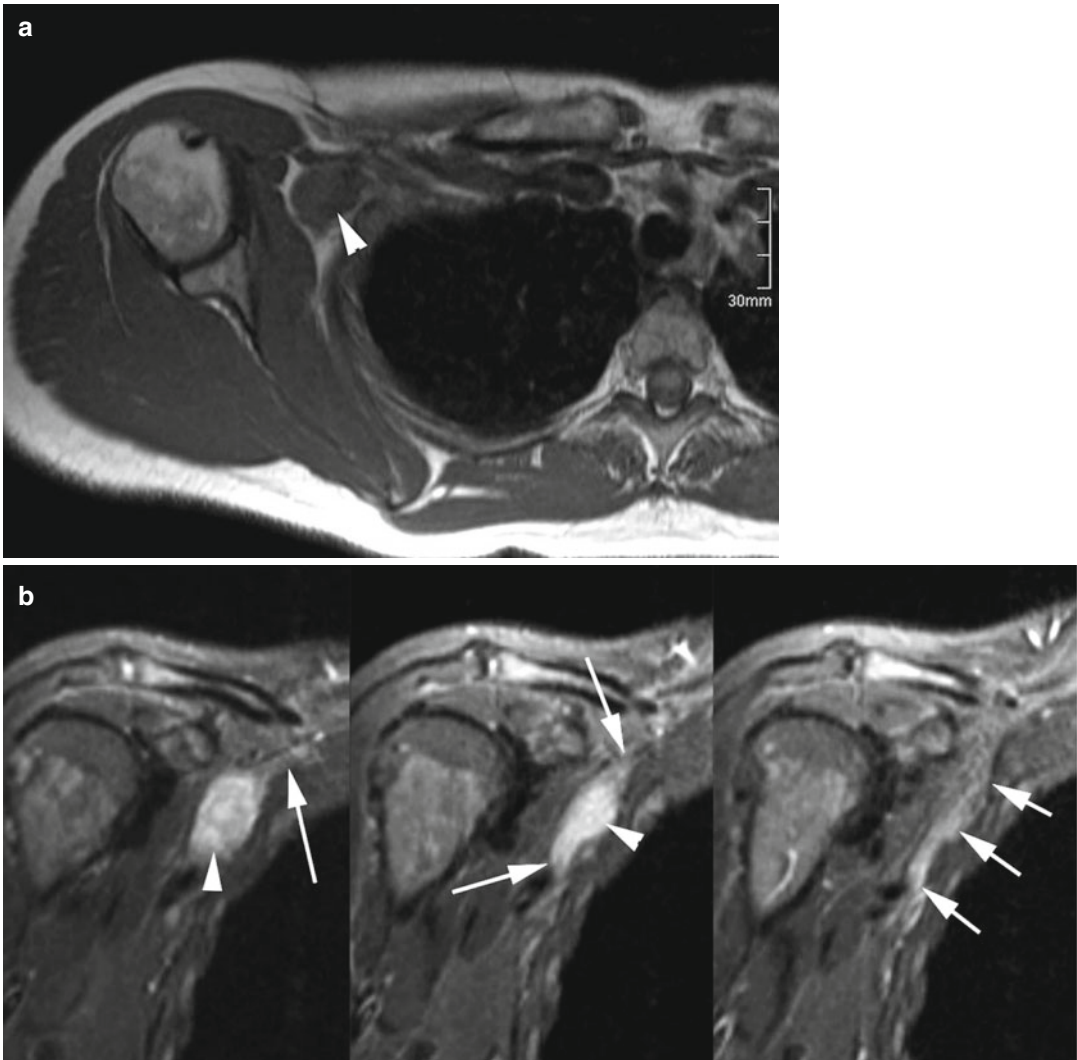


Fig. 2.2 (a) Axial T1-weighted image at the level of the right shoulder joint. A slightly oval mass of indeterminate origin (lymph node, primary soft tissue tumor) is noted in the axillary space (*arrowhead*). Note the progressive, cone like enlargement of the nerve at the proximal and distal

margin of the tumor. (b) Coronal T2-weighted inversion recovery images (TIRM) show the mass (*arrowhead*) arising from the enlarged and swollen trunk of the brachial plexus (*arrows*) indicating a primary peripheral nerve tumor. The lesion was histologically classified as a schwannoma

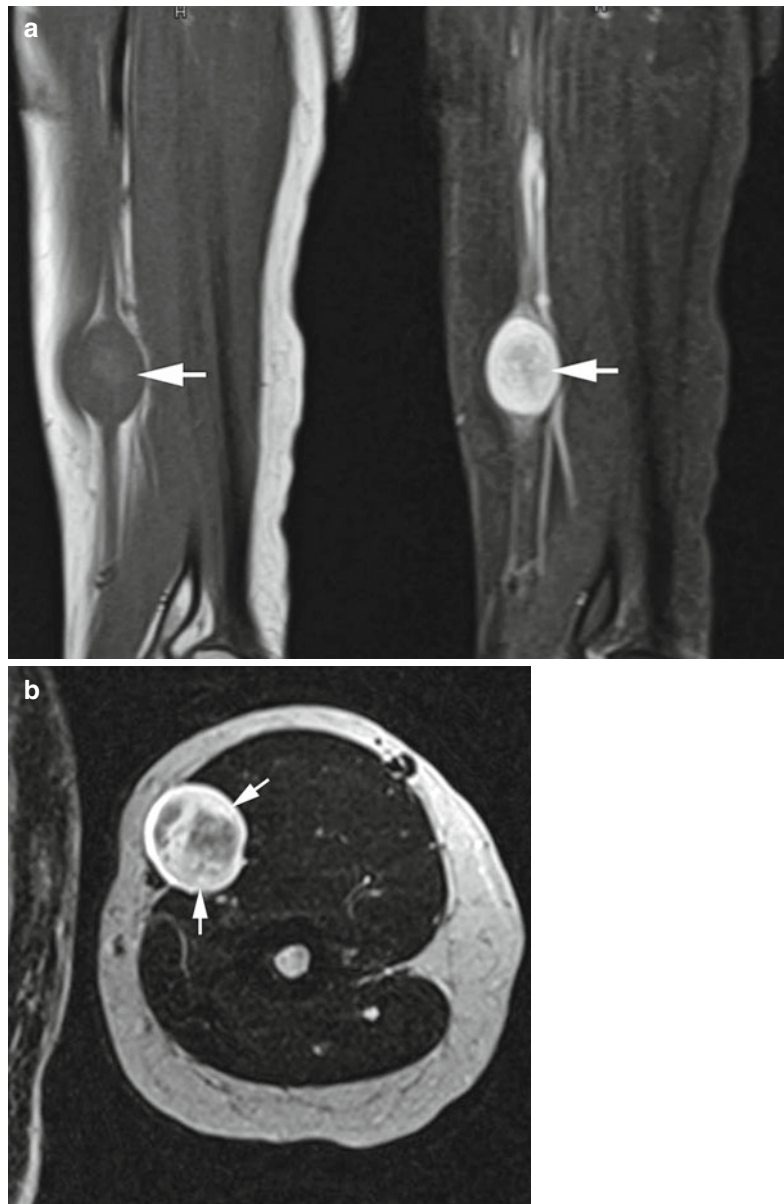
Peripheral nerves can reliably be imaged in MRI down to a diameter of about 2 mm. In T1-weighted images, used for a detailed anatomic survey, nerve structures have intermediate signal intensity, comparable to peripheral musculature. In order to be able to separate nervous from muscle fibers, we therefore have to rely on tissue of different signal behavior that separates nervous structures from musculature or skeletal bones. This is well known from sagittal images of the

spine where the nerve roots and ganglia can be easily identified within the neuroforamen at the level of the thoracic and lumbar spine due to the surrounding perineural fat. In the cervical spine, however, there is substantially less fatty tissue within the neuroforamen, so that the nerve root is less easily identifiable, especially in patients with low body mass index. In large nerves, there is always a sufficient amount of surrounding fat causing high signal in T1-weighted images to

make them easily identifiable. In even larger nerves, like the sciatic nerve, there is also adipose tissue interspersed between the perineural sheets of the individual fascicles which renders them visible. In smaller nerve fibers that abut musculature or have an intramuscular course the lack of surrounding fatty tissue impedes their detection, even when their diameter is substantially larger than the minimal resolution provided by the imaging sequence. Therefore, routine use of MRI

in the peripheral nervous system is somewhat restricted: apart from the cervical-brachial and lumbosacral plexus, larger nerves of the upper extremity like the radial, ulnar, and median nerve down to the forearm and the median and ulnar nerve at the level of the wrist are routinely examined by MRI. In the lower extremity, the sciatic nerve as well as the tibial and peroneal nerves can be imaged down to the level of the lower leg (Maravilla and Bowe 1998).

Fig. 2.3 (a) Sagittal T1-weighted (*left*) and T2-weighted inversion recovery image (TIRM – *right*) of the left upper arm showing a “tumor on a string” (*arrow*): the enlarged median nerve proximal and distal of the tumor can be clearly identified due to the surrounding fat in the T1-weighted image (*left*) and the bright edema on the T2-weighted image (*right*). Note the progressive, cone-like enlargement of the nerve at the proximal and distal to the tumor. (b) Axial T2-weighted image showing the extent of the tumor within the median bicipital groove and its internal inhomogeneity (*arrows*). (c) Series of axial T2-weighted images with spectral fat saturation: enlarged and abnormally bright median nerve (*arrowhead*) giving rise to the mass (*arrows*)



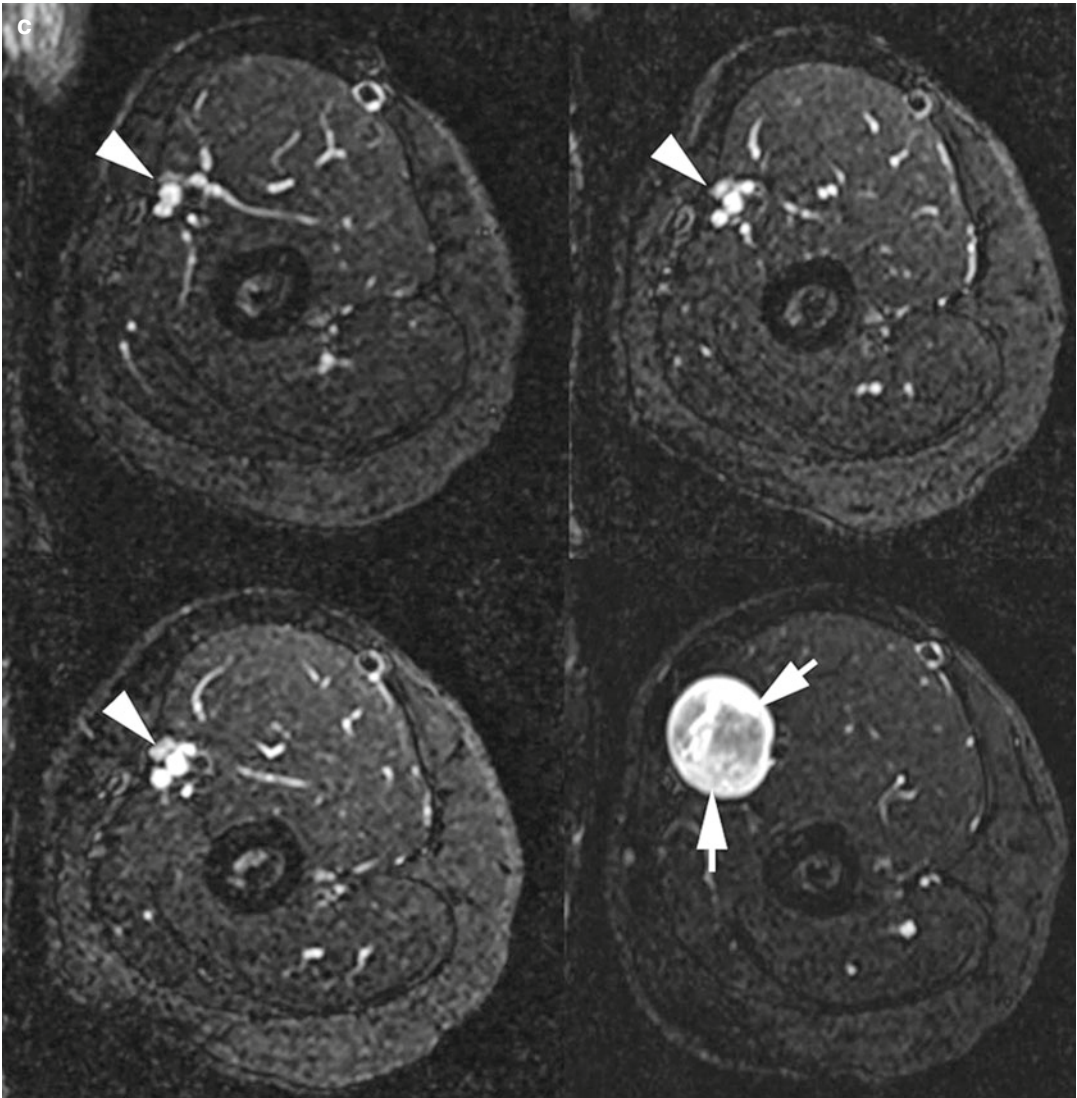


Fig. 2.3 (continued)

There are limitations in the assessment of pathologies of smaller nerves with MRI, especially in patients with degenerative nervous diseases. In these cases, there is only a very limited edematous reaction of the nerve secondary to the disease so that T2-weighted images fail to depict an enlarged and unusually hyperintense nerve. Contrast administration shows a markedly increased uptake in cases of acute inflammation; however, in chronic changes the inflammatory changes are much too subtle to

reveal pathologic hyperperfusion. Nevertheless, MRI can be of great diagnostic value also in these cases: denervation of musculature causes signal changes in the muscle groups affected, which can readily be depicted by MR imaging. Muscle edema in early denervation and fatty degeneration and atrophy of the musculature at a later stage of a disease pinpoint the site of nervous damage, although the structural damage of the nerve itself cannot be visualized (Chhabrand and Andreisek 2012).

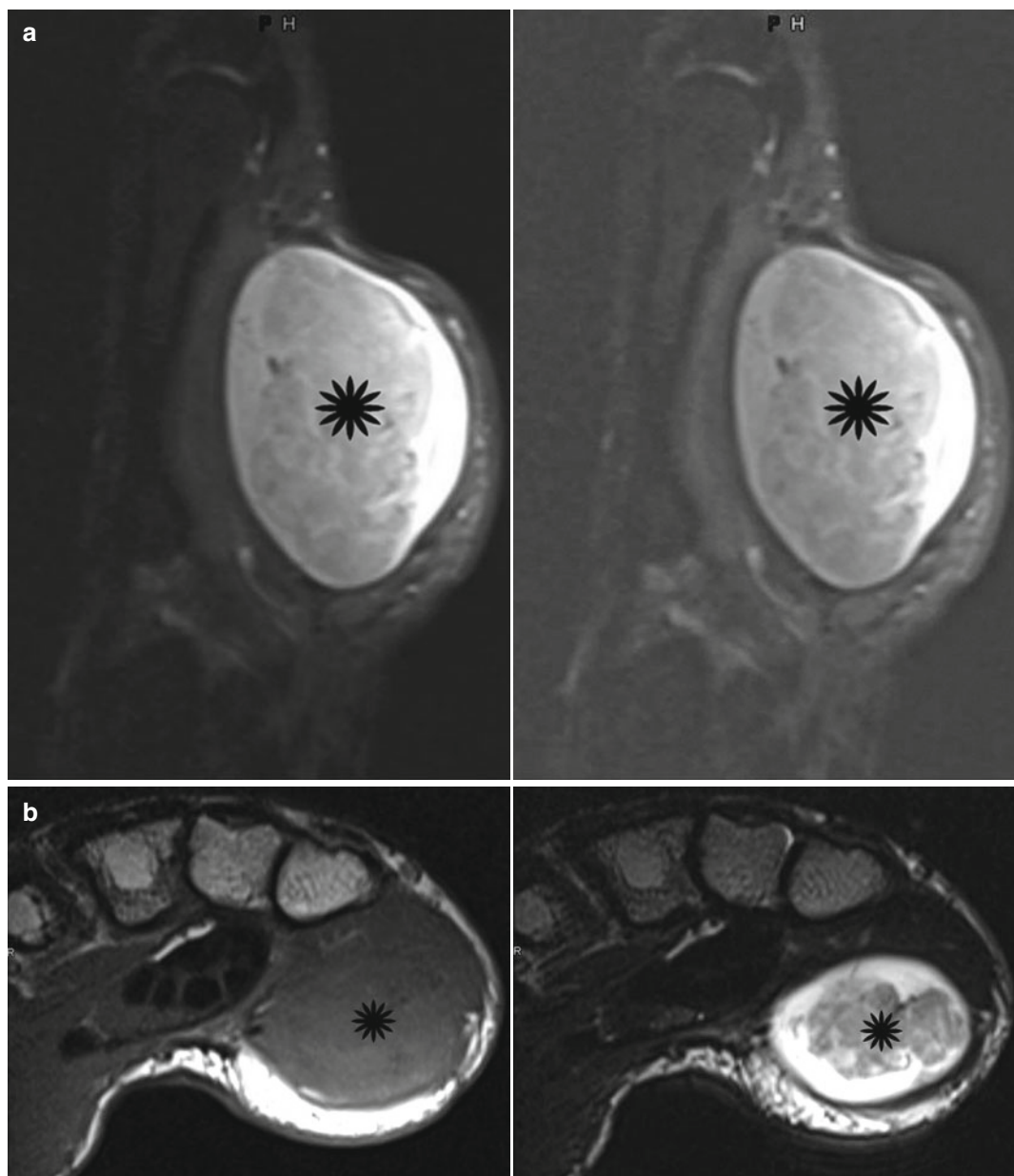


Fig. 2.4 Schwannoma (*asterisk*) of the ulnar nerve: (a) sagittal TSE T1 (*left*) and T2 TIRM (*right*) images of the hand. At the proximal end of the tumor, a portion of the ulnar nerve can be identified with a cone-shaped enlarge-

ment connected to the tumor: mass with “nervous tail.” (b) Axial TSE T1- (*top*) and T2-weighted (*bottom*) images showing the extent and the inhomogeneous signal characteristics of the schwannoma (*asterisk*)

2.2 Measurement Sequences and Protocol Design

Imaging of peripheral nerves requires first of all a very detailed anatomical survey of the region of interest. This is best achieved by spin echo or turbo spin echo T1-weighted sequences. These images should be angulated along the direction of a nerve under investigation and, in a second plane, perpendicular to a nerves' course producing axial cross-sectional images. These sequences yield a high tissue signal thus allowing for very small imaging voxels with little background noise that would otherwise obscure image contrast. These sequences can be measured with almost all commercially available scanners; however, the stronger the static magnetic field, the higher the resonance signal gets. In lower-field scanners the same signal increase, and thus the ability to measure equally fine detailed images can be achieved by increasing the number of excitations: two excitations means that the same image plane is measured twice and the signal is internally averaged prior to image reconstruction. The gain in signal-to-noise ratio is unfortunately only by a factor of $\sqrt{2}$. However, an increase of the base magnetic field from 1.5T to 3T offers an approximately twofold signal gain. In order to achieve the same signal-to-noise ratio with the 1.5T scanner, four excitations would therefore be needed thus quadrupling imaging time: although lower-field scanners allow for adequately detailed anatomical imaging to assess the peripheral nervous system, time limitations could make such diagnostic procedures problematic in daily clinical practice.

Apart from the static magnetic field strength, coil technology is crucial for an optimal exploit of a resonance signal. Coils are antennas, picking up the resonance signal from within the patient's body. The smaller the coil, the better its signal gain; however, the overall scan area and the depth of penetration are at the same time reduced. Sophisticated multichannel array surface coils greatly facilitate high-resolution imaging by combining a set of smaller coils into one coil compound. This technology is quite demanding on scanner hardware and software and therefore

cost intensive but allows for detailed imaging of more extensive areas of the patient's body while maintaining reasonable scan times.

The second set of sequences routinely used in imaging of peripheral nerves are turbo spin echo T2-weighted images with frequency-selective fat saturation. Alternatively, T2-weighted short TI inversion recovery images (STIR) can be measured – a comparable sequence where a different method to suppress the fat signal is used. These sequences are even more demanding for the scanner as they yield substantially less signal from the area under examination and the images can easily be obscured by background noise especially in low-field scanners. These images however are of high diagnostic interest: they mainly show the water content within anatomic structures and thus are very sensitive to edematous changes in any tissue. Whereas a normal, small peripheral nerve can be overlooked on these images, it is clearly shown as soon as it is enlarged due to an edema and its accordingly elevated water content (Fig. 2.5). This effect can equally be detected in cases of nerve entrapment or in posttraumatic lesions as in traction injury (mechanical edema), in infection (inflammatory edema), or in tumors where a combination of mechanical edema and inflammatory edema caused by an immunological reaction to the tumor growth occurs.

The use of contrast agents is generally not warranted in peripheral nervous imaging. Intravenous gadolinium should however be administered in patients with suspected infectious disease: inflammatory changes lead to a hyperperfusion of nerve bundles that can be visualized by “dying” the blood with a contrast agent. Inflammatory hyperpermeability of the endothelium also causes increased extravasation and thus accumulation of contrast agent in the extracellular space. To increase conspicuity, a fat-saturated T1 sequence should be used to cancel the bright signal from normal adipose tissue so that only the hyperintense signal from (hyper)perfused tissue remains. To distinguish contrast agent effects from normal bright structures in an image, it is mandatory to measure the exact same sequence before and after contrast administration.

Intravenous contrast agents should also be used in all cases where tumor formation is suspected. Gadolinium gives important information about the degree of vascularization of the tumor, helps to identify necrotic changes, and can at times aid in classifying the entity of the tumor.

Alternatively to fat-saturated spin echo or turbo spin echo T1 sequences, sometimes short TE volumetric 3D gradient echo sequences with either fat saturation or selective water excitation are used for pre- and postcontrast imaging. Although these sequences generally have a very high T1 contrast showing contrast agent accumulation in tissue with great conspicuity, their anatomical clarity is inferior and they are prone to produce various imaging artifacts.

Similarly, T2*-weighted 3D sequences can also be used instead or in adjunction to T2 or STIR sequences for the visualization of edematous changes of peripheral nerves. The use of such volumetric data acquisition methods is advantageous when secondary reconstructions of the acquired 3D data sets are needed. So, even a tortuous course of a nerve can be visualized in a single plane by calculating secondary curved reconstructions.

Apart from conventional imaging with T1- and T2-weighted spin echo or turbo spin echo

sequences and 3D imaging, various modern and more sophisticated imaging techniques are presently under investigation for assessing peripheral nerves anatomically and possibly also functionally.

One of these novel approaches is called magnetization transfer imaging and emphasizes on the ratio and exchange rate of protein-bound and free water protons present in nerve tissue (Gambarota et al. 2012). Although the measured magnetization transfer ratio shows a physiologic variation between differently sized nerves (possibly due to differences in fascicle content), it seems to be sensitive for nerve damage within equally sized nerves or when compared to a healthy contralateral side. However, the value of this method has yet to be proven in daily clinical practice.

Diffusion-weighted imaging (DWI) on the other hand is a standard imaging scheme and widely used in central nervous system imaging. It has also been used to facilitate the detection of peripheral nerves in a whole-body MR examination (Yamashita et al. 2009). Apart from the intensity of the random microscopic motion (Brownian motion) of water molecules, their prevailing direction can also be assessed in diffusion-weighted sequences. Since the motion of

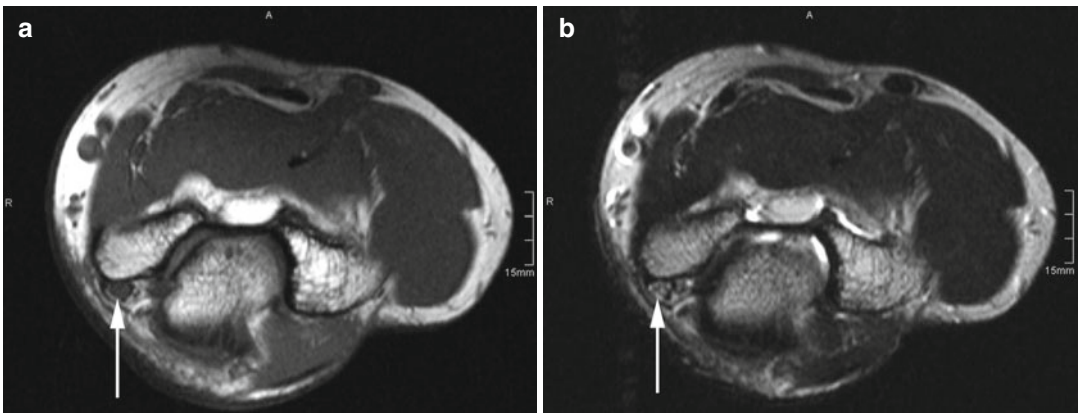


Fig. 2.5 (a) Axial T1-weighted image of the elbow at the level of the humeral condyle. The *arrow* indicates an enlarged ulnar nerve surrounded by perineural fat and abutting the bone. (b) Axial T2-weighted image demonstrating edematous changes within the swollen nerve (*arrow*). (c) Axial reconstructions of a 3D T2*-weighted sequence (DESS 3D) with selective water

excitation: the ulnar nerve (*arrows*) can be easily followed in its course proximal, within, and distal to the ulnar nerve groove due to its bright signal (neural edema). (d) Single source image of the original 3D DESS data set in coronal orientation showing the portion of the ulnar nerve (*arrow*) running posterior to the medial humeral epicondyle

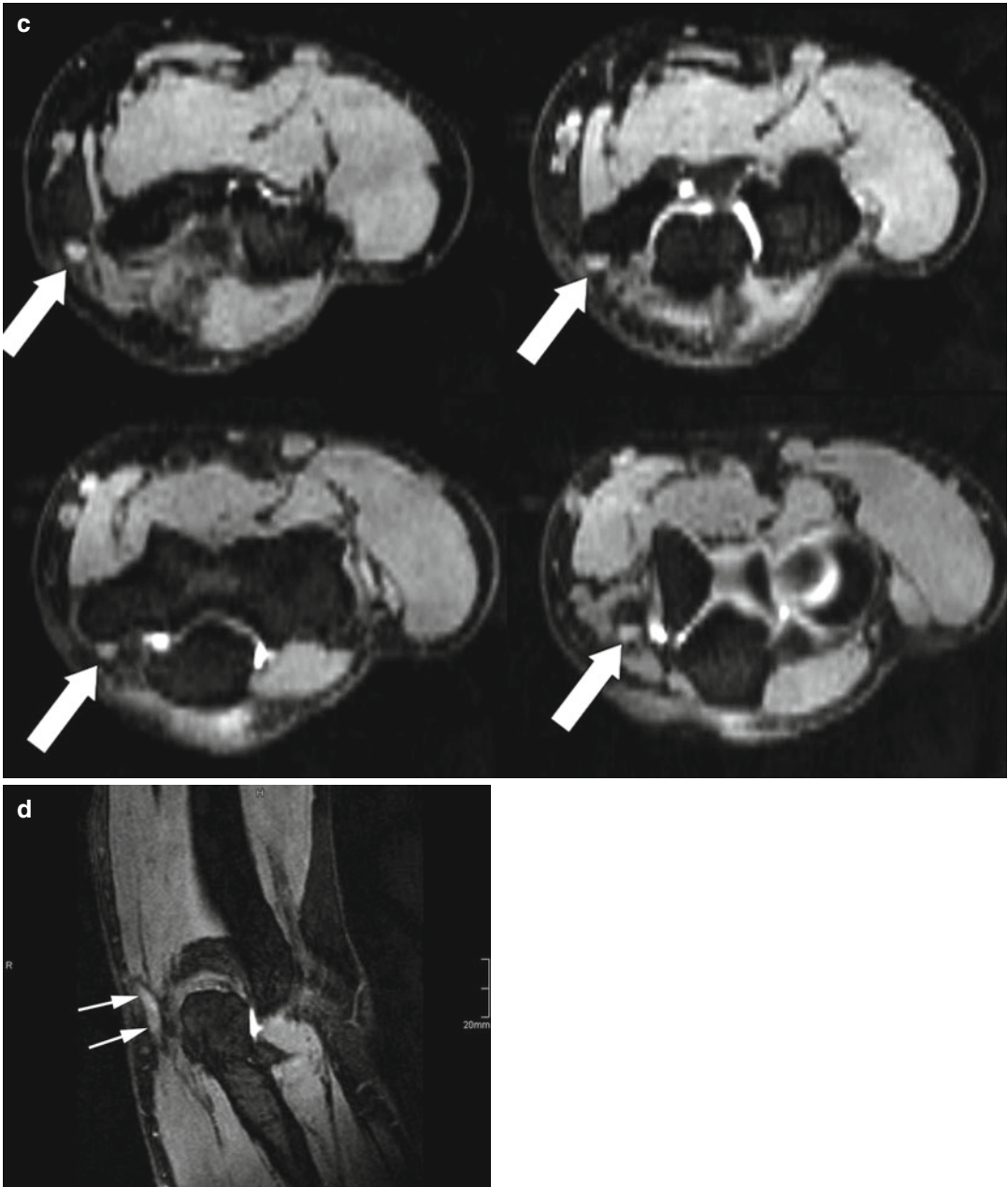
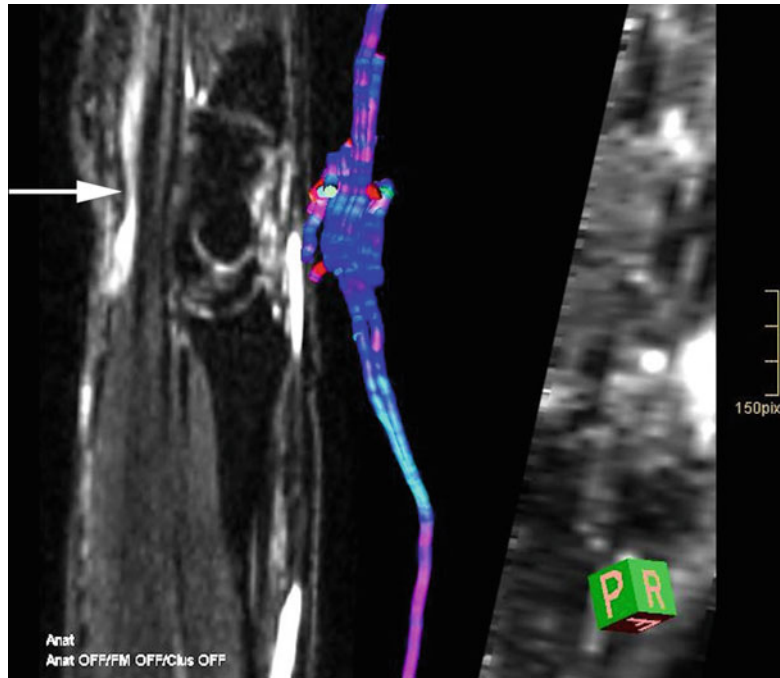


Fig. 2.5 (continued)

water molecules is impeded by membranes, its foremost direction follows the course of nerve bundles (Fig. 2.6). In the central nervous system, these anisotropic diffusion properties of nervous tracks are used to identify the course of nerve fibers within the medulla and the brain. One of its clinically important uses is to preoperatively help

identify displaced tracts and thus permit to save their integrity when a space-occupying lesion needs to be resected. This variant of DWI is called diffusion tensor imaging (DTI) and shows promising results also for the peripheral nerve system, not only showing the nerve bundles themselves but also permitting to assess their integrity

Fig. 2.6 Recurrent CTS (same patient as in Fig. 2.1). Direction-sensitive diffusion-weighted imaging called “diffusion tensor imaging” (DTI) allows for a 3D reconstruction of the molecular water motion within the nerve fascicles. Intact nerves can be followed by using seed points from where the computer generates images along a nerve’s course and displays color coded its direction. Note the compression of the median nerve at its entrance into the carpal tunnel depicted on one of the sagittal source images (*arrow*)



(Skorpil et al. 2007; Kakuda et al. 2011). This measurement scheme, however, suffers from an inherent low signal-to-noise level. To obtain satisfactory images in small peripheral nerves, it is mandatory to use a high-performance gradient system and, preferably, a high-field MR scanner.

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