MR Neurography – Diagnostic Criteria to Determine Lesions of Peripheral Nerves

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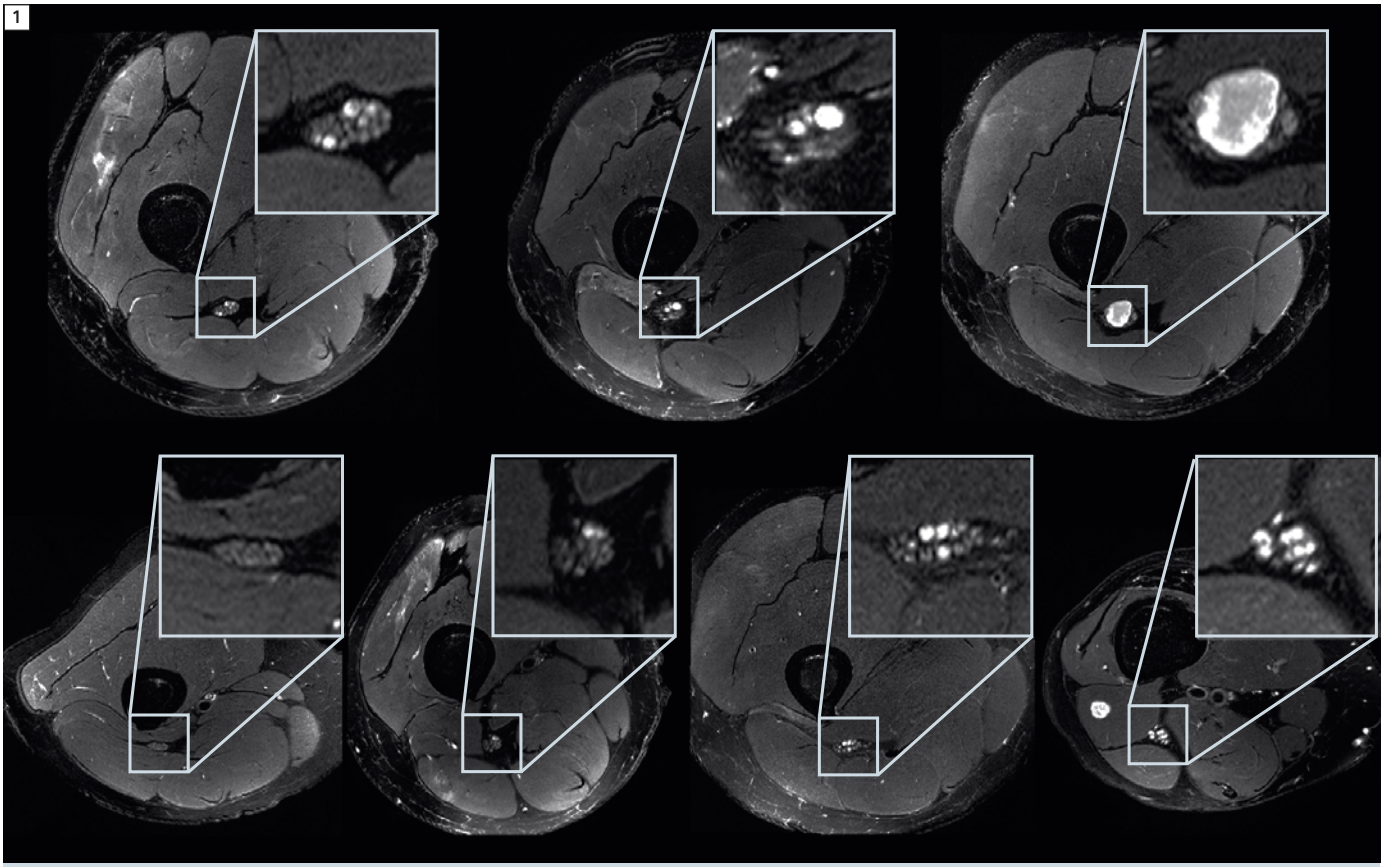
I) Introduction with potential clinical indications

Clinical examination and electrodiagnostic testing comprise the traditional methods of diagnostic investigation in peripheral nerve disease. These are excellent tools to assess function of peripheral nerves but can be limited in localizing a lesion. Recent developments in MR scanner and coil technology and the refinement of pulse sequences for increasing structural resolution have allowed imaging of fine details in healthy and diseased peripheral nerve [1, 2]. MR Neurography (MRN) at high magnetic field strength of 3 Tesla allows for the visualization of peripheral nerves at the fascicular level – the fascicle being the first order subunit of a peripheral nerve. The major limitation of clinical and electrophysiological examination is precisely the strength of MRN: the exact localization of nerve lesions. Lesion localization and spatial lesion patterns in the periph-



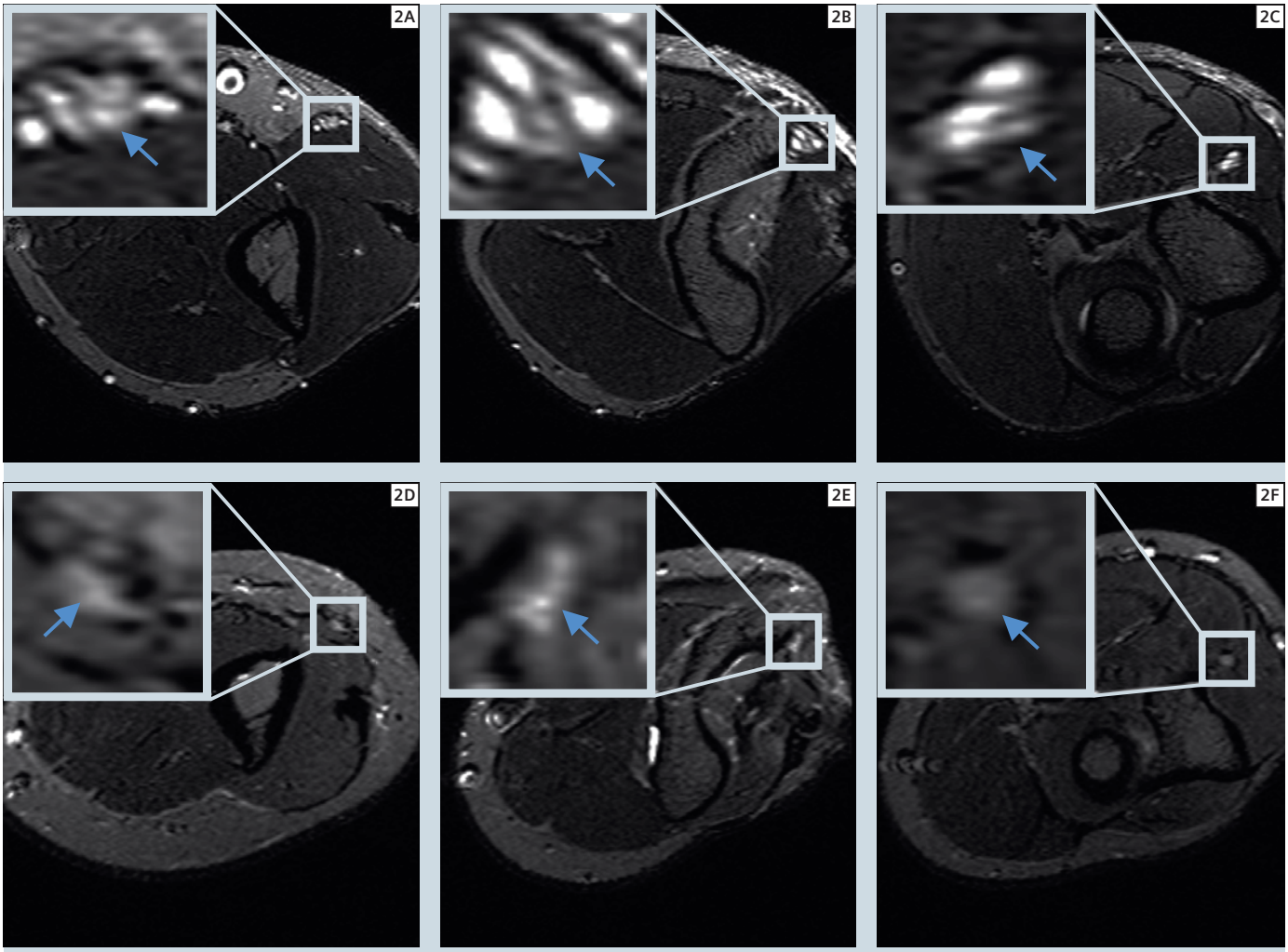
1 T2-weighted sequence with fat saturation at high resolution allows for imaging of peripheral nerves at the fascicular level. The sciatic nerve is shown here in hereditary NF2 polyneuropathy with various lesions ranging in size from pretumorous microlesions affecting only individual fascicles with no significant caliber change (lower row) to severe caliber thickening and enlargement of the entire nerve cross-section as in true, full-blown schwannomas (upper row, right panel). *Modified from Baumer P. et al. Accumulation of non-compressive fascicular lesions underlies NF2 polyneuropathy. J Neurol. 2012, with permission.*

eral nervous system are, as in many diseases of the CNS, arguably among the most important pieces of diagnostic information.
One typical example for the use of MRN is the differentiation between spinal nerve root compression (radiculopathy), plexus affection and peripheral nerve lesion (peripheral neuropathy). Another frequent and important situation is the differentiation of a focal mononeuropathy, which is potentially surgically amenable, from neuropathies with involvement of more than one nerve. These oligo- or polyneuropathies almost exclusively exhibit a disseminated lesion pattern stemming from an inflammatory, immune-mediated, metabolic or hereditary origin, so that nerve surgery is not a primary therapeutic option.
In traumatic nerve injuries, exact lesion localization is the central diagnostic step in pre-surgical work-up. The assessment of nerve continuity and the identification of potential scar tissue within and around the nerve yield essential diagnostic information. In cases of true neuroma with discontinuity of the nerve, early indication for reconstructive nerve surgery by MRN can improve outcome. However, in instances where MRN shows a neuroma in continuity, surgery may become unnecessary since spontaneous recovery may occur under clinical monitoring.

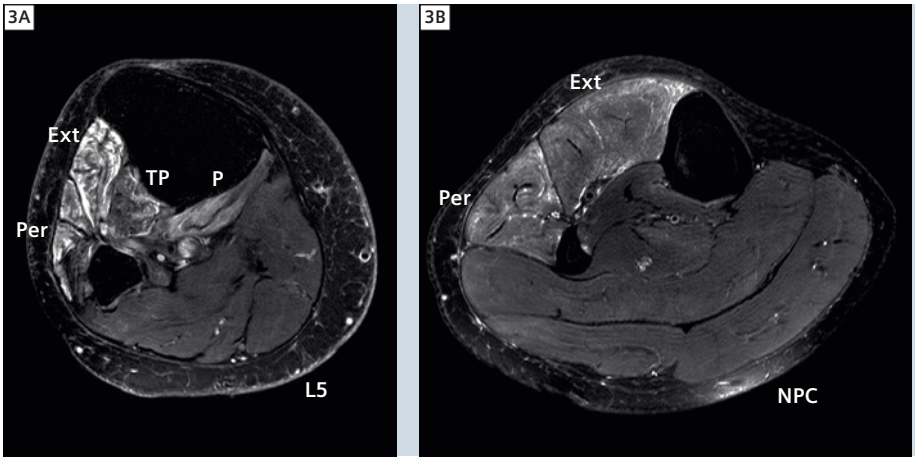
II) How I do it

a) MRN protocol

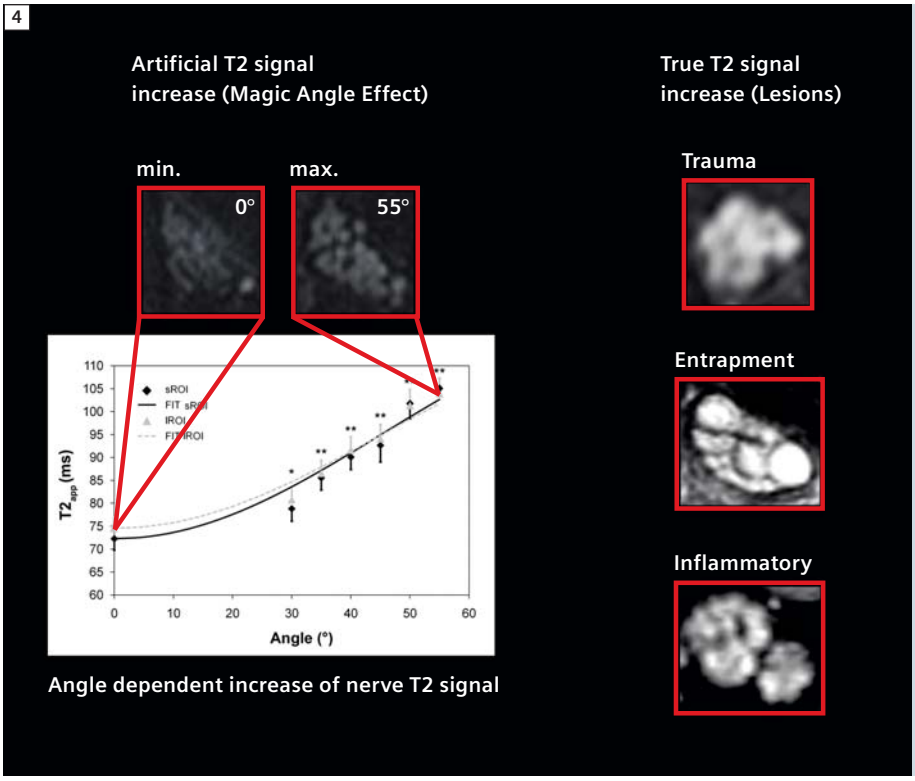
A magnetic field strength of 3 Tesla is advisable to achieve high-resolution images at the fascicular level of peripheral nerves. We perform clinical examinations on a Siemens MAGNETOM Verio 3 Tesla MR System (Siemens Healthcare, Erlangen, Germany) which allows comfortable positioning due to its wide bore diameter. The MRN protocol varies depending on the body region of interest and the clinical-diagnostic question. In the vast majority of patients, T2-weighted fat-saturated sequences are acquired, which show high contrast of nerve lesions to



2 Typical findings in cubital tunnel syndrome, a common entrapment neuropathy. The upper row depicts a typical compressive focal ulnar nerve lesion at the elbow from proximal **(2A)** to distal **(2C)**. Nerve T2w signal and caliber are severely increased compared with healthy control (lower row). *Modified from Baumer P. et al. Ulnar neuropathy at the elbow: MR neurography-nerve T2 signal increase and caliber. Radiology. 2011;260(1):199-206, with permission.*



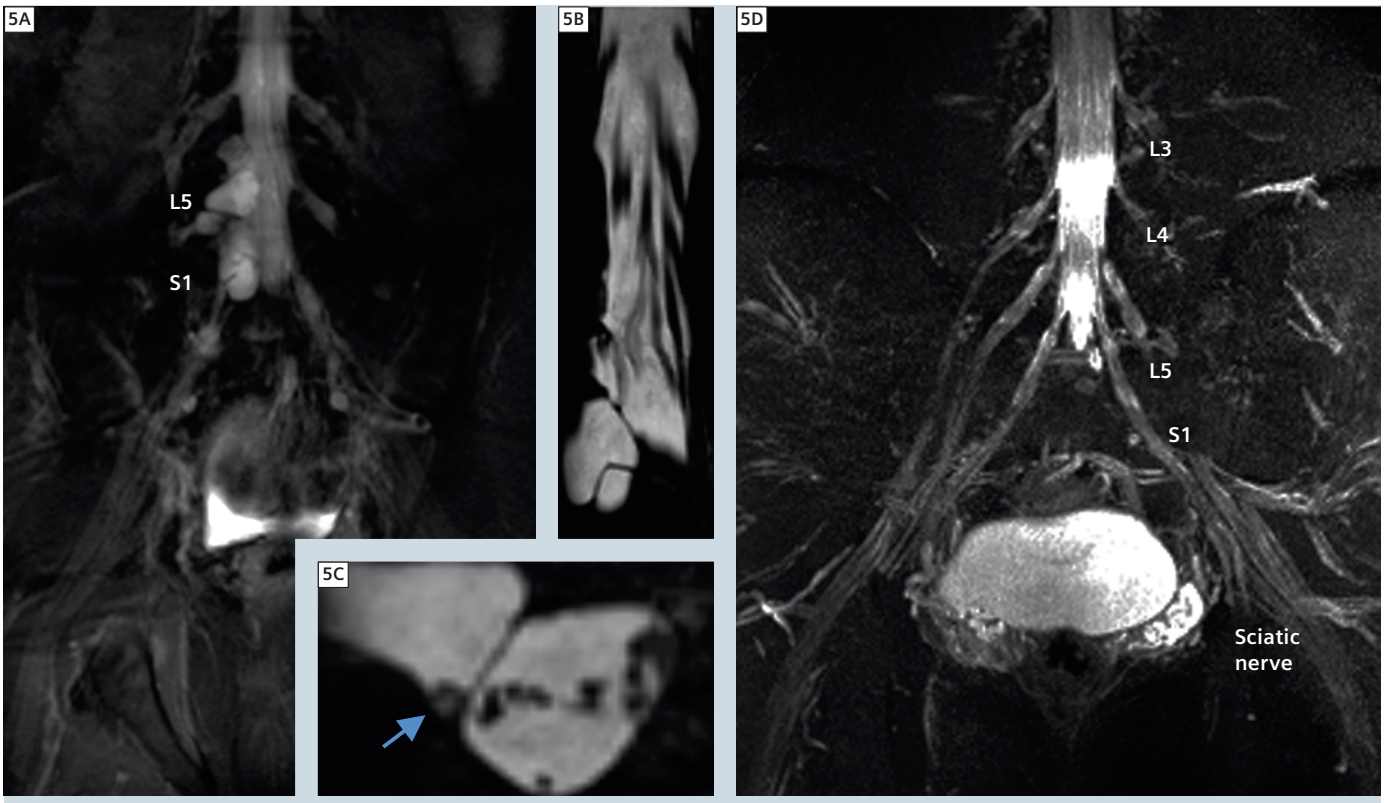
3 Inferring the site of nerve lesion from the comprehensive evaluation of muscle denervation patterns. **(3A)** The denervation pattern in a patient with an L5 lesion additionally includes the posterior tibial muscle and the popliteal muscle. **(3B)** Patient with a lesion of the common peroneal nerve (NPC). The denervation is confined to the extensor compartment (here shown the anterior tibial muscle and extensor digitorum muscle) and the peroneal compartment (long and short peroneal muscle). Both compartments are known to harbor exactly the target muscles of the common peroneal nerve.



4 The magic angle effect occurs in tissue which is densely composed of collagen, such as in tendons, but also peripheral nerve. On the left the increase in T2 relaxation time can be seen as a function of angular deviation of nerve from the main static magnetic field (B_0). The first maximum of this cosine type function is reached at 55°. The T2 signal increase is visually apparent (zoomed inserts above graph) at the maximum magic angle position of 55° in comparison with the neutral position (0°). However, true nerve lesions in neuropathies of various origins can usually be discriminated easily by the much stronger T2 signal increase (right column, traumatic, compressive and inflammatory true nerve lesions). *Modified from Kaestel et al. AJNR Am J Neuroradiol. 2011 May;32(5):821-7, with permission.*

surrounding tissue (Fig. 1). This may be complemented by T1-weighted sequences, with and without contrast administration, and T1-VIBE or TrueFISP for 3D reconstruction. T2-weighted SPACE STIR sequences at isotropic voxel size allow for imaging at submillimeter resolution of brachial and lumbosacral plexus structures. CISS may be added for imaging of intradural filaments in cases of trauma. Choosing appropriate radiofrequency coils is crucial for image quality and diagnostic performance. For extremities, we use an 8-channel knee coil (Siemens Healthcare, Erlangen, Germany) for most regions. For brachial plexus structures, we additionally acquire high-resolution sequences using dedicated surface coils (multichannel phased-array 2 element coil, NORAS GmbH, Höchberg, Germany).

The applicability of diffusion tensor imaging (DTI) by echo-planar-imaging (EPI) has been investigated for many years [3]. It is currently not used in routine clinical examinations and its diagnostic accuracy has so far only been studied for carpal tunnel syndrome [4]. Various technical issues may limit the clinical significance of application of EPI DTI in the near future, most importantly its structural resolution, which is significantly inferior to T2-weighted sequences and constrains its use to large peripheral nerves of the extremities. Segmented EPI could help to overcome these limitations. Extent of coverage of an MRN examination is decided on a case-by-case basis. In the setting of focal nerve damage, the examination can be targeted to one region by different sequences. Occasionally, larger coverage of an entire extrem-



5 Traumatic lumbosacral plexus injury. **(5A)** Coronal SPACE STIR gives an overview of lumbosacral plexus and proximal sciatic nerve. Pseudomeningoceles of L4 – S 2/3 indicate root avulsions on the right side. **(5B)** Additional CISS of the lumbosacral spinal canal in coronal reconstruction confirms roots avulsions of L5 – S2. **(5C)** Axial reconstruction of CISS. Dorsal portions of the right L4 root appear intact at least in their intraspinal course. **(5D)** Coronal SPACE STIR maximum intensity projection (MIP) of a normal lumbosacral plexus including the proximal sciatic nerve.

ity including the plexus and at the same time high resolution may be useful. One such example is the hereditary polyneuropathy in neurofibromatosis type II [5] where a large number of microlesions may lead to motor and sensory loss but a single, surgically removable macrolesion must be ruled out. Also, large coverage MRN is able to characterize the spatial pattern of polyneuropathies such as diabetic polyneuropathy [6].

b) Diagnostic criteria

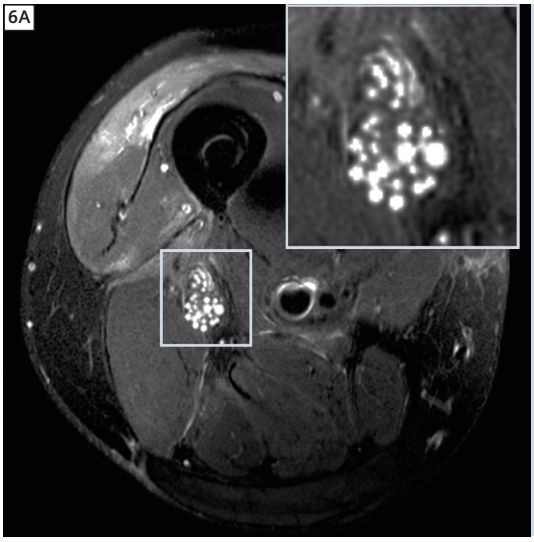
Nerve T2 signal is a highly sensitive and specific diagnostic sign for the presence of neuropathy [7]. Increased T2 signal as a parameter of high pathomorphogical contrast is readily assessed by qualitative visual evaluation. Nerve caliber is a second important diagnostic sign and, when clearly increased, usually indicates the presence of a more severe neuropathy. Looking beyond the nerves, the denervation pattern of muscles adds crucial information [8]. It can help establish the site of a nerve lesion, as in L5 radiculopathy compared to common peroneal neuropathy (Fig. 3).

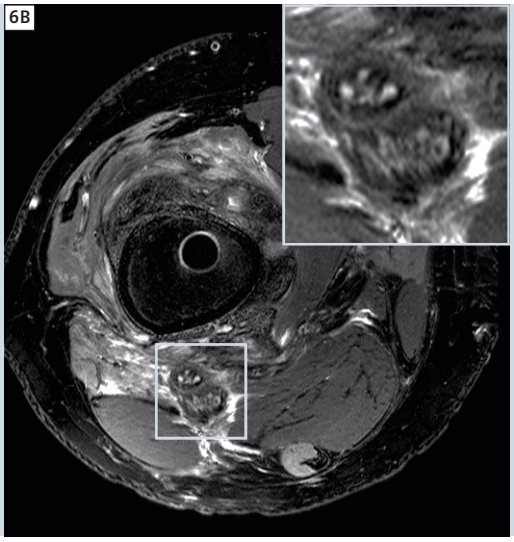
Contrast enhancement of peripheral nerves is observed in cases of peripheral nerve sheath tumors such as neurofibromas, schwannomas and perineuriomas. Whether contrast uptake can discriminate between different tumor entities and dignities has not been formally investigated. In cases of potential nerve trauma, nerve continuity is a straightforward but essential criterion when a 'true' neuroma has to be discriminated from a neuroma-in-continuity.

c) Pitfalls

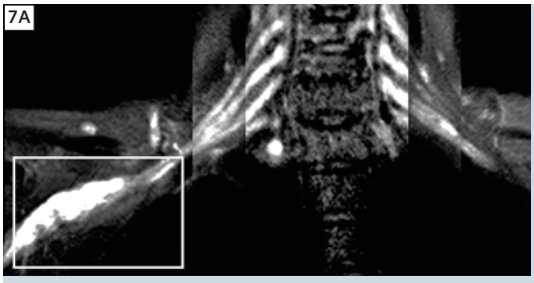
The magic angle effect causes an increase in T2 of fibrous tissue densely packed with collagen which results in artificially bright signal in T2w images. The magic angle effect depends on the angular orientation of the main longitudinal axis of the investigated structure (e.g. a tendon or peripheral nerve) relative to the field direction of the main static magnetic field (B_0) and reaches its maximum at 55°. It is related to the interaction of collage bound protons and can also be observed in the peripheral nervous system [9, 10]. Below an angle of < 30° the artifact becomes negligible so that correct positioning of limbs in an MRN examination can usually avoid its occurrence [10]. There are two regions where an oblique anatomical orientation of nerves cannot be avoided in the scanner: the supraclavicular brachial plexus and the proximal common peroneal nerve. Hence, in these regions, the magic angle must always be considered in image interpretation.

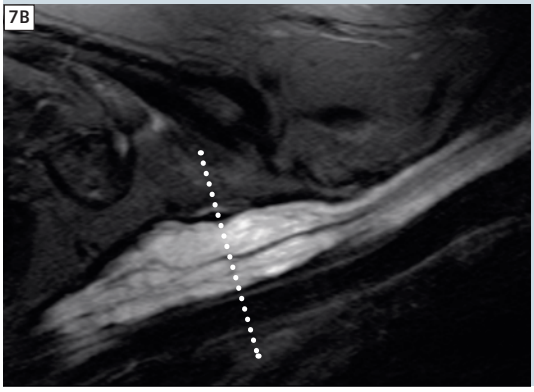
A second pitfall in MRN image interpretation is the presence of small epineural (outside the epineurium as the outer nerve sheath), epineurial (inside the epineurium), and intraneural vessels (within the interfascicular space). Small veins

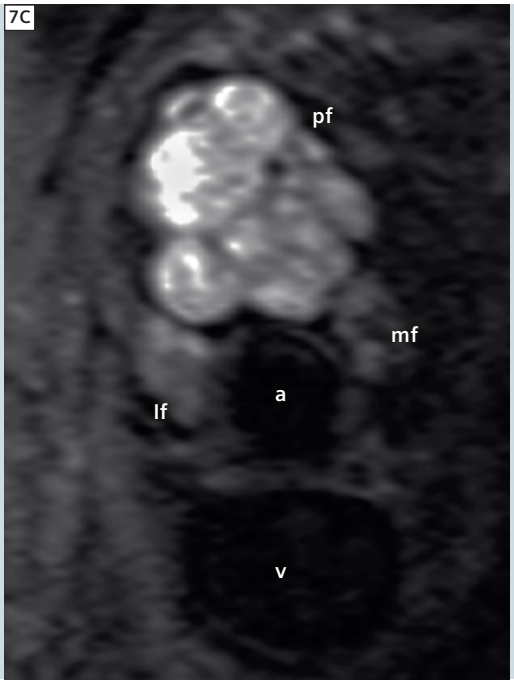




6 Neuroma of sciatic nerve. (**6A**) Patient with severe trauma and complete disruption of sciatic nerve continuity. Proximal neuroma stump with severely swollen, T2w hyperintense fascicles. (**6B**) Distal neuroma stump with pronounced swelling of epineural tissue.







7 Confirmation and localization of inflammatory neuropathy. **(7A)** Composed coronal SPACE STIR sequence in maximum intensity projection (MIP) provides an overview of the brachial plexus on both sides. Spinal nerves are well delineated and can be differentiated from each other. Note the severe distal plexus enlargement on the right side. **(7B)** Additional coronal T2-weighted TIRM gives a high resolution image of the more distal plexus portions of truncs and cords. **(7C)** Sagittal-oblique TIRM through the cords allows precise localization of lesions. In this case the posterior cord is severely enlarged with minor involvement of the lateral and medial cord.

and nerve lesions can have a similar T2 signal intensity. In most cases, small veins are readily discriminated from nerve lesions due to their winded course, strong and relatively homogeneous T2w hyperintense signal, and their eventual anatomical entry or exit into the nerve via its epineurial surface. When in doubt, one proposed method to discriminate the two is to acquire an SSFP sequence [11, 12]. Another approach is to acquire T1-weighted images with fat saturation after administration of contrast media since nerve lesions do not enhance as strongly as vessels.

III) Useful applications of MR Neurography

a) Focal compressive and traumatic lesions

Typical frequent referrals for an MRN exam include suspected compressive neuropathies such as ulnar neuropathy at the elbow or at the wrist. MRN has a high diagnostic accuracy in confirming or excluding these [7, 13]. Main diagnostic criteria are T2 signal and caliber increase. Other frequent focal neuropathies are traumatic nerve injuries. For patients in whom the region of the nerve lesion is known, MRN is most useful in determining whether continuity of the nerve is intact as well as the precise localization of neuroma (Fig. 6).

In other cases, the exact lesion localization and pattern can only be established by MRI. This is often the case in plexus injuries where electrodiagnostics are limited (Fig. 5). Precise determination of lesion pattern and lesion localization by MRN allows targeted surgery.

Table 1: Exemplary MRN sequences.

Sequence	TR	TE	TI	Slice thickness	Pixel spacing	FOV	Matrix	Slices	Averages	Coil
SPACE STIR coronal	3800	267	180	0.8	0.781 x 0.781	250	320/314	72	2	neck (Siemens)
T2 SPAIR sagittal-oblique	5530	45		3.0	0.469 x 0.469	150	320/198	51	4	dedicated surface coil (NORAS GmbH)
T2 fat-saturated axial	7020	52		3.0	0.300 x 0.300	130	512/358	45	3	knee 8-channel phased-array (Siemens)

b) Disseminated inflammatory lesions
Known or suspected disseminated nerve lesions require an examination tailored to the needs of the individual patient. In suspected inflammatory neuropathy, the precise spatial pattern of involvement of nerves is diagnostically important for classification and treatment. MRN is an excellent method to investigate this even in the most complex nerve structures like the brachial plexus. Figure 7 illustrates the precision of the method.

c) Distal symmetric polyneuropathies such as diabetes mellitus associated PNP
In addition to its manifold clinical applications, MRN contains immense potential for understanding and monitoring the evolution of peripheral nerve disease. In diabetic neuropathy for example, as a typical symmetric polyneuropathy with mainly distal symptoms, the MRN findings of a largely proximal lesion pattern are enhancing our understanding of the pathophysiology of the disease. MRN could for the first time document proximal nerve lesions *in-vivo* [6]. These findings promise a useful research purpose for MRN: to monitor the evolution of nerve lesions in diffuse polyneuropathies and better understand if proximal nerve lesions cumulate to cause distal symptoms, an intriguing pathomechanisms which so far has not been proven by any other clinical-diagnostic or scientific method of investigating nerve pathology.

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