# Magnetic Resonance Neurography
## Diffusion Tensor Imaging and Future Directions

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**KEYWORDS**

• MR neurography (MRN) • Three-dimensional (3D) • Whole-body MR
• Diffusion-weighted imaging (DWI) • Diffusion tensor imaging (DTI) • Magnetization transfer imaging
• MR contrast

**KEY POINTS**

- Magnetic resonance (MR) neurography is an excellent technique for axial and multiplanar depiction of peripheral nerve anatomy and disorders.
- Three-dimensional isotropic spin-echo–type imaging is currently being used on high-field scanners for longitudinal demonstration of nerve disorders for the benefit of referring physicians.
- Whole-body MR imaging is being widely used to image tumors. Whole-body MR neurography holds promise in the depiction of diffuse peripheral nerve disorders and neurocutaneous syndromes.
- Diffusion-weighted imaging and diffusion tensor imaging permit functional imaging of nerves and related lesions, and allow tractography for presurgical planning and postsurgical follow-up.
- Magnetization transfer imaging and nerve-specific MR contrast agents are under development and in feasibility stages for the assessment of nerve degeneration and regeneration, which is beyond the scope of anatomic pulse sequences.

## INTRODUCTION

Magnetic resonance (MR) neurography (MRN) is a noninvasive technique using high-resolution magnetic resonance (MR) imaging to diagnose peripheral nerve disorders and their underlying causes, such as indirect or direct penetrating injury, compression, stretch, friction, and iatrogenic insult, as well as to monitor processes of peripheral nerve degeneration and regeneration. At present, anatomic MRN is being widely used for a variety of nerve disorders.[1–9] Because of the continuous technological advancements, MRN diagnostic capabilities have improved in the last 2 decades, and MRN is therefore likely to play an important role in the diagnostic algorithm of peripheral nerve disorders.[1,10–16] This article reviews evolving novel MRN technologies currently used and under development with regard to their potential to meet the requirements for noninvasive imaging of peripheral nerves in both clinical and research settings.

## NERVE ANATOMY AND PERIPHERAL NEUROPATHY

To understand the new MRN technologies, as well as related normal and abnormal appearances of

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Neuroimag Clin N Am 24 (2014) 245–256
http://dx.doi.org/10.1016/j.nic.2013.03.031

the peripheral nervous system (PNS) using these techniques, an understanding of the peripheral nerve structure, composition of its different tissues, and knowledge of the widely used classification of peripheral neuropathy is important.

The axon is the functional unit of the peripheral nerve, supported by surrounding Schwann cells and myelin layers. A layer of loose connective tissue, the endoneurium, surrounds each axon and its Schwann cells, to form a nerve fiber. Multiple nerve fibers are enclosed in robust connective tissue, the perineurium, to form a nerve fascicle. All nerve fascicles are surrounded by the epineurium, to form a peripheral nerve.[2,7] Overall, peripheral nerve morphology shows a strong longitudinal order of its different compositional tissues. As a consequence, the axoplasmatic flow within peripheral nerves and, at a molecular level, the diffusion of water protons is aligned along these longitudinal structures.

Peripheral neuropathy is a general term. Three subtypes might be distinguished, namely mononeuropathy, mononeuropathy multiplex, or polyneuropathy. In peripheral neuropathies, it is essential to also determine whether the primary pathophysiology is of demyelinating or axonal type.[17,18] Nerve injuries are traditionally classified according to the Seddon and Sunderland grading systems. The Seddon classification divides nerve injuries based on their severity into neurapraxia, axonotmesis, and neurotmesis. Neurapraxia, the mildest type of injury, involves only pathologic changes in the myelin sheath around the axon resulting in a conduction block and transient functional loss. It is associated with a good prognosis. In axonotmesis, the axon suffers injury resulting in wallerian degeneration of its distal segment; however, the supporting structures, including the perineurium and epineurium, remain intact. The prognosis for recovery remains good, but time is required for axonal regeneration (~1 mm per day) from the point of injury to the target tissue. Neurotmesis is the most severe type of injury and refers to complete severance of the nerve. The functional loss is complete, and unless early surgical intervention is performed clinical recovery is not expected.

Sunderland proposed a 5-degree classification system with first-degree and second-degree injuries corresponding with neurapraxia and axonotmesis and third, fourth, and fifth degrees corresponding with endoneural, perineural, and epineural injuries, respectively.[1,19,20]

## LIMITATIONS OF CURRENT DIAGNOSTIC TESTS AND IMAGING

In addition to the clinical examination, nerve conduction and electromyography (EMG) studies and quantitative neurosensory testing are most commonly used to assess peripheral neuropathies and nerve injuries. Although these techniques remain the reference standard, there are limitations. First, the information about the exact location, extent, and cause of nerve disorders is often limited.[21] In addition, electrodiagnostic studies depend on operative and interpretative skills of the examiner and are not practical in patients with, for example, skin disorders or bleeding diathesis. In some studies, the positive predictive values are in the 30%–40% range and asymptomatic slowing of nerves is common. Nerve biopsy is often too invasive and may lead to considerable morbidity.[2,8,22–25] Another fundamental issue is the evaluation of stage-specific interventions, to improve nerve regeneration. Key to this is the ability to follow the growth state of the neuron and associated axonal elongation/regeneration in the nerve (pathway) before its reconnection with target tissues.[8,26–31] Current anatomic MRN techniques using fat-suppressed T2-weighted sequences are not able to sufficiently show nerve function and recovery.[32,33] Therefore, further development of functional MRN technologies are of foremost interest if they can provide useful information not only on gross nerve morphology but also on microstructure, collagen integrity, demyelination, and, if possible, nerve function.

## HIGH-RESOLUTION MRN AND NEW THREE-DIMENSIONAL SEQUENCES

The increasing use of 3-T MR scanners, new phased-array surface coils, and parallel imaging techniques allow the acquisition of high-resolution and high-contrast images in short imaging times. Current state-of-the-art MRN provides detailed anatomic depiction of peripheral nerves and improved characterization of pathologic states (**Figs. 1** and **2**).[1,27,29,30]

Axial T1-weighted and fluid-sensitive fat-suppressed T2-weighted images serve as the mainstay in MRN interpretation for prudent assessment of peripheral nerve imaging characteristics, such as signal intensity evaluation, course, caliber, fascicular pattern, size, and perineural fibrosis, or mass lesions.[1,10] Normal nerves show intermediate signal intensity (similar to muscle) on T1-weighted images and intermediate to minimally increased signal intensity on T2-weighted images, depending on the amount of endoneural fluid and background fat suppression (see **Fig. 1**).[34] MRN is a highly sensitive technique and may show abnormalities not revealed with electrophysiologic tests (**Fig. 3**).