Application of magnetic resonance neurography in the evaluation of patients with peripheral nerve pathology


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Currently, diagnosis and management of disorders involving nerves are generally undertaken without images of the nerves themselves. The authors evaluated whether direct nerve images obtained using the new technique of magnetic resonance (MR) neurography could be used to make clinically important diagnostic distinctions that cannot be readily accomplished using existing methods.

The authors obtained T2-weighted fast spin-echo fat-suppressed (chemical shift selection or inversion recovery) and T1-weighted images with planes parallel or transverse to the long axis of nerves using standard or phased-array coils in healthy volunteers and referred patients in 242 sessions.

Longitudinal and cross-sectional fascicular images readily distinguished perineural from intraneural masses, thus predicting both resectability and requirement for intraoperative electrophysiological monitoring. Fascicle pattern and longitudinal anatomy firmly identified nerves and thus improved the safety of image-guided procedures. In severe trauma, MR neurography identified nerve discontinuity at the fascicular level preoperatively, thus verifying the need for surgical repair. Direct images readily demonstrated increased diameter in injured nerves and showed the linear extent and time course of image hyperintensity associated with nerve injury. These findings confirm and precisely localize focal nerve compressions, thus avoiding some exploratory surgery and allowing for smaller targeted exposures when surgery is indicated.

Direct nerve imaging can demonstrate nerve continuity, distinguish intraneural from perineural masses, and localize nerve compressions prior to surgical exploration. Magnetic resonance neurography can add clinically useful diagnostic information in many situations in which physical examinations, electrodiagnostic tests, and existing image techniques are inconclusive.

Key Words • brachial plexus • diagnostic imaging • magnetic resonance imaging • nerve compression syndrome • neurological diagnosis • neuroradiography • peripheral nerve

Issue-selective images of bone and blood vessels play prominent roles in clinical diagnosis. Direct images of nerves, however, have not been available in the past. The advent of magnetic resonance (MR) neurography now makes it possible to learn how such images can alter and improve the process of neurological diagnosis.

Radiological images of structures adjacent to nerves are used extensively in diagnosis, however, data concerning the nerves themselves arise primarily from the patient’s clinical history, neurological examination, and electrodiagnostic tests. The x-ray-absorptive properties of nerves provide little distinction from surrounding tissues; conventional MR imaging of nerves has been restricted to a limited number of sites in the body and their ultrasound imaging is even more limited.

Recently, there have been reports of MR imaging protocols that achieve dramatic increases in the conspicuity of nerve. The result is a novel type of medical image termed an “MR neurogram.” The “diffusion-based” methods of this technique first reported have very high nerve selectivity, but require strong magnetic field gradients not generally available for clinical MR imaging.
A second method, T2-based neurography, used standard clinical MR equipment but initially had a poor signal-to-noise ratio and lower selectivity. By applying custom-built high-resolution phased-array coils, optimizing vessel suppression, and applying postprocessing techniques, Tsuruda and colleagues succeeded in producing striking high-resolution projection images of a severely injured sciatic nerve in a human patient. The image also provided the unanticipated benefit of demonstrating internal fascicular anatomy of the nerve because the signal from the interfascicular epineurium was suppressed along with signals from other nonneural tissues.

Magnetic resonance neurography can be defined as tissue-selective imaging directed at identifying and evaluating characteristics of nerve morphology: internal fascicular pattern, longitudinal variations in signal intensity and caliber, and connections and relations to other nerves or plexuses. Abstracts and preliminary works report...
ing wider clinical use of neurography have appeared. Here, we report on imaging results and clinical utility in a series of patients evaluated using a protocol described previously14 as well as using T1-weighted and fast multiplanar inversion recovery (FMPIR) sequences.

In addition, we report the results of neurography of normal nerves, both as a baseline for comparison to pathology and with a view toward aiding image-guided interventions such as placing nerve blocks or developing new percutaneous methods to replace open surgeries.

Clinical Material and Methods

Imaging Subjects

Patients referred for suspected peripheral nerve pathology underwent a detailed clinical history and neurological examination and were then referred for electrodiagnostic studies and imaging (Table 1). Informed consent was obtained from the patients and was based on our institution’s human subjects institutional review board–approved protocol.

In addition, during supplementary imaging sessions we collected images of normal nerves from patients who had peripheral nerve lesions elsewhere in the body as well as from normal volunteers (Table 1). In the case of normal studies, the volunteers had no history of pain or dysfunction referable to the nerve in question. Normality was further verified by comparisons among numbers of patients with and without pathology and by comparison with healthy volunteers. Where possible, images were collected from both left and right sides so that uniformity of image intensity could be verified against any possible subtle abnormality affecting a nerve on a given side.

Imaging Techniques and Data Acquisition

Fast spin–echo (FSE) images were obtained as indicated in Table 2. In each case, the magnet was reshimmed with the imaging subject in place before commencing data acquisition. Several phased-array radiofrequency (RF) coils were specially built for this study23,24 and met industry standards for patient comfort and ease of use. To obtain cross-sectional images we used an echo train length of 4 to optimize spatial resolution, but used a train of 8 for lon-
gitudinal nerve images. The field of view was minimized for each study. In all patient studies, T\textsubscript{1}-weighted spin-echo and FMPIR (inversion time 90–150 msec) as well as FSE images were collected.

**Orientation of Imaging Planes**

Several T\textsubscript{1}-weighted images in standard planes (axial, sagittal, or coronal) were used to plan initial oblique images. Standard anatomy was assumed to orient this initial plane parallel or transverse to the nerve. Images were then collected in one or two additional oblique image planes that were oriented either parallel or perpendicular to the long axis of the nerves of interest.

In the nerve-perpendicular images, the clarity of the fascicle pattern could be used as a means of verifying the orthogonality of the image plane. For more complex nerve trajectories, we obtained longitudinal nerve depictions to serve as “nerve scout images” to optimize the orientation of a series of image planes to achieve good orthogonal cross-sectional orientation.

To obtain longitudinal nerve images, one of four techniques was used, depending on the complexity of the course of the nerve or plexus and on the size relative to the field of view. For nerves that travelled a straight course and had a diameter similar to the thickness of the image slice, we used the scout images to orient an image plane to be as nearly parallel as possible to the long axis of the nerve in the area of interest. When a single imaging plane included nearly the entire nerve segment of interest, we used multiplanar reformatting to reorient the image plane orientation after the full dataset was collected.

In situations in which the trajectory of a nerve or plexus was too complex to capture in a single-image slice, we reconstituted the longitudinal nerve images by preparing additive overlays of several nearly longitudinal image planes. This took advantage of the high nerve conspicuity in the raw images, which allowed application of maximum intensity projection techniques in the Interactive Vascular Imaging package.

To prepare longitudinal nerve images that could be rotated in three dimensions, we selected a volume of interest to include a series of cross-sectional nerve images obtained in a standard imaging plane (for example, axial) as the basis for maximum intensity projection reconstruction of longitudinal shape.

**Results**

One hundred forty-eight patients and normal volunteers (84 males and 64 females) participated in the study. These individuals ranged in age from 10 to 83 years. Four patients received nerve graft prior to undergoing MR neurography. Thirty-six patients underwent surgery after imaging. Some patients underwent MR neurography both pre- and postsurgery. This occurred in five cases in which a mass was excised, two cases of neurolysis, one case of nerve graft placement, and one of decompression.

Nineteen patients underwent more than one imaging session: 10 patients had two sessions, six patients had three, and three patients had four sessions. In cases in which the patient underwent more than one neurography session, the longest interval between sessions was 19 months.

This study demonstrated that a variety of aspects of normal and pathological nerve morphology are well shown in direct nerve images collected with MR neurography imaging protocols. These images not only confirmed diagnoses made using traditional examinations, but also solved diagnostic problems that previously could not be resolved without open exploratory surgery or extended periods of
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expectant management. In cases brought to surgery after imaging we found close correspondence between image anatomy and actual anatomy.

Clinical Findings

In cross-sectional and longitudinal images, the fascicular pattern clearly distinguished the nerve from schwannomas and cysts (Fig. 1), despite the intrinsic high-image intensity of such lesions.\(^4\)\(^7\)\(^9\) This aided surgical planning by clarifying intraneural versus perineural location, potential for resection, and need for intraoperative electodiagnostic monitoring. Proximal nerve hyperintensity was seen (Fig. 2) as well as distal hyperintensity (Fig. 3).

Neurographic imaging used in diagnosis of severe trauma allowed the assessment of gross continuity of nerves (Fig. 4) and of the site of formation of posttraumatic neuromas. Unlike electromyography (EMG), which may not show denervation changes for 1 to 2 weeks, MR neurography allowed assessment of nerve continuity immediately after injury. This not only confirmed the need for surgical repair, but also allowed for preoperative planning of sural nerve graft harvest. Images proved highly effective as intraoperative references and helped guide more limited initial surgical exposure. After graft repair, bright proximal and distal nerve ends were delineated sharply from dark sural nerve graft material. This distinction persisted for more than 1 year after grafting.

In patients with injuries involving loss of axons but maintained nerve continuity, hyperintensity occurred distal to the injury. In moderate-to-severe stretch injury, we saw diffuse increase in nerve intensity over considerable lengths along the nerves. Some very severe injuries, however, resulted in such considerable amounts of local edema and nerve disruption that nerve identification was difficult.

In less severe focal trauma, we found nerve hyperintensity present at the site of injury when pain and numbness persisted more than 1 month postinjury. Repeat imaging in such patients 8 to 10 months later showed substantially decreased hyperintensity correlated with substantial resolution of symptoms.

Neurographic evaluation allowed precise localization of focal injuries in nonroutine locations demonstrating hyperintensity\(^17\) but no residual anatomical compression or fascicular discontinuity and thus helped in the decision not to pursue surgical exploration (Fig. 5). In repetitive strain/sports-related injuries, we used neurography to confirm specific surgically treatable syndromes such as suprascapular nerve entrapment (Fig. 6 left and center). In all of our cases, the hyperintensity could be localized to the nerve fascicles because the interfascicular epineurium remained dark even in areas of severe injury. Hyperintensity occurred in some nerves in which EMG did not reveal corresponding pathology (Fig. 6 right). In some cases of radiculopathy, we found pronounced hyperintensity of the symptomatic root although EMG findings were normal and routine imaging yielded only minimal evidence of pathology\(^8\) (Fig. 7).

General Technical and Anatomical Findings

The FSE neurographic technique renders nerves sufficiently conspicuous as to be susceptible to maximum intensity projection and other overlay or reformatting tech-

![Image](image.png)

Fig. 5. Magnetic resonance (MR) neurograms of the distal sciatic nerve in a 36-year-old bus driver who presented with a focal left lower-extremity painful neuritis of unclear cause. After a 10-hour drive, she developed pain in the buttock that progressed to lower-extremity weakness and gross muscle atrophy. Routine computerized tomography and MR imaging were normal, but electromyography and nerve conduction studies suggested a lesion near the popliteal fossa or fibular head. Upper: Maximum intensity projection reconstruction of the tibial and peroneal nerves created from a selected volume containing the nerve cross-sections. There is diffuse hyperintensity over a distance of some 10 cm. The annotation (PN = peroneal nerve) indicates the location of the cross-section (Fig. 4 lower, ii) demonstrating the most severe injury. The hyperintensity extends both proximal and distal to this point (maximum intensity projection). Lower: Cross-sections of the sciatic nerve as it divides into tibial and peroneal components. The fascicles in more proximal images are small (i), with many becoming grossly swollen in the middle of the lesion (ii). In an image collected with lower spatial resolution, this effect would appear as a further increase in nerve image intensity because bright fascicles consume nearly all of the space within the nerve at the expense of dark interfascicular tissue. The normal fascicular anatomy is seen to be reconstituting in the more distal cross-sections (iii and iv), with the exception of one particularly bright and swollen fascicle (f) in the peroneal component. Fast spin–echo protocol: 6-in phased-array coil; 512 × 256 resolution; number of excitations: 2; field of view: 12 × 12 cm.
Techniques performed on MR image slices. These allow reconstruction of the complete longitudinal or three-dimensional structure of the nerve. The FMPIR protocol gave more uniform fat suppression in a large volume of imaging studies but had a reduced signal-to-noise ratio and was less effective at demonstrating nerve hyperintensity.

For normal nerves, projection reconstruction of longitudinal nerve images and identification on the basis of fascicular morphology can be performed reliably, although there is a greater dependence on careful orientation of imaging planes than for nerves affected by pathological processes.

Longitudinal nerve images (Fig. 8 upper) can serve as a guide for collecting cross-sectional images of the nerve at any point along its course (Fig. 8 lower). In the wrist, the caliber and number of fascicles varied along the course of the nerve and among individuals.

Lumbar dorsal root ganglia were reliably well seen (Fig. 9 left) and added to the “MR myelogram” effect described elsewhere. Previous studies demonstrated imaging of proximal roots in the foramen, primarily from the appearance of fat displacement. Neurography extended imaging several centimeters beyond the foramen and demonstrated the neural tissue itself, independent of the proximity of fat.

Overlay techniques permitted reassembly of series of lumbar and/or sacral spinal nerves (Fig. 10). Individuals varied in the angle of progression of spinal roots and the spacing between them.

Discussion

Historically, the introduction of skeletal x-ray film studies, angiography, brain CT scanning, and other techniques that allowed direct imaging of specific tissues of clinical interest has both simplified the diagnostic process and
Improved its accuracy. The MR neurograms obtained for this study provided analogous benefits.

In general, medical imaging has diagnostic utility because it is effective for demonstrating changes in the physical characteristics of tissue, such as continuity, position, gross shape, and local response to injury (for example, edema) that are associated with many kinds of pathology. Without direct tissue-selective imaging, these signs of a pathological change in nerve cannot readily be used in diagnosis. The image data reported here not only show that such information about nerves can be obtained but also that it has specific and unique clinical value.

Nerve Fascicle Pattern

The ability of MR neurography to distinguish intraneural and perineural masses and to confirm nerve continuity in traumatic injury are due in large part to the technique’s ability to depict fascicle pattern. The fascicular image pattern is based on differences between the MR signal of nerve fascicles within the perineurium as opposed to the interfascicular epineurium between fascicles (Fig. 11). The fascicular image signal is dominated by endoneurial fluid and axoplasmic water, whereas the interfascicular image signal is dominated by fibrofatty connective tissue susceptible to fat suppression.

With correct orientation of the image plane, the fascicular pattern can be appreciated in high-resolution image sequences that provide contrast between the fascicles and the interfascicular epineurium (Fig. 11). In T1-weighted sequences, there is a better signal-to-noise ratio than in the T2-weighted sequences and thus fascicles can be observed with less specialized RF coils. However, in T1-weighted sequences, the fascicles are dark within a bright signal surrounding the fat. This causes the fascicles to be less visible in pathology.

The use of fat-suppressed T2-weighted sequences allows the nerve fascicle signal itself to predominate and provides an improved view in the setting of pathology. Low signal-to-noise ratio can be compensated either by increasing the number of excitations or with phased-array coils or other specialized surface coils to minimize the examination time.

Injury-Associated Nerve Hyperintensity

In addition to demonstrating morphology, MR neurography localizes pathology because it can demonstrate evidence of a local response to injury as injury-associated nerve hyperintensity. At present, however, there does not appear to be any straightforward correlation between the presence of this phenomenon and the severity of the nerve injury. In patients with cervical radiculopathy, hyperin-
tensity occurs in patients with radicular pain but no EMG findings. The individual shown in Fig. 6 had hyperintensity in the suprascapular nerve associated with marked EMG changes, but also had hyperintensity in the axillary nerve, although there were no EMG abnormalities in muscle supplied by that nerve.

The increased intensity reflects a prolonged $T_2$ relaxation time of one or several water compartments. Axoplasmic flow is impeded by nerve compression, and increased axoplasm proximal and distal to the site might cause hyperintensity. Two other possible causes are disordered flow of endoneurial fluid and perineurial edema due to local venous obstruction. Simple perineurial edema seems unlikely because it is not clear why such fluid would be excluded from the interfascicular epineurium. However, within the fascicle, venous obstruction might increase production of endoneurial fluid.

Endoneurial fluid is a promising candidate for the cause. It is a relatively low protein fluid confined by the perineurial blood–nerve barrier. It is limited to the fascicles and thus could cause fascicles to swell as extra fluid is added to the endoneurial space. In addition, because it is subject to bulk proximal-to-distal flow, it is reasonable to expect that increased intensity in a proximal nerve will be reflected in intensity in a distal nerve.
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to hypothesize that a blockage will affect the flow dynamics of this fluid for several centimeters upstream. The final intriguing phenomenon that indicates the cause may be endoneurial fluid is the reconstitution of increased nerve intensity distal to a graft site. This fluid is ultimately a filtrate of capillary blood flow and thus will be generated in a distal, severed nerve long after the axons have degenerated. Here, the endoneurial fluid flow might demonstrate some stasis without the driving force usually derived from the more proximal segments of the nerve.

Titelbaum, et al., have reported a transient increase in nerve intensity distal to a site of axonotmesis or neurorrhaphy that resolved by 30 to 45 days after the injury, possibly due to the active process of wallerian degeneration with its attendant inflammatory changes. However, both the proximal and distal nerve intensity increases shown in the present study were detectable many months after injury and were detectable in patients who had neurapraxic injury alone. The nerve intensity changes observed in many of our patients cannot be due to wallerian degeneration alone.

Nerve Identification

Use of neurography to confirm and localize nerve compressions depends in part on its ability to identify nerves reliably where they occur alongside lymph nodes, adipose collections, vessels, ligaments, and other structures of similar shape, size, and location. In cross-sectional T2-weighted images, a number of structures appear as dark variegated nerve whether or not the nerve is affected by pathology, and intraneural MR contrast agents (for delivery by axonal transport) remain at an early stage in their development. Routine MR imaging protocols can demonstrate specific nerve structures at locations particularly favorable for imaging. However, with the exception of these few sites, definitive identification is problematic throughout the body. Contrast agents at present do not offer a reliable alternative solution to the problem of nerve identification. Intravenously administered gadolinium enhances nerves in a variable fashion, differing from site to site along a single nerve whether or not the nerve is affected by pathology, and intraneural MR contrast agents (for delivery by axonal transport) remain at an early stage in their development.

Spatial relationships to other tissues are not always helpful because nerves change both shape and location with changes in joint position. Firm nerve identification must rely on internal appearance and connections and only rarely on relations to nonneural tissues.

Longitudinal Nerve Images

Longitudinal nerve images lend themselves more readily to evaluation for alterations in diameter and image intensity than is possible with sectional images alone. Longitudinal images prove helpful in surgical planning and as intraoperative references during procedures on or near nerves and plexuses. In the future, because these images allow for rapid-summary visual interpretation by the interventionalist, they should prove helpful in the development of image-guided procedures.

Longitudinal nerve sections as they are used in standard MR protocols rarely capture a nerve continuously in a single plane. It is the high conspicuity of the nerve in the neurographic protocol reported here that allows projection reconstruction of the nerve in a wide variety of locations.

Conclusions

This study establishes that the use of direct nerve images provides several important advantages over preoperative planning and nerve diagnosis without the use of such imaging in the management of selected cases of nerve-related disorders. The diagnostic information from images obtained in this study correlated well with general findings from physical examinations and electrodiagnostic studies and provided additional information that was confirmed in detail in each of the surgical cases.

Magnetic resonance neurography images offer an improvement over surgical exploration without preoperative nerve imaging as a means of assessing nerve continuity and the need for surgical repair after severe traumatic injury and as a means of selecting a surgical technique appropriate to excision of intraneural versus perineural masses.

In locations such as the carpal tunnel, the precise localization by MR neurography can distinguish proximal from distal compression and thus allow for smaller exposure or percutaneous approaches without increasing the risk of failure due to inadequate release in nonstandard cases.

When a nerve can be followed along its course, it is far easier to detect, localize, and describe the changes in shape, internal anatomy, and T2 signal that occur at sites of pathology. Phased-array coils provide adequate spatial resolution to permit visualization of fascicular pattern in many settings.

At present, we believe that when standard MR imaging of perineural tissues is used in the evaluation of nerve-related disorders, an MR neurography protocol should be added to the imaging study to provide direct nerve images as well. In the future, improved local imaging coils, new vessel suppression techniques, and implementation of diffusion techniques on clinical scanners should further improve neurographic selectivity and thus further extend the clinical utility of direct nerve images.

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