MR neurography and muscle MR imaging for image diagnosis of disorders affecting the peripheral nerves and musculature

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Medical imaging, including MR imaging [1], is playing an increasingly important role in the diagnosis of disorders affecting the peripheral nerves and muscles [2,3]. In the past, the practical application of MR imaging of nerves has been limited by technical difficulties in obtaining good image contrast to help distinguish nerve from neighboring tissues [4–9]. By comparison, the limited capabilities of ultrasound [10] for nerve identification have seemed useful. Recently, however, advances and enhancements of MR imaging techniques have transformed the evaluation of a variety of conditions that have posed diagnostic challenges in the past.

The term MR neurography is used to describe the new techniques for nerve imaging that greatly improve the reliability of identification of peripheral nerves in images and often make it possible to generate tissue-specific images of nerves analogous to angiograms. These images enable the physician to examine the peripheral nerve for anatomic abnormalities.

A series of discoveries in basic MR science beginning in 1992 has led to the establishment of MR neurography as a distinct area of imaging [11,12]. The technique has now been applied in thousands of clinical cases. A series of publications cover the basic science [13–15], imaging science [16,17], and clinical application [18–23] of the technique. Large, well-controlled formal...
outcome trials [24,25] have established, at least in some settings, that MR
neurography can be more reliable than electrodiagnostic studies in localizing
peripheral nerve disorders and in guiding treatment planning.

The referring physician should be aware of some of the technical aspects
of MR nerve imaging. Many radiologists have limited experience with nerve
imaging, and many imaging centers are not adequately equipped to carry
out these studies successfully. It is important for the referring physician to
have a clear idea of how a useful high-quality nerve image should appear.
Awareness of some of the general technical aspects of the nerve imaging
process can help the referring physician understand and address image-
quality problems that can arise as this new technique is introduced in a
community.

Clinical role

In many settings, tissue-specific imaging of nerves provides information
about the anatomy of nerves of interest and also is capable of demonstrating
detailed information about pathology [26]. Direct anatomic information can
be used to locate small nerve tumors that may be otherwise difficult to
localize precisely. Imaging can also provide information about gross nerve
continuity in settings of trauma. Further, nerve-compression syndromes of
sufficient severity to cause significant weakness or sensory loss seem to be
associated with the development of image hyperintensity within the nerve
and often with swelling of the nerve as well. This appearance resolves if the
offending insult to the nerve can be relieved. Excess endoneurial fluid
accumulation associated with nerve compression seems to be the basis of the
nerve image hyperintensity.

Because mechanical changes in nerve diameter and, particularly, changes
in local fluid content can be detected reliably, MR neurography can have
a sensitivity and specificity similar to that of needle electromyography in the
evaluation of some nerve-compression syndromes. Studies comparing out-
comes in carpal tunnel [27–30] and ulnar nerve release surgeries [31] show
that MR neurography is as effective as needle electromyography for
identifying patients who are helped by surgical treatment.

In conditions such as thoracic outlet syndromes (TOS) [32,33] and in
lumbar radiculopathy after unsuccessful spine surgery, where electrophys-
siologic studies have so far been of only varying effectiveness [34,35], the
application of MR neurography can have considerable clinical significance.
There has also been significant interest in the use of MR neurography for
pediatric patients who may have a low tolerance for needle electromyo-
graphy [36].

The MR physics of nerve imaging

The basis for MR imaging of nerve derives from the existence of a variety
of unique types of tissue water in nerve. Clinical use of MR neurography is
based on the application of new findings about nerve image characteristics. It is also based on a specific strategy of using imaging to evaluate nerves. The two major types of neurographic techniques that have been described are diffusion neurography and T2-based neurography. Diffusion neurography was the first reported [12,37,38]. This method has extremely high selectivity for nerves and should be sensitive to a variety of types of pathology. The technical demands necessary to perform diffusion neurography have delayed its clinical application, however.

T2-based neurography can be applied reliably using many existing top quality clinical scanners with minor modifications. Even when the technical equipment requirements can be met, however, there may be limitations on the provision of MR neurography because of lack of expertise in prescribing, postprocessing, interpreting, and acting upon the MR data.

T2-based neurography

Once the diffusion method was understood, it was possible to show that structures with long T2-decay times in fat-suppressed spin-echo images were, in fact, nerves. Previously, nerves had been misinterpreted as exhibiting short T2-decay times [39]. This error arose because nerves are a mixture of different tissues, including protein-laden axoplasmic water, myelin, fatty interfascicular epineurium, and connective tissues. Older methods allowed the image signals from these various component tissues to mix. In a variety of different imaging techniques, the result of the signal mixing was a featureless gray image of the nerve that left it difficult to distinguish clearly in an image and caused confusion about the fundamental imaging characteristics of nerve (Fig. 1).

The physiologic basis of T2 neurography

Several pieces of evidence suggest that the low-protein endoneurial fluid is what is seen most prominently in T2 neurography images. The endoneurial fluid is a low-protein liquid that lies within the privileged space of the endoneurium, is confined by the perineurial blood/nerve barrier, and bathes the axons [40,41]. It has a bulk proximal to distal flow along the nerve [42] that may be disrupted by nerve compression and edema.

Although endoneurial fluid is responsible for only a fraction of the imagable protons in a nerve, it is one of the most distinctive types of tissue water in nerve from the point of view of MR imaging. It is possible, by applying a chemical shift–selective pulse, to suppress fat around nerves and also to suppress much of the fat signal from within nerves. Then, by selecting an appropriate echo time (around 90 milliseconds), a T2 weighting can be achieved that results in suppression of muscle signal, leaving most of the signal from the endoneurial fluid intact. A method must also be used to suppress bright fluid signals from flowing blood.
The use of all three measures—fat suppression, T2 weighting, and blood suppression—creates the conditions that allow the generation of selective nerve images. These pulse sequence manipulations are not sufficient to obtain useful images, however.

**Optimizing the performance of the MR imaging main magnet**

Another source of quality variation among MR scanners that has a large impact on image quality is the homogeneity of the main magnetic field of the imager. Essentially, MR scanners are designed to provide a precise level of magnetic-field strength over a useful volume. At a minimum, this volume must large enough to cover the entire brain when the head is positioned at the exact center of the magnet. An imager of only that volume, however, will be useless for collecting a brachial plexus image, which requires a larger field of view and which will be off center in the magnet. Good versatile nerve imaging therefore requires an MR scanner with good magnetic-field homogeneity off center in the magnet and over a relatively large volume.
Another this design factor concerns the fat suppression by chemical shift–selective pulse (CHESS), which is essential for most neurography. CHESS works well only when the main magnetic field is accurate and uniform, conditions accomplished by a process called shimming. All MR scanners come with an ability to shim the magnet to improve the field performance. In some imagers shimming is done once a month as a maintenance function. Such a scanner is adequate for most brain, spine, and general imaging work. Top-performing MR scanners for nerve imaging are shimmed at the beginning of each imaging sequence on the volume of interest with the patient in position. Nerve imaging is one of the few applications when per-patient local shimming is important; many expensive academic MR scanners do not offer the necessary shimming capabilities and so produce neurography images of poor quality.

**Phased-array coils**

Signal-to-noise performance can be greatly enhanced by the use of a specialized class of radiofrequency antennas as the receiver coil for collecting the image data. These antennas are called phased-array coils [43]. The basic idea behind phased array is to use more than one antenna to collect the weak signal.

Two phased-array receiver coils can be placed at two different positions within the imager. Each collects data that contain both signal and noise; however a considerable part of the noise derives from physical aspects of the scanner, so that the noise spectrum looks slightly different in different locations of the scanner. The actual data signal from the tissue, however, is effectively the same anywhere in the scanner. By comparing the information from the two antennas, it is possible to discard signals that differ between the two antennas, because they are likely to be noise, and to keep signals that are identical in the two antennas. This strategy results in greatly enhanced signal-to-noise performance. Phased-array coil technology may allow four or even more receivers to be run simultaneously, achieving even greater signal-to-noise enhancement. The referring physician should be aware that phased-array capability is critical for high-resolution imaging and that performance varies among phased-array coils from different manufacturers.

**Image plane orientation and postprocessing**

For most types of routine MR imaging the original scan can be collected in three standard planes—axial, coronal, and sagittal—and then printed on film and read. MR neurography is considerably more demanding and is essentially wedded to an electronic reading format. The initial scanning must be done with attention to the main orientation of the nerves of greatest interest.

Even when the image plane orientation is correct during image collection, the raw image captures only pieces of nerves in individual images. The full
image of the nerve can be reconstructed in several ways. The first method of reconstruction is oblique reformatting. This step is mandatory before reading any MR neurography scan and needs to be conducted on an image postprocessing system approved by the Food and Drug Administration. By shifting the effective image plan a few degrees and changing the effective slice thickness, it is possible to reassemble significant lengths of nerve or plexus. Without this step it is impossible for the reader of the image to comment on local variations in nerve image intensity or distortions in the course of the nerve. Starting with the image resulting from the first oblique reformat maneuver, a new image plane that is oblique to two of the original image planes can be generated to improve visualization further.

Although some oblique reformatting is mandatory for nearly all MR neurography studies, further processing on a full-scale three-dimensional workstation is preferable. The additional postprocessing makes it possible to create maximum intensity projections (MIP), which essentially stack up the image slices and have the effect of reassembling the nerves (Fig. 2). A fundamental aspect of the design of MR neurography protocols is to render the nerve as the brightest object in the image. Achieving this objective makes the use of MIP possible.

Another category of three-dimensional postprocessing is the use of curved reformatting. This step can often produce an image of extended lengths of nerve or nerve plexus. On some workstations, the process of curved reformatting generates a trace of the course of the nerve (Fig. 3). This nerve trace is also useful for interpreting the image, because it documents any unusual deviations in the course of a nerve or plexus.

Spatial resolution and signal-to-noise ratio

Useful imaging of a peripheral nerve requires a balance between large-area survey imaging and high-resolution, small field-of-view work. Nerve imaging may be most effective when the referring physician has a clear idea of the suspected location of the lesion. When the required imaging volume can be reduced to an area that is about 10 cm on each side, it is possible to image the volume with maximum spatial resolution and provide good fascicular detail. Selecting an even smaller volume to image does not currently result in any further gain in spatial resolution because of limitations of the imaging system. These considerations do make 200-micron spatial resolution possible on the best-quality MR scanners.

Image appearance of nerve pathologies

MR neurography makes it possible to view images that depict many types of nerve pathologies which previously could only be inferred (Fig. 4). Nerve swelling, including edema at the fascicular level, can often be seen (Fig. 5). Mechanical deviations in the physical course of a nerve can indicate entrapment or adhesions (see Fig. 2), and hyperintensity associated with
nerve injury may be appreciated in nerves affected so severely as to be associated with significant motor deficits. Physical discontinuities in nerve and the development of traumatic neuromas may be readily appreciated. In hereditary neuropathies, disordered distribution of interfascicular lipid can be detected.

Fig. 2. Assembly of raw images by maximum intensity projection (MIP). This process can greatly enhance the diagnostic value of the images. (A) Series of four oblique coronal image sections, each showing portions of the exiting cervical spinal nerves and proximal brachial plexus. Isolated segments of nerve elements appear at various locations, and some are difficult to identify reliably. (B) An overlay MIP made possible because the nerves are among the brightest elements in the image. It is easy to match the dorsal root ganglia (d) with the cervical spinal nerves because of the appearance of physical continuity. Nerve hyperintensity (h) associated with motor symptoms is readily appreciated in the right C6 cervical spinal nerve because the lower intensity of all the other elements is easily seen. Evidence of downward distortion of the right C7 and C8 cervical spinal nerves (s) by an enlarged scalene muscle is also readily seen because of the assembled view of the entire proximal plexus bilaterally.
MR neurography extends the capabilities of diagnostic imaging to a wide variety of pathologies affecting the peripheral nerves [3]. The principles of localization and characterization of lesions in the nervous system are well known. The lack of use of imaging for peripheral nerves in the past reflects only the longstanding inability of existing imaging technology to provide those images. CT scanning advanced the diagnosis of intracranial lesions relative to pneumoencephalography and angiography because of the improved detail of localization and extent of identification of lesion type. MR imaging, at a minimum, extended the capabilities of localization to include accurate views of the contents of the posterior fossa while generally improving the quality of lesion characterization throughout the body. MR neurography now plays a similar role with regard to the peripheral nervous system [22,23].

The indications for MR neurography include visualization of the distal spinal roots and spinal nerves and plexuses for the effects of degenerative disease, entrapments, adhesions, and the effects of trauma. In addition, this
Fig. 4. Hyperintensity associated with nerve injury: brightness and swelling on T2-neurography at a site of nerve trauma (*) resulting from an oral surgery procedure. The lingual and inferior alveolar components of the mandibular nerve (M) are well seen.

Fig. 5. Nerve image hyperintensity showing fascicular-level swelling. Distal sciatic nerve of a 36-year-old bus driver presenting with a focal left lower extremity painful neuritis of unclear cause. (A) Cross-sections of the sciatic nerve as it divides into tibial (t) and peroneal (p) components. Use of phased-array coil allows evaluation at the fascicle pattern. (A2) Some fascicles become bright and swollen at the site of injury at the expense of the interfascicular epineurium. (A3, A4) One fascicle in the peroneal nerve is particularly enlarged reflecting Wallerian degeneration. (B) MIP reconstruction of the tibial and peroneal nerves created from a selected volume containing the nerve cross-sections. In this case, the precise location of a severe fascicular disruption could be shown with great accuracy, and it could also be demonstrated that there was no persisting lesion near the nerve that might require surgical treatment.
technique permits reliable identification and precise localization of nerve tumors as small as 2 mm in diameter.

In problematic conditions such as TOS, MR neurography allows the diagnostic sorting of this condition into a series of distinct and reliably diagnosed types of specific pathology. Sorting by accurate diagnosis before treatment is already beginning help in optimizing both the details of treatment planning and treatment.

**Entrapments and compressions**

*Sciatica of nondisc origin*

*Lumbar and sacral spinal nerves*

Persistent sciatica not responsive to conservative measures is one of the most common indications for MR imaging. Of 1.2 million MR imaging scans obtained each year for back pain and sciatica, however, only about one in four scans demonstrates a surgically treatable lesion. Among patients treated with surgery, a significant fraction fail to improve; in many cases this lack of improvement results from misdiagnosis before surgery, and in other cases it results from inadequacies of the surgery. For all of these reasons, neurologists and neurosurgeons are commonly asked to evaluate patients with persisting sciatica who do not have a herniated disc or whose surgery has failed.

Successful treatment of persistent radiculopathy after lumbar spine surgery requires effective diagnostic categorization of the causes. Electrodiagnostic studies often can demonstrate only that the radiculopathy present before surgery is still detectable.

Use of image-based diagnosis can help further differentiate among the cases that should be directed toward reoperation, radiofrequency neurolysis, or medical treatments directed at inflammation.

Direct imaging of the lumbar/sacral spinal nerves and the proximal sciatic nerve with neurographic techniques can help resolve the diagnosis in many of these patients [44]. The lumbar spinal nerves, ganglia, and the proximal sciatic nerve can be imaged reliably and effectively. In general only the larger, more proximal lumbar nerves can be imaged reliably at present; however, there is no strict physical limit on the size of nerves that can be imaged under optimal conditions.

*Foraminal pathology.* The normal course of the lumbar spinal nerves is in a smooth straight line (Fig. 6A). In patients with a nondiagnostic MR study and myelogram, MR neurography can demonstrate distortions of the course of the exiting nerve in the distal foramen, which are readily susceptible to surgical correction (Fig. 6B,C). MR neurography is particularly helpful for imaging foraminal spinal disease in the presence of scoliosis because the
three-dimensional aspects of the imaging tend to resolve some of the ambiguities that may otherwise make diagnosis challenging.

Even when myelography is capable of demonstrating a nerve root cutoff, a MR neurogram can provide considerable additional information. The full length of the foraminal impingement requiring treatment can be easily appreciated, and this visualization can avoid an incomplete foraminotomy.

In addition, the ability of MR neurography to demonstrate hyperintensity in the lumbar root adjacent to the impingement helps confirm the significance of the impingement.

**Postsurgical radiculopathy.** MR neurography is the study of choice for evaluating persistent, exacerbated, or altered radiculopathy after lumbar spinal surgery. It allows clear differentiation of several different causes of this problem and identifies cases that are best treated by reoperation, by allowing additional time to elapse, or by referral for electronic stimulators or other treatments for chronic, irremediable pain. In a number of common situations, MR neurography can provide a specific diagnosis determining treatment by revealing pathology that cannot be detected by any other methodology.

Postoperative hyperintensity in the ganglion can be connected with a specific anatomic feature not adequately treated by the surgery, such as a persistent bone spur. In other cases, MR neurography has demonstrated impaction of a disk fragment in the distal foramen compressing the root (Fig. 7A), which is treatable by reoperation. The study may also show
Fig. 7. MR neurography in patients with persistent radiculopathy after spine surgery. (A) MR neurography demonstrates flattening of the exiting nerve root (**) by a persistent fragment of disc material (fr) in the foramen. The contralateral nerve root (*) has a normal caliber. (B) A 36-year-old man with right S1 dysesthetic pain after microdiscectomy. Postoperative imaging showed good decompression, but the neurography demonstrated persistent hyperintensity of the dorsal root ganglion (DRG) consistent with intraoperative mechanical trauma. No further surgical treatment was recommended.

Fig. 8. Evaluation of components of the sacral roots and nerves. (A) A 59-year-old woman with persistent severe left L5 radiculopathy exacerbated by instrumented fusion of the lumbar spine and not relieved by subsequent removal of the instrumentation. The image demonstrates perforation of the left L5 root by the course of the pedicle screw (ps). No further surgical treatment was recommended. (B) Persistent sciatica after a fall with no improvement after discectomy. The image demonstrates inflammation around the nerve (S1) consistent with a sacral fracture (fx) abutting the foramen. (C) The MR neurography imaging protocol results in an MR myelogram as well as neurographic images of the exiting nerve roots.
hyperintensity only in the ganglion with no associated mechanical impinge-
ment. This finding would be consistent with intraoperative mechanical
trauma to the nerve (Fig. 7B), for which there is no surgical treatment.

The imagable effects of mechanical trauma on nerve roots are varied. One
cause of trauma is mechanical distortion of the shape of the root, as in
Fig. 8A, which depicts a root penetrated by a pedicle screw. Alternately,
there may be nerve pain associated with inflammation nearby, as in the
radiculopathy associated with a sacral fracture depicted in Fig. 8B. Because
of the myelographic effect present in lumbar MR neurography (Fig. 8C), it

Fig. 9. Sciatic nerve hyperintensity in patients with piriformis syndrome. A variety of muscle
and nerve abnormalities can be observed in the pelvis in patients with sciatica of nonspinal
origin. In some cases, nerve fascicle swelling and hyperintensity can be observed. (A) Axial view
just below the exit from the sciatic notch where the sciatic nerves (arrows) lie over the surface of
the ischium with the piriformis muscle immediately posterior. (B) Coronal view demonstrating
a linear fascicle pattern in the right sciatic nerve (right arrow) with hyperintensity and loss of
fascicle pattern in the left sciatic nerve (left arrow). These arrows indicate the curve of the sciatic
nerve as it turns downwards after exiting the sciatic notch. The three arrows on the right
indicate the attachment of the piriformis muscle on the sacrum and across the sacroiliac joint.
The three arrows on the left indicate the inferior surface of the piriformis muscle where the
sciatic nerve and some gluteal vessels emerge from underneath it.
is possible to assess the effects of stenosis and disk herniation as well as details about nerve pathology.

Another diagnosis made possible by neurography in lumbar monoradiculitis, a condition that is easily mistaken for a herniated disk syndrome if any disk abnormality happens to be seen in the patient’s MR image.

**Piriformis syndrome**

Imaging is increasingly capable of helping provide a reliable for diagnosis of piriformis syndromes [45]; in some patients with severe symptoms, hyperintensity or shape changes are seen (Fig. 9). When MR neurography can identify specific focal entrapments, open MR imaging can guide surgical procedures with limited surgical exposure to approach the site of the abnormality for decompression or release of adhesions.

It is straightforward to use a T1 image to obtain volume and shape assessments of the piriformis muscles to assess asymmetries reflecting either hypertrophy or atrophy. In addition, these images can readily demonstrate variant courses of the distal lumbosacral plexus that may actually pass through the muscle. This course is an important piece of preoperative information, because surgical strategies aimed at extensive muscle removal may be modified to reduce the risk of nerve injury. A correlated neurographic image can confirm the identity of the structure as a nerve. Scanning of the distal lumbosacral spinal nerves, lumbosacral plexus, and sciatic nerve may also reveal tumors as the cause of sciatic distribution pain.

**Thoracic outlet syndromes**

TOSs have been problematic diagnostically because of the difficulty of obtaining surgically useful localization of sites of brachial plexus compression. Indeed, the limitations in the quality of diagnostic techniques have led to ongoing disagreements about the very existence of this class of nerve-entrapment syndromes.

In part these problems arise because of the difficulty in placing diagnostic electrodes for electrophysiologic studies in this region. Also, because many cases of TOS result from nerve compression by the scalene muscle, patients often present with pain elicited by motions such as arm raising but do not have sufficient motor symptoms to produce an abnormal electromyography. Finally, the diagnosis of TOS is greatly complicated because the term describes a variety of diverse underlying pathologic conditions that have in common only the fact that they affect some part of the brachial plexus. MR neurography has shown promising capabilities for discriminating among several different types of TOS lesions and in many cases can depict well-delineated and readily treatable specific pathologic conditions [32,33].

Anterior scalene muscle syndromes can be detected by observing asymmetries in the course of brachial plexus elements as they traverse the scalene border. Entrapment by fibrous bands in the region can also have
a distinct appearance in the form of kinking of the elements (Fig. 10). In a hypertrophied scalene muscle with no fibrous band, the distortion of the course of the plexus is smoother but nonetheless can be readily distinguished from the normal straight course through the region (Fig. 11). Surgical treatment of such proximal pathology in the region of the anterior scalene muscle may be more effectively treated by a supraclavicular approach.

A variety of types of more distal pathology can also be distinguished. Passage of the plexus over the first rib can demonstrate a distortion
associated with entrapment at the level of the clavicle (Fig. 12). Patients with this sort of entrapment are often best managed with first rib resection when conservative management fails.

In addition, brachial plexus entrapments in the axillary region can be defined as distinct entities (Fig. 13). On physical examination, these patients may have tenderness and Tinel’s sign in the axilla. Entrapment in this region may be a consequence of chronic degenerative change but may also occur as a complication of breast surgery or shoulder surgery.

A related problem that has been difficult to document properly in the past is axillary nerve entrapment. These patients typically present with shoulder pain and deltoid weakness. Unfortunately, this set of findings is sometimes
mistaken for the consequence of a rotator cuff tear, leading to unnecessary and unsuccessful rotator cuff surgery.

Abnormalities in the axillary nerve detected in an MR neurography study can be confirmed by proceeding to a nerve block at the location of the

![Image 12](image12.png)

**Fig. 12.** Entrapment of middle plexus at the costo-clavicular passage. (A) The right side demonstrates an S-shaped course passing under the clavicle and over the first rib. (B) The brachial plexus elements on the left side travel along a comparatively straight course. This type of entrapment may be best treated by first rib resection.

![Image 13](image13.png)

**Fig. 13.** Imaging of axillary nerve entrapments. (A) Hyperintense axillary nerve (ax). Adhesion of the distal plexus may result in axillary nerve irritation because of differential motion at the quadrangular space through which it passes after a short distance of travel. Patients often present with failed rotator cuff surgery undertaken for shoulder pain that has been misdiagnosed. The axillary nerve syndrome presents with pain in the axillary nerve distribution over the shoulder joint and deltoid weakness. (B) Shoulder of a 17-year-old tennis instructor with shoulder pain and difficulty positioning his arm for his serve. The axillary nerve (ax) is seen arching out across the neck of the humerus (hu) after branching off the posterior cord (pc) of the brachial plexus at the origin of the radial nerve (rn) (the beaded appearance of the axillary nerve in this three-dimensional projection image is an artifact of the slice spacing).
apparent abnormality. Such a block may be performed in an open MR scanner in which an image plane that duplicates the anatomy of the diagnostic MR neurography study can be used to guide needle placement (Fig. 14). If the pathology can be confirmed, it is often possible to treat the axillary nerve entrapment with a transaxillary neurolysis, which is a relatively simple procedure with rapid postoperative recovery.

In addition to surgically treatable entrapments, MR neurography is also helpful in identifying complaints attributable to the nerve inflammations. These patients often present with painless hand atrophy, with no associated sensory abnormality. This presentation has sometimes been termed a Gilliatt-Sumner hand syndrome. Brachial plexus elements appear bright and swollen but demonstrate no distinct evidence of impingement (Fig. 15).

MR neurography is also helpful when it demonstrates a completely normal course and caliber for all nerve elements that are under suspicion. With such findings, it is possible to take a firm stance against surgical treatment of the hand, arm, or shoulder problems that may have been tentatively attributed to a TOS.

The information gained by MR neurography has proven helpful because it permits the treatment of TOS with more limited surgeries directed at individual
pathologic conditions. Operations such as supraclavicular scalenotomy or transaxillary neurolysis are less invasive and may have lower surgical risks than transaxillary first rib resection. Use of MR neurography may make it possible to reserve the use of first rib resection for the small number of patients in whom the less-invasive operations are not appropriate.
Although electromyography and nerve conduction velocity studies are effective for evaluating large and medium-sized nerves, they may provide only limited detail about the precise location of an impingement. This limitation is particularly problematic when the problem is at an atypical location. MR neurography can be expected to demonstrate hyperintensity at the fascicular level that may be useful for evaluating even small nerves. In many situations, however, identification of the smallest nerves is difficult because current MR

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**Focal entrapments of small nerves**

Although electromyography and nerve conduction velocity studies are effective for evaluating large and medium-sized nerves, they may provide only limited detail about the precise location of an impingement. This limitation is particularly problematic when the problem is at an atypical location. MR neurography can be expected to demonstrate hyperintensity at the fascicular level that may be useful for evaluating even small nerves. In many situations, however, identification of the smallest nerves is difficult because current MR

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**Fig. 16. Movement of the median nerve with wrist flexion: images of the same location in the hand in the same individual. (A) In flexion the median nerve (mn) at the wrist located near the palmar aspect of the carpal tunnel with the tendons (te) posterior to it. (B) In extension the median nerve is posterior to the tendon in this image.**
neurography techniques tend to leave vessel images bright, and the brightness makes images of many small nerves difficult to distinguish.

**Nerve adhesions**

Image-based diagnosis of focal neuropathies has further elucidated the role of adhesive entrapments and in some cases has been able to distinguish them from compressive entrapments. MR neurography has been particularly helpful for demonstrating the degree to which nerves move across some joints. In Fig. 16, two images of the median nerve at the carpal tunnel reveal different positions for the nerve within the carpal tunnel. Both images are from the same individual and are obtained at the same location in the wrist; they differ only in that in one image the wrist is flexed, and in the other the wrist is extended. Imaging of a series of patients with clinical and electrodiagnostically confirmed electromyography revealed that although most had compressive lesions, some demonstrated only nerve adhesion with loss of normal mobility of the nerve on flexion and extension of the wrist.

From the points of view of electrodiagnosis and surgical treatment, there is little difference between adhesive and compressive carpal tunnel syndrome. They produce similar clinical and diagnostic pictures and respond to the same surgical treatment. From the point of view of imaging, however, it is important to understand that patients may have moderate to severe carpal tunnel symptoms with no evident nerve compression if there is adhesive entrapment.

Clinically, this demonstration is of potentially great importance, because in many cases it is possible to demonstrate with imaging that a nerve is not gliding normally across a joint. Restriction of movement of a nerve can cause repeated trauma to a nerve as well as symptoms of pain exacerbated by extremes of motion or by assuming particular postures or limb positions. When this situation has been documented preoperatively, special measures can be planned to reduce the risk of recurrent scar formation postoperatively [46].

**Reflex sympathetic dystrophy**

There is no typical image signature associated with complex regional pain syndromes or reflex sympathetic dystrophy. Often, however, idiopathic distortions of the course or contour of a nerve can be identified in patients with reflex sympathetic dystrophy. In some patients, the typical history of a trauma associated with delayed onset of symptoms of reflex sympathetic dystrophy may indicate a surgically treatable cause for the pain syndrome (Fig. 17).

**Nerve trauma**

Management of severe nerve trauma has traditionally been complicated by the difficulty of distinguishing between situations in which a nerve will recover with the passage of time and those in which a nerve graft or other
sort of surgical treatment is appropriate. The problem arises because the recovery after axonotmesis may require several months, but there are few reliable means of distinguishing this situation from neuronotmesis in which no recovery can be expected without surgical intervention. MR neurography can be fairly efficient in establishing the existence of significant nerve injury and in demonstrating true discontinuities in nerve (Fig. 18). At present, hemorrhage immediately after a trauma may obscure some details of the nerve image. In the future it is likely that enhancements in MR neurography pulse sequences will help resolve this problem.

There is still no completely reliable means of confirming a true nerve root avulsion by imaging. An MR neurography study includes an effective MR myelogram and can therefore demonstrate the meningoceles, which may be associated with nerve root avulsions. The procedure is less invasive than a CT myelogram and provides information of similar quality.

**Obstetric brachial plexus injury**

A particularly complex situation arises in the management of obstetric brachial plexus injuries. Imaging of infants is difficult, and the need for sedation entails significant additional risks. It has proven possible, however, to identify growing terminal neuromas in some locations (Fig. 19A) and to
demonstrate continuity of nerves at other sites. As computer techniques for postprocessing of images have progressed, it has become possible to generate fairly detailed image representations of complex brachial plexus injuries in children under 4 months of age (Fig. 19B).

**Follow-up of nerve grafting procedures**

After nerve grafting or after primary early repair of a nerve laceration, several months must elapse before it becomes clear whether the graft has

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Fig. 18. Confirmation of total nerve disruption in trauma. (A) The right brachial plexus of a 15-year-old with flail arm, 2 months after a motorcycle accident. The image demonstrates gross discontinuities in the upper plexus elements (ue), meningoceles proximally (me), and bright swollen nerve trunks (st). (B) Disconnected and retracted lower trunk (lt) in traumatic injury of brachial plexus.
been successful. MR neurography has proven helpful for evaluation of a nerve suture repair site when recovery did not ensue [15]. In this case, the demonstration of a neuroma at the repair site led to a plan to re-explore and revise the suture repair.

Nerve tumors

MR neurography permits a directed examination for nerve tumors that has a far greater sensitivity than other MR methods. Standard MR imaging scans obtained for the evaluation of pain typically miss a small neuroma (Fig. 20). Even low-quality MR neurography studies performed in imagers with poor field homogeneity or without phased-array coils may fail to demonstrate a tumor that shows well on a high-quality study. In the pelvis the sciatic nerve can be readily evaluated for nerve tumors (Fig. 21), whose
symptoms are often mistaken for sciatica in routine spinal pathologic studies. In some cases, the level of detail also allows distinguishing among types of tumors such as the reported capability of distinguishing perineur- iomas [48] from schwannomas.

In addition to the potential for diagnosing a nerve tumor, MR neurography can be extremely helpful in surgical planning for the treatment of these lesions. For a brachial plexus lesion it is possible to distinguish definitively which elements of the plexus are involved in the lesion (Fig. 22A,B). It is also often possible to identify the relationship of the main nerve trunk to the mass of the tumor and so to plan the safest possible surgical approach (Fig. 22C).

Imaging may play a role in the initial diagnosis of neurofibromatosis and is also helpful in tracking and analysis of advanced stages of the disease (Fig. 23). Other types of tumor-associated neuropathies can often be evaluated productively by neurography (Fig. 24) [49].

**MR findings in systemic neuropathies**

MR neurography can help make or confirm the diagnosis of neuropathy on a noninvasive basis. The two important types of nerve abnormality that have now been observed can be classed as intrafascicular pathology and interfascicular pathology.
In the setting of Charcot-Marie-Tooth familial neuropathy, the normal fascicle pattern is altered by an increase in the relative amount of fatty interfascicular epineurium with a relative decrease in the cross-sectional area of the fascicles themselves (Fig. 25). Externally, upon direct examination, this pattern would manifest as a relative hypertrophy or increase in nerve caliber, whereas the fascicles themselves actually seem to be subject to some degree of relative atrophy.

An entirely different image is seen in chronic inflammatory demyelinating polyradiculoneuropathy. In these patients there is gross dilatation of the fascicles themselves (Fig. 26). This alteration reflects an apparent increase of low-protein water inside the fascicles and is somewhat similar to the pattern seen in Wallerian degeneration (see Fig. 5). Although some onion-bulb formations are seen in sural nerve biopsies in these patients, there are

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Fig. 21. Sciatic schwannomas. (A1) Axial view of a 32-year-old man who had back school physical therapy, lumbar discectomy, and piriformis muscle section all without benefit proved to have schwannomas in the sciatic nerve just above the level of the ischial tuberosity. (A2,3) Coronal reformats in slightly different planes demonstrate and confirm the relationship of the larger (*) and smaller (**) tumors to the sciatic nerve (s). His symptoms resolved after tumor excision. (B) This mass (m) in the sciatic nerve (s) was discovered in a patient with sciatica, positive straight leg raising, and lumbar spondylosis.
perivascular mononuclear cells, and there is notable edema in the endoneurial fluid compartment [50]. This edema is most likely the basis for the image findings.

**MR imaging for the diagnosis of pathologies affecting muscle**

The role of imaging in the diagnosis of muscle pathology has steadily expanded as the various classes of imageable properties of muscle have been
appreciated. In addition to exploring physiologic aspects of muscle function such as fiber type [51], fiber architecture [52], and activation patterns [53,54], a variety of pathologic conditions [55–57] can be assessed. MR imaging can contribute to diagnosis by providing precise information about the location and distribution of involved muscle tissues and by providing qualitative

Fig. 23. Survey images for the evaluation of neurofibromatosis. (A) Multiple schwannomas of the cervical spinal nerves in a patient with neurofibromatosis. (B) In some cases, the neurofibromatosis is subtler. In this patient with chronic complaints of body wall pain, diagnosis would be quite difficult with conventional imaging.

Fig. 24. Late plexopathy after mastectomy and irradiation for breast cancer. (A) This patient had bright, irregular nerves of normal caliber suggesting radiation neuritis treatable with steroids. (B) Hyperintense brachial plexus elements of extremely narrow caliber suggest encircling mechanical entrapment associated with postirradiation fibrosis. Surgical neurolysis may be helpful. (C) Grossly swollen nerve roots and hydrothorax associated with aggressive tumor recurrence and nerve invasion by tumor.
information about several types of abnormalities. Abnormal muscle may
demonstrate hypertrophy, atrophy, or excess fluid, which cause brightness on
T2 imaging, or fatty replacement, which causes brightness on T1 imaging. The
pattern of muscle involvement in these abnormalities and the distribution of
these findings within individual muscles and muscle groups can provide
valuable diagnostic information.

Fig. 25. T1-weighted image of the tibial nerve in the popliteal fossa in a 32-year-old man with
Charcot-Marie-Tooth neuropathy. There is an excessive amount of interfascicular fatty tissue,
and the fascicles (dark spots) appear somewhat atrophied.

Fig. 26. Dilated neural elements in chronic inflammatory demyelinating polyradiculoneuropathy.
(A) Coronal view demonstrating gross dilation of the L4 and L5 spinal nerves. (B) Axial
view at the level of the first sacral vertebral element demonstrating fascicular level dilation of
neural elements. PSIS, posterior superior iliac spine; SC, spinal canal.
Imaging of denervated muscle

In a variety of situations, MR imaging can be a useful adjunct to electrodiagnostic studies for the evaluation of muscle denervation. When this phenomenon is present, it greatly simplifies the task of identifying individual muscles involved in a selective focal or distal injury (Fig. 27).

The development of signal alterations in muscle after denervation was first reported by Shabas [58] and by Jolesz and colleagues [59]. It is now known that abnormal muscle appearance may be detected as early as 4 days after an axonometric or neurometric injury. The signal abnormalities become progressively more intense as months pass, reaching a maximum about 4 months from the date of injury. In 1 to 2 years, the abnormality changes in quality but continues to persist unless the nerve regrows or is restored through grafting.

The initial change is an increased intensity on T2-weighted imaging. This change has been observed using an inversion recovery pulse sequence called short tau inversion recovery (STIR) but is also well seen in the T2-weighted, fat-suppressed sequence used for neurography. Animal work [60] showed how the appearance of increased signal occurs. There is no increase in water content of the muscle; use of radiolabeled tracer compounds allowed the authors to establish that there was an expansion of the extracellular fluid.

Fig. 27. Muscle hyperintensity with denervation. Nine months after onset of weakness, this 28-year-old woman presented with weakness of finger extensors. Her diagnosis of entrapment of a distal branch of the posterior interosseous nerve can be made specifically based on the hyperintensity seen in the extensor digitorum muscle (arrow).
volume at the expense of the intracellular fluid. This shift was apparently associated with atrophy of the muscle cells.

A larger detailed human study by Fleckenstein et al [56] established that the onset of the imaging changes varies from patient to patient and that there is variability in the effect even among muscles in the distribution of a single damaged nerve. In 1 to 2 years, the quality of the abnormality changes as the muscles are replaced with fat. This additional change may correlate with the development of nonreceptivity to regrowing nerve fibers, which is known to take place at a similar interval after denervation. This connection, however, has not yet been firmly established. Fleckenstein et al also point out that muscle edema from trauma and several other confounding sources of image abnormalities must be kept in mind in considering this type of data.

Additional information about the clinical utility of muscle imaging appears in a report on imaging of 32 cases by West et al [61]. They document a similar range of alterations in image appearance in a case-study format. These authors advocate the use of MR imaging to assess muscle denervation in small children who do not tolerate electrodiagnostic tests well, in patients needing serial testing, and in patients for whom a complete view of the detailed pattern of innervation is required for surgical planning.

**Muscle MR imaging in the setting of nerve injury**

In other patients, muscle MR imaging is helpful when a small, deep muscle is affected in isolation. Splinting and abnormal movement associated with one group of muscles compensating for the inactivity of another may confuse the picture on electromyography, but the denervation pattern on MR imaging can sometimes resolve the diagnosis. The opportunity to image the muscle in several different image planes may be helpful for the confirmation of the diagnosis. Used with nerve imaging, MR imaging of denervated muscle can clarify complex or unusual patterns of injury and recovery (Fig. 28).

The changes in imaging properties of muscle may be detectable even closer to the time of injury with the use of intravenous gadolinium contrast agent. Bendzus and Koltzenberg [62] have reported the incidental discovery that enhanced uptake of gadolinium-DTPA can be observed in fat-suppressed T1-weighted images of muscle as early as 24 hours after the nerve to the muscle was cut. This incidental observation was followed by confirmatory laboratory studies, but its general clinical reliability has not yet been established.

**MR imaging for assessment of normal and abnormal muscle activation patterns**

Improvements in the spatial and temporal resolution of MR imaging have gradually improved the clinical utility of muscle activation imaging. It has been known for a number of years that the T2-decay time of muscle
Recovery from muscle denervation. An 8-year-old boy with partial reinnervation of right leg muscles 8 months after being struck by a motor vehicle. Initially he had flaccid paralysis of the sciatic innervated muscles but by 5 months began to develop flexion at the knee, which had 80% strength at the time of the imaging examination. (A1) Sagittal image of right thigh shows the femur fracture (fx), damaged sciatic nerve (sc), and patella (pat) for orientation. (A2) The sciatic nerve was fully transected by the initial injury, and its healed stump is seen with marked nerve injury hyperintensity. Several new growth nerves are seen emerging from the stump to reinnervate the long head of the biceps femoris. (B1) The semitendinosus and semimembranosus demonstrate muscle denervation hyperintensity (*). (B2) The short head of the biceps femoris (**) also continues to demonstrate hyperintensity of denervation. (C) Axial image 3 inches below the level of the sciatic stump (ps) demonstrating the hyperintense semimembranosus and semitendinosus (*) and short head of the biceps femoris (**). There is normal muscle image appearance in the long head of the biceps femoris (**). The femur (fe) is labeled for orientation, and the placement of the sagittal image slices for B1 and B2 are also marked as ps(B1) and ps(B2), respectively.
lengthens in the course of exercise [53,63]. More recently, it has been shown that the pattern in which the motor system selectively and preferentially uses some neuromuscular units within a muscle can also be demonstrated by imaging [64]. The clinical application of this phenomenon is at an early stage, but it may someday be possible to establish characteristic patterns of normal and pathologic neuromuscular unit activation associated with various neuropathies and myopathies.

**Myopathic and neuropathic effects on muscle image patterns**

In a number of myopathies and neuropathies, two aspects of muscle degeneration can be appreciated with imaging. There may be an increase in the T2-relaxation time of resting muscle caused by effective edema in the muscle fibers [65–67]. In addition, characteristic patterns of fatty replacement or degenerative change have been described for several conditions. These changes can be readily appreciated in fat-suppressed T-weighted imaging (Fig. 29) [68–70]. Changes in T2 or T1 image parameters of muscle and the distribution of those changes have also been reported for amyotrophic lateral sclerosis [71], for Duchenne muscular dystrophy [72], for various inflammatory myopathies [73], and for myositis syndromes (Fig. 30) [74]. Painful myopathies in diabetics can be evaluated with MR imaging to learn whether muscle infarction is playing a role as opposed to more strictly neuropathic sources for the pain [75].

For purposes of image interpretation a system of 12 different patterns of fatty replacement of muscle has been described [57]. In general, this classification has some usefulness for distinguishing among the various muscular dystrophies. In addition, longitudinal follow-up with serial imaging of the affected individual can be used to document progression or

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Fig. 29. Fatty replacement of muscle tissue in three generations of a family with Bethlem myopathy. A T1 transverse section of thigh muscles in the three cases is shown. (A) In the 6-year-old young girl the vastus lateralis (VL) is only marginally affected at its periphery. The periphery of the same muscle is also more markedly affected in her mother (B) and in her grandmother (C) with obvious sparing of the central part. (From Mercuri E, Cini C, Counsell S, et al. Muscle MRI findings in a three-generation family affected by Bethlem myopathy. Eur J Ped Neurol 2002;6:309–14; with permission.)
remission of the disease. Myotonic disorders are characterized by muscle hypertrophy in characteristic patterns, whereas atrophic disorders can be identified by their characteristic patterns of atrophy.

Another class of information available derives from MR spectroscopy. In general, spectroscopic methods are plagued by low spatial resolution and a variety of other confounding issues. Nonetheless, particularly in studies of larger muscles, P-31 spectroscopy can provide a detailed view into the relative state of high-energy phosphate compounds such as ATP and phosphocreatine and provide relative quantitative assessments of adenosine diphosphate, inorganic phosphate, and phosphorylation potential. It has

Fig. 30. Proton-density weighted images at the level of the junction of the upper one third and lower two thirds of both thighs with muscle outlines (R) and (L). (A) Asymmetric involvement of the vasti and normal signal in both rectus femoris muscles. (B) Severe involvement of the vasti and rectus femoris muscles. (C) Normal signal in all muscles. (From Phillips BA, Cala LA, Thickbroom GW, et al. Patterns of muscle involvement in inclusion body myositis: clinical and magnetic resonance imaging study. Muscle Nerve 2001;24:1526–34; with permission.)
been reported that fatigue associated with dermatomyositis can be objectively monitored in this fashion [76].

**Image ordering for the referring physician**

Unlike brain or spine imaging, there are a range of choices for the referring physician in ordering an MR neurography scan, particularly with regard to the volume of interest. When a survey of a limb or the entire brachial plexus is needed, the coronal or sagittal view is most helpful, but fine detail in the axial plane is lost. Because slices for neurography are usually about 3 mm thick, an order for the entire arm and hand could require more than 200 slices. An individual MR image sequence is usually limited to about 40 slices, so the full survey would require six different imaging sequences. Most MR scanning protocols allow only for a single sequence.

When the radiologist is able to view the coronal or sagittal survey images during the imaging session, it is possible to prescribe high-resolution axial images through any pathologic condition that is seen. In general, axial images of the nerves should be nerve perpendicular and therefore may not always be simply perpendicular to the main axis of the limb. In the brachial plexus, the nerve-perpendicular images can only be prescribed once the initial image of the plexus is obtained in the coronal plane. Such issues may ultimately tend to involve the neurologist in the MR imaging process in the way that he or she is currently involved in tests such as electromyography. Radiologists who have a special interest in MR nerve imaging can often provide this level of service, however, and spare the referring doctor a trip to the imaging center.

**Future prospects**

Use of MR neurography for imaging of smaller nerves in the periphery may be limited because the nerves cannot be distinguished from blood vessels that also appear in the images. There are a variety of strategies for suppressing blood vessel images in neurography images, but, because of the demanding signal-to-noise characteristics of the image, additional manipulations may impair the quality of the nerve image. On a routine basis, radiofrequency saturation pulses are sent into the blood vessels proximal and distal to the volume of imaging just before collecting the nerve image in the desired field of view. As a result, the blood that flows into the imaging volume during the nerve image acquisition is unresponsive to the imaging signal and so tends to have low signal intensity.

One approach through pulse sequence design is to add flow-weighting pulses to the basic MR image acquisition process. The result leads to some further sacrifice in signal-to-noise performance but generally preserves the intensity of the nerve image while greatly reducing the signal intensity of vessels.
One further approach under active development is the use of black blood contrast agents. These are typically iron oxide contrast agents that are designed to remain in circulation in the blood stream during the image session and to obliterate the image signal from the blood. These agents have the additional benefit of suppressing the bone image and so further improve the conspicuity of nerve in the image.

MR imaging clearly shows promise for documenting the severity, degree, and rate of progression of various myopathies and other muscle disorders. It also has clear value for making and confirming the initial diagnostic impression that a muscle disorder exists. In the future further developments in pulse sequence design and contrast agent research will probably further improve the diagnostic specificity of MR neurography.

Summary

Recent advances in the technology of MR imaging are beginning to transform the fundamental methodology of diagnostic evaluations in neuromuscular disorders. When properly implemented, MR neurography is capable of providing high-quality information about nerve compression, nerve inflammation, nerve trauma, systemic neuropathies, nerve tumors, and recovery of nerve from pathologic states. Muscle MR imaging can identify denervation on a precise anatomic basis, document the progression of various conditions causing myopathy and myositis; and even provide insight into abnormal patterns of muscle activation. There is an essential role for the neurologist as well as for the specialist radiologist that requires a high level of familiarity of the various new types of image findings in this steadily advancing field.

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