THE RATIONALE FOR SURGICAL LYSIS OF ADHESIONS IN THORACIC OUTLET SYNDROME

Despite the use of the single term “thoracic outlet syndrome,” there is good evidence that a variety of different types of neurologic entrapment may be involved. These subcategories of thoracic outlet syndrome include fibrous bands proximal to the anterior scalene muscle, anterior scalene syndromes involving spasm or hypertrophy of the anterior scalene muscle, entrapment of the plexus between the clavicle and first rib, anomalous cervical rib syndromes, and distal plexus entrapments due to adhesions.

An attractive aspect of first rib resection in the treatment of thoracic outlet syndrome is the potential to relieve entrapments that occur at each of these several different locations. First rib resection is undoubtedly the best treatment for entrapment of the plexus between the first rib and clavicle. However although it may be effective for each of the other types of entrapment it is not necessarily optimized for the treatment of any one of them. Further, it may actually exacerbate arm pain due to plexitis that has been mis-diagnosed as an entrapment syndrome.

For these reasons, an alternative strategy has been developed in which MR Neurography imaging is employed to make a specific diagnosis in advance of surgery that can assign most patients to one of the subcategories of thoracic outlet syndrome. Then, based on the specific diagnosis, a neurolysis (or “neuroplasty”) procedure can be planned that focuses on the particular pathology at hand.

Surgical neurolysis procedures have the principal advantage of allowing for fine manipulation around the nerve elements under close direct vision in a limited field of view. As long as there is uncertainty about the actual location of the neurogenic pain generator, this sort of targeted approach bears the risk of missing the actual pathology.
However, to the extent that MR Neurography can successfully identify the location of the pathology, the use of surgical neurolysis can result in better outcomes, smaller surgeries and reduced surgical risk.

The development of recurrent adhesions after neurolysis surgery is an additional significant concern. Use of new adhesiolytic agents such as Seprafilm and Adcon-L however, appears to greatly reduce the incidence of recurrent adhesions. When recurrence develops after otherwise successful first rib resection, then surgical neurolysis with placement of adhesiolytic agents is also a useful treatment option.

**NEUROLYSIS SURGERY FOR THORACIC OUTLET SYNDROMES**

There are two important approaches for lysis of adhesions in the brachial plexus: supraclavicular and transaxillary. The supraclavicular approach provides good access to all neurologic components proximal to the clavicle, while the transaxillary approach is useful for entrapments occurring between the clavicle and the point of entrance of the neurovascular bundle into the arm at the axilla.

For either type of surgery it is extraordinarily helpful to utilize EMG and SSEP monitoring during the procedure. EMG electrodes should be placed in the deltoid, triceps, biceps and hypothenar muscles. In addition, it may be helpful to drape the arm in a clear plastic drape such as a fluoroscopy drape so that direct vision of arm movements can be used to supplement the information from the EMG traces.

**Procedure for Supraclavicular Approach**

The incision for the supraclavicular approach can be made parallel to the clavicle and about one centimeter above it. The incision begins two centimeters from the midline and extends laterally for no more than four to five centimeters. If the incision extends further lateral to this, it is likely that small cutaneous supraclavicular cutaneous nerve branches will be cut producing numbness on the chest below the incision which is a minor but annoying post-operative problem.

After the initial incision, the platysma is cut parallel to the skin incision and blunt dissection is used to create an exposure between the sternal and clavicular heads of the sternocleidomastoid muscles. The omohyoid muscle is swept upwards and the exposure is maintained by the use of hinged Whetlander retractors or with a cervical discectomy retractor system such as the Caspar retractor.

The superior surface of the scalene fat pad is then carefully mobilized off of the jugular vein. The vein is retracted medially as the fat pad is retracted laterally. The fat pad can be palpated to locate the underlying anterior scalene muscle. As dissection through the fat pad proceeds, electrical stimulation is used to search for the location of the phrenic nerve where it lies on the surface of the anterior scalene muscle. Once the phrenic nerve is located, the remainder of the fat pad is freed from the medial vascular structures and held behind a retractor blade. During this portion of the dissection, care must be taken to avoid disruption of any large chyle containing vessels. If a chyle leak does occur, the thoracic duct vessel may be cauterized with the bipolar coagulator and packed with a small amount of fibrin soaked gel foam.

At this point, a search is undertaken either with the stimulating electrode or with direct vision to identify the upper trunk of the brachial plexus that usually lies just superfi-
cial to and lateral to the anterior scalene muscle. In addition, if there is significant shoulder pain involved it is also useful at this point to explore deep and lateral to the upper trunk to locate the proximal part of the suprascapular nerve and to explore deep to the suprascapular nerve to identify the distal accessory nerve. When there is significant shoulder pain involved in the thoracic outlet syndrome, particularly when upper trunk symptoms are prominent, the suprascapular and/or accessory nerve may be involved in the same process of fibrosis which affects other portions of the brachial plexus.

The phrenic nerve is then fully mobilized from the surface of the anterior scalene muscle and protected. Dissection around both medial and lateral surfaces of the anterior scalene muscle is then conducted to reveal the middle trunk of the brachial plexus that is directly deep to the anterior scalene muscle and is usually in contact with it. Once the muscle has been elevated from the middle trunk, 0-silk ties can be passed around the scalene muscle and tied in preparation for division of the muscle.

If the anterior scalene muscle is cut in a single straight line, the ends will retract at surgery; however, there is a significant risk of reconnection of the two cut ends over time post-operatively. To minimize this particular recurrence risk, the surgeon should plan to completely remove a portion of the anterior scalene muscle that is nearly two centimeters in length. Each cut is made by carefully coagulating the muscle with bipolar cautery, followed by incision with a Metz scissors. Great care is needed to guard against injury to the phrenic nerve during this portion of the procedure. Also the distal cut is directly over the subclavian artery and it is crucial to avoid injury to the artery and to its variant branches such as the transverse cervical artery which may cross the anterior surface of the scalene muscle.

Once the scalene muscle has been resected, a further exploration is carried out deep to the middle trunk and medial to it in order to locate the lower trunk of the brachial plexus. It is the lower trunk that is most frequently involved in the symptoms of thoracic outlet syndrome and it must be identified and subject to particular surgical attention. The current-controlled EMG stimulator is often very helpful at this point for locating the lower trunk. Optimally, both the C8 and T1 spinal nerves are also identified at this point. Resection of portions of the middle scalene muscle is often required to complete this portion of the exposure.

The neurolysis itself can begin at this point. Each of the involved elements is identified, inspected and subjected to removal of adhesions. One useful technique is to use DeBakey pickups to grasp the adhesion surface and a crile directed parallel to the nerve to pry open the adhesions without applying undue pressure to the nerve elements directly. Neurolysis should follow the elements up to the spinal foramina and distally towards the level of disappearance under the clavicle. Hemostasis should generally be achieved with gentle pressure so that electrical bipolar coagulation directly adjacent to nerve elements can be avoided. Resection of any enlarged cervical transverse process, cervical rib, or remnant of incomplete first rib resection can be carried out at this time if necessary.

Once the neurolysis is complete the area is flooded with body temperature antibiotic irrigation and a Valsalva maneuver completed to test for pneumothorax. After irrigation, all nerve elements, including the phrenic nerve are again stimulated to assure and assess function at the close of the procedure. Finally, pieces of Seprafilm are placed along all dissected nerve surfaces or Adcon-L is applied.

The first layer of closure involves reapproximating the scalene fat pad to the jugular vein. This can be done with 3-0 vicryl sutures through the thin fascia on the superficial surface of the fat pad and its remnant on the superior surface of the jugular vein. This
maneuver takes advantage of the fat pad as a natural barrier to adhesions between nerve elements and surrounding muscle and vascular structures. The platysma, if present, is then closed and a cosmetic closure completed. Postoperatively, pain is usually easily controlled and early mobility is encouraged. If a patient suffers from reflex sympathetic dystrophy (complex regional pain syndrome), then a percutaneous catheter can be placed for a forty-eight hour infusion of marcaine into the surgical site to control cutaneous burning pain around the site of surgery.

Procedure for Transaxillary Approach

The transaxillary approach is made through a three centimeter incision in the axilla which is placed higher in the axilla than the usual incision for a first rib resection. The ideal location is the apex of the axilla. The author prefers a supine position for the patient but others prefer a lateral decubitus position.

The neurovascular bundle lies just below the subcutaneous tissues. It is identified by palpation of its vessel contents and with electrical stimulation. An Omni retractor can now be positioned so that a renal vein retractor can lift the pectoralis mass upwards from the operating table providing a good view of the plexus.

The sheath of the neurovascular bundle is opened and the individual neural and vascular elements are separated as adhesions are freed. Using long instruments, it is typically possible to maintain good vision and access along the plexus elements up to and just past its passage below the clavicle. If there is a significant component of shoulder pain, then the axillary nerve needs to be identified after its separation from the radial nerve as it plunges into the quadrangular space. The axillary nerve is then followed proximally to assure release from any adhesions.

Palpating along the inferior or deep surface of the neurovascular bundle, sharp fibrous bands are often encountered passing from anterior to posterior below the plexus and these can be cut. Adhesions to the pectoralis mass anterior to the plexus or to other structures superior to the plexus are also sought out and released while protecting any small nerve branches. Attention is also paid to the proximal ulnar, median, radial and musculocutaneous nerves as they transition into the upper arm.

After irrigation and placement of the adhesiolytic material, the surgical wound can be closed with 3-0 vicryl in the subcutaneous layer and a 4-0 vicryl subcuticular closure, then dressed with steri-strips, a small amount of gauze and an opsite film.

OVERVIEW OF MR NEUROGRAPHY

The role of medical imaging, including magnetic resonance imaging (MRI) in the diagnosis of peripheral nerve disorders is a rapidly expanding field. In the past, the practical application of MRI of nerves has been limited due to technical difficulties in obtaining good image contrast to help distinguish nerve from neighboring tissues. In this setting the very limited capabilities of ultrasonound for nerve identification have seemed useful. Recent advances and enhancements of techniques of MRI, however, have now transformed the evaluation of a variety of conditions that have posed diagnostic challenges in the past.

The term “Magnetic Resonance Neurography” (MRN) is used to describe these new techniques which greatly improve the ability to identify peripheral nerves in im-
ages and often make it possible to generate tissue specific images of nerves analogous to angiograms. This enables the physician to examine the peripheral nerve for anatomic abnormalities.

MR Neurography derives from discoveries in basic MR science since 1992. The technique has now been applied in thousands of clinical cases. A series of publications cover the basic science, imaging science, and clinical application of the technique. Well controlled outcome trials have established at least in some settings, that MR Neurography can be more reliable than electrodiagnostic studies in localizing peripheral nerve disorders and guiding treatment planning.

There are a variety of technical aspects of MR nerve imaging that the referring physician needs to be aware of. Many radiologists have very 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. It may also be helpful for the referring physician to be aware of general technical aspects of the nerve imaging process so that quality problems can be understood and corrected.

Clinical Role

Tissue specific imaging of nerves provides not only information about the anatomy of nerves of interest but also is capable of demonstrating pathology in many settings. Direct anatomical information can be used to locate small nerve tumors that may be otherwise difficult to localize precisely. It 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 appear 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. The hyperintensity appears to be due to excess endoneurial fluid accumulation associated with nerve compression.

In the evaluation of some nerve compression syndromes, MR Neurography can have a sensitivity and specificity similar to that of needle electromyography (EMG) because mechanical changes in nerve diameter and particularly, changes in local fluid content can be detected reliably in some settings. Studies comparing outcomes in carpal tunnel and ulnar nerve release surgeries show that MR Neurography is as effective as needle EMG for identification of patients who are helped by surgical treatment.

Of potentially greater clinical significance however is the application of MR Neurography in the evaluation of thoracic outlet syndromes (TOS's) where electrophysiological studies have so far been of only varying effectiveness.

The MR Physics of Nerve Imaging

The concept underlying MRI of nerve is that there are a variety of unique types of tissue water in nerve (Figure 43-1). MR pulse sequences generally are designed to highlight particular classes of tissue water and the unique aspects of nerve water allows for the design of unique pulse sequences for nerve imaging. Although water is always chemically the same substance, MRI pulse sequences produce tissue contrast because the environment in which a water molecule exists affects its behavior on MRI scanning. Important parameters include the presence of large quantities of protein in the water, proximity to lipids, and the presence of iron containing molecules in the tissue.
In addition the properties of movement of water, due either to diffusion or to bulk flow affect the MR behavior.

The chemical environment of the protons in lipids causes them to have a significantly different resonant frequency from protons in water so that it is possible to design pulse sequence strategies which selectively affect protons in water or selectively affect protons in lipids. This is the basis of "fat suppression" techniques. Fat suppression is critical in most nerve imaging because the layers of fat which often surround nerves as they travel generate very strong image signals which can obscure the nerve. In addition, imaging strategies that are designed to demonstrate fascicle structure depend on fat suppression to black out the signal from the interfascicular epineurium between the fascicles.

**Clinical Use of MR Neurography**

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.\(^8,18\) This method has extremely high selectivity for nerves and should be very sensitive to a variety of types of pathology. However, the technical demands necessary to perform diffusion Neurography may delay widespread application.

T2-based Neurography can be carried out on many existing top quality clinical scanners with minor modifications. At most imaging centers, the principle limitation on the provision of MR Neurography is the lack of expertise in prescribing, post-processing, interpreting, and acting upon the MR data.

**Technical Aspects of 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.\(^19\) This was 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 signal from these various component tissues to mix. In a variety of different imaging techniques, the result of the image signal mixing was a featureless gray image.
of the nerve which left this tissue difficult to distinguish clearly in an image and caused confusion about the fundamental imaging characteristics of nerve (Figure 43-2).

**The physiological basis of T2 Neurography**

Several pieces of evidence suggest that, 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, confined by the perineurial blood/nerve barrier, that bathes the axons.\(^{20,21}\) It has a bulk proximal to distal flow along the nerve\(^{22}\) that may be disrupted by nerve compression and edema.

Although endoneurial fluid is responsible for only a fraction of the imageable protons in a nerve, it is one of the most distinctive types of tissue water in nerve from the point of view of MRI. By applying a chemical shift selective pulse, it is possible to suppress not only fat around nerves, by also to suppress much of the fat signal from within nerves. Then, by selection of an appropriate echo time (around 90ms), 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.

When all three measures are taken: fat suppression, T2-weighting, and blood suppression, the conditions are created to allow the generation of tissue-selective nerve images. However, these pulse sequence manipulations alone are not sufficient to obtain useful images.

![Figure 43-2. Voxel alignment in nerve for T2 based Neurography. The endoneurial fluid (En) is contained in the privileged space inside the perineurium of the nerve fascicles and bathes the myelin sheaths of the axons. It is a low protein fluid which appears bright in T2-based Neurography sequences. The fatty tissues of the interfascicular epineurium (In) appear black in these sequences. If a voxel is oriented diagonal to a nerve (1) or is aligned but of too large a size (2) then a mix of bright fluid and dark fat results in a gray pixel. However a small aligned voxel inside a fascicle (4) gives a white signal and a voxel inside the interfascicular epineurium gives a black signal (3).](image-url)
**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 called "phased array coils." The basic idea behind phased array is to use more than one antenna to collect the weak signal.

The most important things for the referring physician to be aware of is that phased array capability is critical for high resolution imaging and that performance varies among phased array coils from different manufacturers. Typically, an imaging center with phased array capability has to carefully select which phased array coils it will purchase based on its usual mix of imaging study types. There are some phased array coils specially designed for imaging of peripheral nerve e.g. a brachial plexus array (Figure 43-3), however, many general purpose phased array coils can achieve nearly equivalent performance.

**Image plane orientation and post-processing**

For most types of routine MRI scanning the original scan can be collected in three standard planes: axial, coronal and sagittal, then printed on film and read. MR Neurography is considerably more demanding and is essentially wedged to an electronic reading format. The initial scanning must be done with attention to the main orienta-

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Figure 43-3. Specially designed brachial plexus phased array coil set (Ultralmage/Medical Advances). Collection of image data from multiple locations at close proximity to the tissue of interest results in significant improvements in signal to noise performance. This design also achieves improved reliability for fat suppression due to a high "filling factor" meaning that there is very little empty air space between the coils and the tissue of interest.
tion of the nerves of greatest interest (Figure 43–4). This is because of the imaging mechanics discussed earlier.

Even when image plane orientation is attended to during image collection, the raw image will capture only pieces of nerves in individual images. The full image of the nerve can then be reconstructed in at least one of several ways. The first of these is oblique reformatting. This step is essentially mandatory prior to reading any MR Neurography scan and needs to be conducted on an FDA approved image post-processing system. By shifting the effective image plan a few degrees and changing the effective slice thickness it is typically possible to re-assemble 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 which is oblique relative to two of the original image planes can then be generated to further improve visualization.

**Figure 43-4.** Unlike routine brain or spine MRI scanning, MR Neurography imaging exams require alignment of the imaging plane orientation with the main course of the nerves of interest. For a brachial plexus study, the neck is flexed forward to help bring the origins of the cervical spinal nerves into alignment in a plane which extends through much of the proximal plexus. Despite the use of specialized oblique image planes for various nerves of interest and adjustment for individual anatomy, virtually all MR Neurography imaging exams require oblique reformatting after the image is collected to further optimize image plane alignment.
Although some oblique reformatting is mandatory for nearly all MR Neurography studies, further processing on a full-scale 3D workstation is preferable. The additional post-processing makes it possible to do maximum intensity projections (MIP) which essentially stack up the image slices and have the effect of re-assembling the nerves (Figure 43-5). A fundamental aspect of the design of MR Neurography protocols is to render the nerve as essentially the brightest object in the image. Achieving this objective makes the use of MIP possible.

Figure 43-5. Assembly of raw images by maximum intensity projection (MIP) 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.
Yet another category of three-dimensional post-processing is the use of curved reformatting. This step is often capable of producing 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 (Figure 43–6). This nerve trace is also very useful for interpreting the image since it documents any unusual deviations in the course of a nerve or plexus.

**Image ordering for the referring physician**

Unlike brain or spine imaging, there is a range of choices for the referring physician in ordering an MR Neurography scan particularly with regard to the volume of interest. In the situation where a survey of a limb or the entire brachial plexus is needed, the coronal or sagittal view will be most helpful, but fine detail in the axial plane will be lost. Since axial slices are usually about 3mm thick for Neurography, an order for the entire arm and hand could require more than two hundred slices. An individual MR image sequence is usually limited to about forty slices, so the full survey would require a six different image sequences while most MRI scanning protocols only allow 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 axials through any

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**Figure 43-6.** Complete bilateral brachial plexus with curved reformatting. (A) The plexus image extends from axilla to axilla although this image does not follow the plexus into the proximal arm. The patient had bilateral arm and hand pain with different sets of symptoms on right and left, negative cervical spine MRI and no wrist or elbow entrapments on electrodiagnostic studies. This image demonstrates an exaggerated sinusoidal course (*) on the right side where the plexus passes below the clavicle and over the first rib. The left side image shows a very different configuration at the same location (**) with some focal narrowing of the upper trunk. The proximal C6 spinal nerve (***) is flat and broad. (B) The image in (A) is produced by an experienced technician or physician who positions the curved reformat nerve trace segments using a 3-D work station.
pathology that is seen. In general, nerve axials should be ‘nerve perpendicular’ and this may not always mean that they are simply perpendicular to the main axis of the limb. In the brachial plexus, the nerve perpendicular images can only be prescribed once the initial plexus image is obtained in the coronal plane. Issues like this may ultimately tend to involve the neurologist in the MRI process in the way that he or she is currently involved in tests such as EMG. Radiologists who have a special interest in nerve MRI can often provide this level of service however and spare the referring doctor a trip to the imaging center.

**Image appearance of nerve pathologies**

MR Neurography makes it possible to view images which depict many types of nerve pathologies which previously could only be appreciated during open surgery. Nerve swelling, including edema at the fascicular level can often be seen (Figure 43-7). A further consideration which can often be evaluated is the loss of normal nerve mobility due to adhesions (Figure 43-8). Mechanical deviations in the physical course of nerve can indicate entrapment or adhesions (Figure 43-9) and nerve injury associated hyper-intensity 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.

![Figure 43-7](image-url). 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 a phased array coil allows evaluation of the fascicle pattern. Some fascicles become bright and swollen at the site of injury (A2) at the expense of the interfascicular epineurium. (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 which might require surgical treatment.
Figure 43-8. (A) The median nerve (mn) at the wrist located near the palmar aspect of the carpal tunnel with the tendons (te) posterior to it. (B) The median nerve is posterior to the tendon in this image. A & B are images of the same individual at the same location in the hand but, image A is obtained with the wrist in flexion and image B is obtained in extension.
Figure 43-9. Image evaluation of thoracic outlet syndrome. A 52 year old woman presenting with a two year history of right 4th and 5th digit pain and negative EMG/NCV of the ulnar nerve at elbow and wrist, who has no cervical disc disease. The preoperative Neurography (Pre-Op) shows a kink distorting the course of the lower trunk of the brachial plexus. The diagram identifies the anatomy and shows a fibrous band extending from the C7 transverse process to the first rib that causes the image finding. After a supraclavicular approach for resection of the anterior scalene and neurolysis of the lower trunk, the patient experienced complete relief of right hand and arm symptoms, now maintained at nearly two years follow-up. The postoperative and contralateral images from the same patient show the mechanical result of the surgery in restoring normal anatomy.
IMAGING OF THORACIC OUTLET SYNDROMES

Thoracic Outlet Syndromes (TOS) have been problematic diagnostically because of the difficulty of obtaining surgically useful localization of brachial plexus compression sites. 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 of placement of diagnostic electrodes for electrophysiologic studies in this region. Also, since many cases of TOS are due to nerve compression by the scalene muscle it is often the case that patients present with pain elicited by motions such as arm raising, but do not have sufficient motor symptoms to produce an abnormal EMG. Finally, the diagnosis of TOS is greatly complicated because the term describes a variety of diverse underlying pathologies 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 pathologies.\textsuperscript{17}

Scalene Syndrome and Other Proximal Entrapments

Anterior scalene muscle syndromes can be detected by observing asymmetries in the course of brachial plexus elements as they traverse the scalene border. Routine T1 images of the appropriate area can also readily demonstrate asymmetry in the size or shape of the scalene muscles (Figure 43-10). Entrapment by fibrous bands in the region can also have a distinct appearance in the form of kinking of the elements (Figure 43-9). Another type of effect of local fibrosis after trauma is a circumferential fibrosis causes constrictive compression of one of the nerve elements (Figure 43-11). This type of pathology is more likely to respond to supraclavicular neurolysis than to first rib resection.

Figure 43-10. The C8 cervical spinal nerve demonstrates decreased caliber and hyperintensity relative to the other ipsilateral brachial plexus elements but does not demonstrate any marked focal kinking or distortion of its course. This is consistent with encasing scar around the nerve.
In the setting of a hypertrophied scalene muscle with no fibrous band, the distortion of the course of the plexus is more smooth but nonetheless can be readily distinguished from the normal straight course through the region (Figure 43–12). Open MRI guidance can be used to help guide injection of the scalene muscle and to help further evaluate the health of the muscle (Figure 43–13). Surgical treatment of proximal pathology such as this in the region of the anterior scalene muscle may be more effectively treated by a supraclavicular approach.

**Entrapments in the Mid-Plexus**

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 (Figure 43–14). Patients with this sort of entrapment are often best managed with first rib resection when conservative management approaches fail.

MR Neurography may also be helpful in planning treatment approaches when first rib resection is not completely successful. One common occurrence is the development of post-operative scarring in the mid plexus (Figure 43–15). Another reason for pain after first rib resection which can be evaluated with MRN is incomplete resection of the proximal portion of the rib (Figure 43–16).

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**Figure 43–11.** This T1 axial image demonstrates asymmetry of the anterior scalene muscles. The arrows point to the anterior scalene muscles. The muscle on the right is about 50% larger than the muscle on the left. This can reflect either hypertrophy of the muscle on the left or spasm/atrophy of the muscle on the right. There is loss of fat between the anterior and middle scalene muscles on the left as well suggesting that the pathology is primarily on the left.
Figure 43-12. Differentiation of thoracic outlet syndrome into different categories of proximal and mid-plexus disease based on imaging characteristics. (A) In the normal plexus, the cervical spinal nerves and trunks of the brachial plexus follow a straight trajectory with even spacing. (B) Scalene syndrome is demonstrated by a gentle deformation of the course of the nerve elements and loss of space between them. In patients with pain only there is usually no nerve hyperintensity. (C1) Distortion of the shape of the C7 element (*) associated with a severe TOS case. (C2) A more anterior image plane in the same patient showing both a sharp kink (K) in the course of the lower trunk associated with a fibrous band and nerve hyperintensity (H) consistent with lower trunk motor symptoms.
Figure 43-13. Open MR image guided injection of the anterior scalene muscle. In the coronal image (A), the arrow indicates a darkened area caused by the injectate within the anterior scalene muscle. In the axial image (B), the titanium needle is seen passing into the anterior scalene muscle. The injectate has expanded the muscle, however the failure of injectate to flow into the more posterior portions of the muscle suggests fibrosis within the muscle.
Figure 43-14. Entrapment of middle plexus at the costo-clavicular passage. The right side (A) demonstrates an S-shaped course passing under the clavicle and over the first rib, while the brachial plexus elements on the left side (B) travel along a comparatively straight course. This type of entrapment may be best treated by first rib resection.

Involvement of the Axillary Nerve and Distal Plexus

In addition, brachial plexus entrapments in the axillary region can be defined as distinct entities (Figure 43-17). On physical exam, 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 then proceeding to a nerve block at the location of the apparent abnormality. Such a block may be performed in an Open MR scanner where an image plane which duplicates the anatomy of the diagnostic MR Neurography study can be used to guide needle placement (Figure 43-18). If the pathology can be confirmed, it is often possible to treat the axillary nerve entrapment with a transaxillary neurolysis that is a relatively small procedure with rapid postoperative recovery.
Figure 43-15. Mid plexus fibrosis after first rib resection. The elements of the brachial plexus both proximal and distal to the area of fibrosis demonstrate normal separation between the nerve elements. At the area indicated by the two arrows, the elements are adherent to each other, and demonstrate some deviation from their normal course. An additional image in the plane of the plexus elements also demonstrated a posterior deviation at this point. Palpation of the plexus at this location confirmed a Tinel's sign and focal tenderness in the area suggested by this image.

Figure 43-16. Impingement of brachial plexus by first rib remnant. This patient experienced a severe exacerbation of lower trunk symptoms after a first rib resection. The coronal image in "A" demonstrates a sharp kink in the plexus over the elevated cupola of the right lung. The oblique reformatted image in "B" demonstrates the proximal fragment of the rib in contact with the plexus element (* - the rib remnant, ** - focal impingement in C8 root). The rib remnant was then resected via a supraclavicular approach relieving the patient's symptoms.
Figure 43-17. (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 (m) (the beaded appearance of the axillary nerve in this 3D projection image is an artifact of the slice spacing).

Figure 43-18. Open MR injection for confirmation of the diagnosis of axillary nerve entrapment syndrome. After making a tentative diagnosis by MR Neurography in a high field scanner, the patient is imaged in a Siemens Open MR system for an interventional diagnostic injection. A titanium Lufkin needle (*) is advanced to a position adjacent to the area of the axillary nerve which was hyperintense on the Neurography study. Imaging in the Open scanner is by Flash T1 sequences which take about 10 seconds to acquire. The needle causes minimal artifact and appears as a black signal void in the image.
Image Diagnosis of Plexitis

In addition to surgically treatable entrapments, MR Neurography is also helpful in identifying patients with complaints attributable to nerve inflammations. These patients often present with painless hand atrophy, with no associated sensory abnormality. This has sometimes been termed a Gilliatt-Sumner Hand syndrome. Brachial plexus elements appear bright and swollen but demonstrate no distinct evidence of impingement (Figure 43-19).

MR Neurography is also helpful when it demonstrates a completely normal course and caliber for all nerve elements that are under suspicion. In the presence of these findings, it is possible to take a firm stance against surgical treatment of the hand, arm, or shoulder problems which may have been tentatively attributed to a thoracic outlet syndrome.

The above information has proven helpful because it permits the surgical treatment of TOS with more limited surgeries directed at different individual pathologies. 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.

IMAGE DIAGNOSIS AND SURGICAL OUTCOMES

Patients referred for evaluation for possible thoracic outlet syndrome or related brachial plexus pathology were first seen as outpatients and if the history and exam warranted, were then referred for MR Neurography brachial plexus imaging. In the course of the study one hundred and fifty four patients were imaged. Of these 40%...
had image findings consistent with scalene syndrome, 23% demonstrated distal plexus entrapments, and 16% had mild abnormalities not sufficient to serve as an indication for surgery. In 5%, no abnormality was seen. In addition to these, 4% demonstrated significant nerve trauma and 6% demonstrated nerve tumors.

Based on these imaging results, seventy-seven patients were referred for surgery. Of these there were nine with bilateral disease and eleven who had pathology in both proximal and distal plexus locations so that ninety-eight primary surgical cases were performed. The outcomes from these cases have been followed up over a six-year period. The supraclavicular cases have resulted in a 15% recurrence rate and the transaxillary cases have had a 12% recurrence rate. Excellent or good outcomes occurred in 85% of cases for both operations at three months, but this dropped to 70% over a period of six months as recurrences developed. Only one recurrence took place at an interval greater than six months post-operatively and the remainder of the patients retained their benefits.

In general, based on these outcomes, MR Neurography proved to be a very reliable predictor of which patients would do well with brachial plexus neurolysis surgery. The similarity of outcomes between supraclavicular and transaxillary approaches also suggests that MR Neurography was successful at identifying which patient needed which operation.

The recurrence rates of 15% are lower than in some other reports and may reflect the use of Seprafilm as an adhesiolytic agent in these cases.

One patient with recurrence was operated on early in the study and did not receive Seprafilm. Also among the recurrences were three patients with pre-existing RSD. Based on this study it seems that the presence of RSD clearly increases the risk of recurrence. One patient who had sarcoidosis diagnosed at the time of surgery and subsequently proved to be allergic to the Seprafilm. Pre-testing by cutaneous application of Seprafilm before surgery in patients with a history of multiple environmental allergies should reduce this recurrence risk. One recurrence was a sudden recurrence in a patient who engaged in a bout of very heavy physical activity three months post-operatively, and one occurred in a patient who suffered a post-operative wound infection.

In summary, for routine neurolysis patients who do not have RSD or other preoperative complicating conditions, and in whom Seprafilm was used, the recurrence rate was below 5%.

The eight patients who had recurrences were treated with reoperation after which four failed to obtain lasting benefit but the other four have remained symptom free for greater than two years. Based on this, reoperation in the setting of recurrence should be considered and this reduced the overall long-term recurrence rate for all patient to 7.5%. There were no significant neurologic or vascular complications, and no post-operative chyle leaks. One patient who had a resection of a cervical rib suffered a pneumothorax that resolved in less than twenty-four hours with placement of a Heimlich valve.

SUMMARY

The use of neurolysis surgery to treat thoracic outlet syndromes is an effective alternative to first rib resection. In general, it offers a somewhat lower surgical risk profile. The use of MR Neurography to provide a specific diagnosis of the location of entrapment is important for guiding the surgeon in selecting the correct type of neurolysis
operation. Recurrence rates were low overall and should not be considered as a reason to avoid neurolysis surgery. Long term outcome evaluation demonstrates that thoracic outlet syndrome can be effectively and permanently treated by this surgical approach on a reliable basis.

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