1 Approach to Nerve Conduction Studies and Electromyography

Electrodiagnostic (EDX) studies play a key role in the evaluation of patients with neuromuscular disorders. Among these studies are included nerve conduction studies (NCSs), repetitive nerve stimulation, late responses, blink reflexes, and needle electromyography (EMG), in addition to a variety of other specialized examinations. *NCSs and needle EMG form the core of the EDX study*. They are performed first, and usually yield the greatest diagnostic information. NCSs and needle EMG are complementary, and therefore are always performed together and during the same setting. Performed and interpreted correctly, EDX studies yield critical information about the underlying neuromuscular disorder and allow use of other laboratory tests in an appropriate and efficient manner. Likewise, the information gained from EDX studies often leads to specific medical or surgical therapy. For example, a patient with a peripheral neuropathy clinically, who is subsequently found to have an acquired demyelinating neuropathy with conduction blocks on EDX studies, most often has a potentially treatable condition.

In practice, EDX studies serve as an extension of the clinical examination and should always be considered as such. Accordingly, a directed neurologic examination should always be performed before EDX studies in order to identify key clinical abnormalities and establish a differential diagnosis. With numerous nerves and literally hundreds of muscles available, it is neither desirable for the patient nor practical for the electromyographer to study them all. *In each case, the study must be individualized, based on the neurologic examination and differential diagnosis, and modified in real time as the study progresses and further information is gained.*

NCSs and EMG are most often used to diagnose disorders of the peripheral nervous system (Figure 1–1, Box 1–1). These include disorders affecting the primary motor neurons (anterior horn cells), primary sensory neurons (dorsal root ganglia), nerve roots, brachial and lumbosacral plexuses, peripheral nerves, neuromuscular junctions, and muscles. In addition, these studies may provide useful diagnostic information when the disorder arises in the central nervous system (e.g., tremor or upper motor neuron weakness). Occasionally, information from the EDX study is so specific that it suggests a precise etiology. In most cases, however, the exact etiology cannot be defined based on EDX studies alone.

LOCALIZATION OF THE DISORDER IS THE MAJOR AIM OF THE ELECTRODIAGNOSTIC STUDY

The principal goal of every EDX study is to localize the disorder. The differential diagnosis is often dramatically narrowed once the disorder has been localized. Broadly speaking, the first order of localization is whether the disorder is neuropathic, myopathic, a disorder of neuromuscular transmission, or a disorder of the central nervous system (CNS). For example, in patients with pure weakness, EDX studies can be used to localize whether the disorder is caused by dysfunction of the motor neurons/

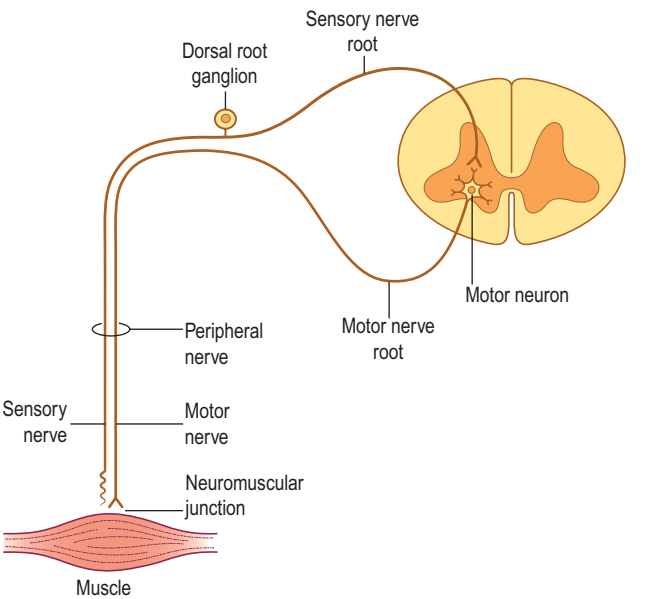

FIGURE 1–1 Elements of the peripheral nervous system. Note that the primary motor neuron resides within the spinal cord, whereas the primary sensory neuron, the dorsal root ganglion, lies outside the spinal cord. The dorsal root ganglion is a bipolar cell. Its proximal process forms the sensory nerve root; the distal process becomes the peripheral sensory nerve.

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axons, neuromuscular junctions, muscles, or has a central etiology. The pattern of nerve conduction and especially EMG abnormalities usually can differentiate among these possibilities and guide subsequent laboratory investigations. For example, a patient with proximal muscle weakness may have spinal muscular atrophy (i.e., a motor neuron disorder), myasthenic syndrome (i.e., a neuromuscular junction disorder), or polymyositis (i.e., a muscle disorder), among other disorders, including those with central etiologies (e.g., a parasagittal frontal lesion). EDX studies can easily differentiate among these conditions, providing key information to guide subsequent evaluation and treatment, which differ markedly among these diseases.

Box 1–1. Disorders of the Peripheral Nervous System

- Motor neuronopathy
  - Amyotrophic lateral sclerosis
  - Spinal muscular atrophy
  - Infectious (poliomyelitis, West Nile virus)
  - Monomelic amyotrophy
- Sensory neuronopathy
  - Paraneoplastic
  - Autoimmune
  - Toxic
  - Infectious
- Radiculopathy
  - Disk herniation
  - Spondylosis
  - Neoplastic
  - Infarction
  - Infectious
  - Inflammatory
- Plexopathy
  - Radiation induced
  - Neoplastic
  - Entrapment
  - Diabetic
  - Hemorrhagic
  - Inflammatory
- Neuropathy
  - Entrapment
  - Polyneuropathy
    - Demyelinating
    - Axonal
  - Mononeuritis multiplex
- Neuromuscular junction disorders
  - Myasthenia gravis
  - Lambert–Eaton myasthenic syndrome
  - Botulism
  - Toxic
  - Congenital
- Myopathy
  - Inherited
    - Muscular dystrophy
    - Congenital
    - Metabolic
  - Acquired
    - Inflammatory
    - Toxic
    - Endocrine
    - Infectious

Once the localization is determined to be neuropathic, myopathic, a disorder of the NMJ or of the CNS, EDX studies can usually add other important pieces of information to localize the problem further (Figure 1–2). For instance, the differential diagnosis of a patient with weakness of the hand and numbness of the fourth and fifth fingers includes lesions affecting the ulnar nerve, lower brachial plexus, or C8-T1 nerve roots. If EDX studies demonstrate an ulnar neuropathy at the elbow, the differential diagnosis is limited to a few conditions, and further diagnostic studies can be directed in a more intelligent manner. In this situation, for instance, there is no need to obtain a magnetic resonance imaging scan of the cervical spine to assess a possible cervical radiculopathy because the EDX studies demonstrated an ulnar neuropathy at the elbow as the source of the patient's symptoms.

In a patient with a CNS disorder who is mistaken as having a peripheral disorder, the EDX study often correctly suggests that the localization is central. For example, transverse myelitis may mimic Guillain–Barré syndrome, or a small acute cortical stroke may mimic the pattern of a brachial plexopathy. In settings such as these, the EDX study is often the first test to suggest that the correct localization is central rather than peripheral.

Neuropathic Localization

Neuropathic is probably the most common localization made on EDX studies. Neuropathic literally means a disorder of the peripheral nerves. However, in common usage, it includes the primary sensory and motor neurons as well. EDX studies are particularly helpful in neuropathic conditions. First, in conjunction with the history and examination, they can usually further localize the disorder to the neurons, roots, plexus, or peripheral nerve. In the case of peripheral nerve, further localization is usually possible to a single nerve (mononeuropathy), multiple individual

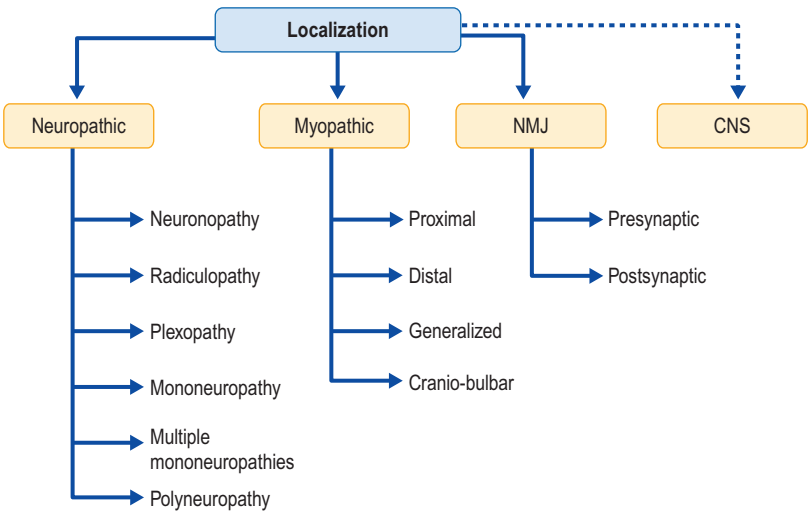

FIGURE 1–2 Possible localizations determined from the electrodiagnostic study.

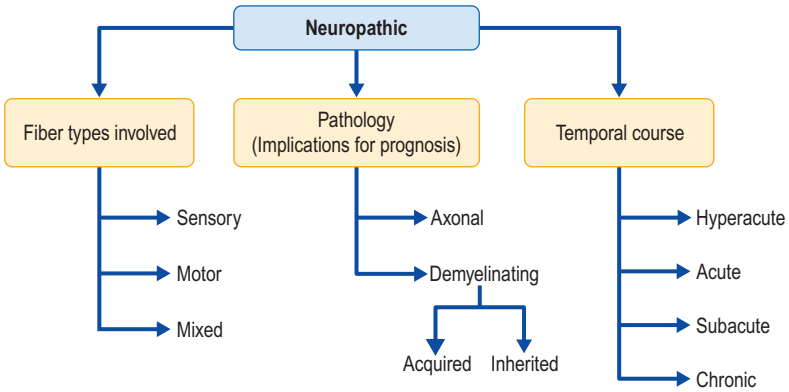

FIGURE 1–3 Key EDX findings in a neuropathic localization.

nerves (mononeuropathy multiplex) or all nerves (polyneuropathy). In the case of a single nerve, the exact segment of nerve responsible for the problem may be localized in some cases.

In the case of neuropathic lesions, EDX studies often yield further key information, including the fiber types involved, the underlying pathophysiology, and the temporal course of the disorder (Figure 1–3).

Information About the Fiber Types Involved and the Underlying Nerve Pathophysiology can be Gained, which then Further Narrows the Differential Diagnosis

In the case of neuropathic disorders, the involved fiber types and the underlying pathology can usually be determined. First, EDX studies are more sensitive than the clinical examination in determining which fiber types are involved: motor, sensory, or a combination of the two. Sensorimotor polyneuropathies are common and suggest a fairly large differential diagnosis. On the other hand, predominantly motor or predominantly sensory neuropathies are rare and suggest a much more limited set of disorders. For instance, a patient with numbness in the hands and feet and diminished reflexes may be diagnosed with a peripheral neuropathy. However, if EDX studies demonstrate abnormal sensory nerve conductions with completely normal motor nerve conductions and needle EMG, then the differential diagnosis changes from a peripheral neuropathy to a pure sensory neuropathy or neuronopathy, which has a much more limited differential diagnosis.

Second, EDX studies often can define whether the underlying pathophysiology is demyelination or axonal loss. Although most demyelinating neuropathies have some secondary axonal loss and many axonal loss neuropathies have some secondary demyelination, EDX studies usually can differentiate between a primary demyelinating and a primary axonal neuropathy. Because EDX studies usually can make this differentiation quickly and non-invasively, nerve biopsy is essentially never required to make this determination. Furthermore, the differentiation between primary axonal and primary demyelinating pathology is of considerable diagnostic and prognostic importance, especially in the case of polyneuropathies. The vast majority of polyneuropathies are associated with primary axonal degeneration, which has an extensive differential diagnosis. In contrast, the number of true electrophysiologic primary demyelinating neuropathies is extremely small. They are generally subdivided into those that are inherited and those that are acquired. EDX studies can typically make that determination as well. The finding of an unequivocal primary demyelinating polyneuropathy on EDX studies often leads quickly to the correct diagnosis and, in the case of an acquired demyelinating polyneuropathy, often suggests a potentially treatable disorder.

Assessing the Degree of Axonal Loss versus Demyelination has Implications for Severity and Prognosis

A nerve that has sustained a demyelinating injury often can remyelinate in a very short time, usually weeks. However, if there has been substantial axonal loss, whether primary or secondary, the prognosis is much more guarded. The rate of axonal regrowth is limited by the rate of slow axonal transport, approximately 1 mm per day. Clinically, axonal loss lesions can rarely be differentiated from demyelinating ones, especially in the acute setting. For example, in a patient who awakens with a complete wrist and finger drop, the etiology usually is compression of the radial nerve against the spiral groove of the humerus. However, the paralysis could result from either conduction block (i.e., demyelination) or axonal loss, depending on the severity and duration of the compression. Clinically, both conditions appear the same. Nevertheless, if the injury is due to axonal loss, it has a much worse prognosis and a longer rehabilitation time to recovery than a similarly placed lesion that is predominantly demyelinating in nature. EDX studies can readily differentiate axonal from demyelinating lesions.

Assessment of the Temporal Course can Often be Made

For neuropathic conditions, there is an orderly, temporal progression of abnormalities that occurs in NCSs and needle EMG. A combination of findings often allows differentiation among hyperacute (less than one week), acute (up to a few weeks), subacute (weeks to a few months), and chronic (more than a few months) lesions. The time course suggested by the EDX findings may alter the

impression and differential diagnosis. For example, it is not uncommon for a patient to report an acute time course to his or her symptoms, whereas the EDX studies clearly indicate that the process has been present for a longer period of time than the patient has been aware of.

Conversely, the temporal course described by the patient may impact the interpretation of the EDX findings. For instance, the finding of a normal ulnar sensory nerve action potential recording the little finger, in a patient with numbness of the little finger, has very different implications depending on the time course of the symptoms. If the symptoms are truly less than one week in duration, the normal ulnar sensory response could indicate an ulnar neuropathy (with incomplete wallerian degeneration), a proximal demyelinating lesion, or a lesion at the level of the nerve root or above. On the other hand, if the symptoms have been present for several weeks or longer, the same finding would indicate either a proximal demyelinating lesion or a lesion at the level of the nerve root or above. *These temporal changes underscore the electromyographer's need to know the clinical time course of symptoms and signs in order to ensure an accurate interpretation of any electrophysiologic abnormalities.*

Myopathic Localization

In the case of myopathic (i.e., muscle) disease, EDX studies can also add key information to further define the condition (Figure 1–4). First, the distribution of the abnormalities may suggest a particular diagnosis: are they proximal, distal or generalized? Most myopathies preferentially affect proximal muscles. Few myopathies, such as myotonic dystrophy type I, affect distal muscles. Some very severe myopathies (e.g., critical illness myopathy) can be generalized. In rare myopathies, there is prominent bulbar weakness; accordingly, EDX abnormalities may be most prominent in the bulbar muscles. Most myopathies are fairly symmetric; the finding of asymmetry either clinically and/or on EDX studies can be very helpful in narrowing the differential diagnosis. For example, inclusion body myositis may present asymmetrically, whereas polymyositis and dermatomyositis do not.

Second, the presence of spontaneous activity on needle EMG is helpful in limiting the differential diagnosis and suggesting certain underlying pathologies. Most myopathies are bland with little or no spontaneous activity. However, myopathies which are inflammatory, necrotic and some which are toxic may be associated with active denervation. In addition, other myopathies may have prominent myotonic discharges at rest. The presence of myotonic discharges in a myopathy markedly narrows the differential diagnosis to only a few possible disorders.

Lastly is the issue of the temporal course. Although this determination is more challenging than with neuropathic lesions, in some myopathies, a determination can be made if the myopathy is acute, subacute, or chronic, a finding which again narrows the differential diagnosis.

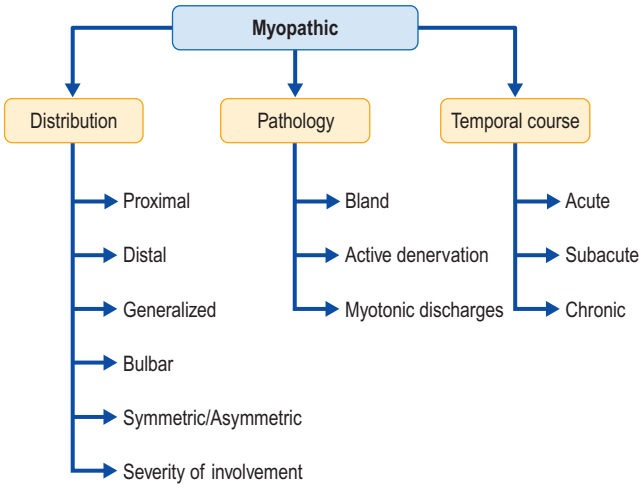

FIGURE 1–4 Key EDX findings in a myopathic localization.

Neuromuscular Junction Localization

Disorders of the neuromuscular junction (NMJ) are distinctly uncommon. However, when they occur, EDX studies not only help in identifying them, but can add other key pieces of information (Figure 1–5). First is the distribution of the abnormalities on EDX testing: are they proximal, bulbar or generalized? For instance, myasthenia gravis preferentially affects oculobulbar muscles and then proximal muscles on EDX studies, whereas myasthenic syndrome is a generalized disorder on EDX studies, although clinically it has a predilection for proximal muscles.

Broadly speaking, the underlying pathology can be divided into pre-synaptic and post-synaptic disorders. EDX studies are usually very good at making this determination. Myasthenia gravis is the prototypic post-synaptic disorder, whereas myasthenic syndrome and botulism target the presynaptic junction.

Lastly is the issue of the etiology of the NMJ disorder, whether it is acquired or inherited. Almost all NMJ disorders are acquired. However, there are rare inherited NMJ disorders. In some of these, there may be unique findings on EDX testing that suggest one of these rare disorders.

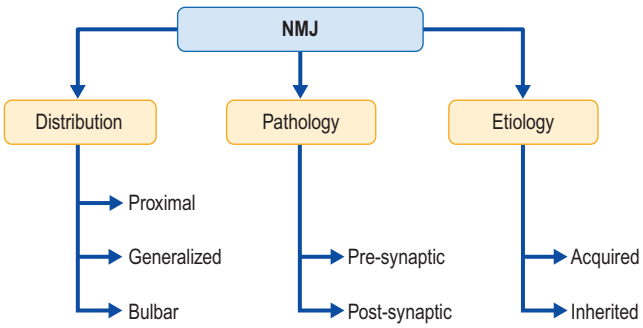

FIGURE 1–5 Key EDX findings in a neuromuscular junction localization.

Box 1–2. Patient Encounter

1. Take a brief history and perform a directed physical examination
2. Formulate a differential diagnosis
3. Formulate a study based on the differential diagnosis
4. Explain the test to the patient
5. Perform the nerve conduction studies and modify which nerve conduction studies to add based on the findings as the test proceeds
6. Perform the needle electromyography study and modify which additional muscles to sample, based on the findings as the test proceeds

PATIENT ENCOUNTER

Every EDX study begins with a *brief* history and *directed* physical examination (Box 1–2). *This point cannot be overemphasized*. Some may (incorrectly) argue that the history and clinical exam are not part of the EDX exam, and that the EDX needs to stand on its own. Nothing could be further from the truth. One is not expected to perform the same detailed history and physical examination that is done in the office consultation setting. *However*, before starting every study, the EDX physician must know some basic facts:

- What are the patient's symptoms?
- How long have they being going on?
- Is there any important past medical history (e.g., diabetes, history of chemotherapy, etc.)?
- Is there muscle atrophy?
- What is the muscle tone (normal, decreased or increased)?
- Is there weakness and, if so, where is it and how severe is it?
- What do the reflexes show (normal, decreased or increased)?
- Is there any loss of sensation and, if so, what is the distribution; what modalities are disturbed (e.g., temperature, pain, vibration, etc.)?

The duration, type, and distribution of symptoms, along with the physical examination, help determine the differential diagnosis, which in turn is used to plan the EDX studies. The EDX study is planned only after the differential diagnosis is determined. For instance, the EDX evaluation of a patient with slowly progressive proximal weakness is very different from that of a patient with numbness and tingling of the fourth and fifth fingers. In the former case, the differential diagnosis includes disorders of the anterior horn cell, motor nerve, neuromuscular junction, or muscle. In the latter case, the differential diagnosis includes an ulnar neuropathy at its various entrapment sites, a lower trunk brachial plexus lesion, or cervical radiculopathy. The EDX plan includes which nerves and muscles to study and whether specialized tests, such as repetitive nerve stimulation, may be helpful. The study can always be amended as the testing proceeds. Before beginning, however, one should first explain to the patient in simple terms what the test involves. Many patients are very anxious about the examination and may have slept poorly or not at all the night before the EDX study. A simple explanation, both before the test begins and while it is ongoing, can greatly reduce a patient's anxiety.

After the test is explained to the patient, the NCSs are performed first, followed by the needle EMG. A proper balance must be maintained among obtaining a thorough study, collecting the necessary information to answer the clinical question, and minimizing patient discomfort. If performed correctly, nearly all NCSs and needle EMG can be completed within 1.0 to 1.5 hours. Rarely, a longer study is needed if specialized tests such as repetitive nerve stimulation are performed in addition to the standard studies. There clearly is a limit to what most patients can tolerate. The electromyographer should always remember the Willy Sutton rule concerning robbing banks: "Go where the money is." If there is any question as to whether a patient will tolerate the entire examination, the study should begin with the area of interest. For instance, in the patient with numbness and tingling of the fourth and fifth fingers, the ulnar motor and sensory studies should be done first. Likewise, needle EMG examination of the ulnar-innervated muscles, as well as the C8-T1 non-ulnar-innervated muscles, are of most interest in such a patient. Plan ahead and consider which nerve conduction studies and needle examination of which muscles should be performed first, in case the patient can tolerate only one or two nerve conductions or examination of only a few muscles by EMG.

CARDINAL RULES OF NERVE CONDUCTION STUDIES AND ELECTROMYOGRAPHY

EDX studies rely on the physician's ability to pay meticulous attention to technical details during the study while keeping in mind the bigger picture of why the study is being performed. As more data are obtained, the study must be analyzed in real time and the test altered as needed. Analysis of online results gives the electromyographer the opportunity to modify the strategy as the testing proceeds, an opportunity that is lost once the patient has left the laboratory. The following cardinal rules of EDX studies should always be kept in mind while an EDX study is being performed (Figure 1–6):

1. *NCSs and EMG are an extension of the clinical examination.* NCSs and EMG cannot be performed without a good clinical examination. Every examination must be individualized based on the patient's symptoms and signs and the resulting differential diagnosis. If marked abnormalities are found on electrophysiologic testing in the same distribution where the clinical examination is normal, either the clinical examination or the electrophysiologic testing must be called into question. One usually finds that

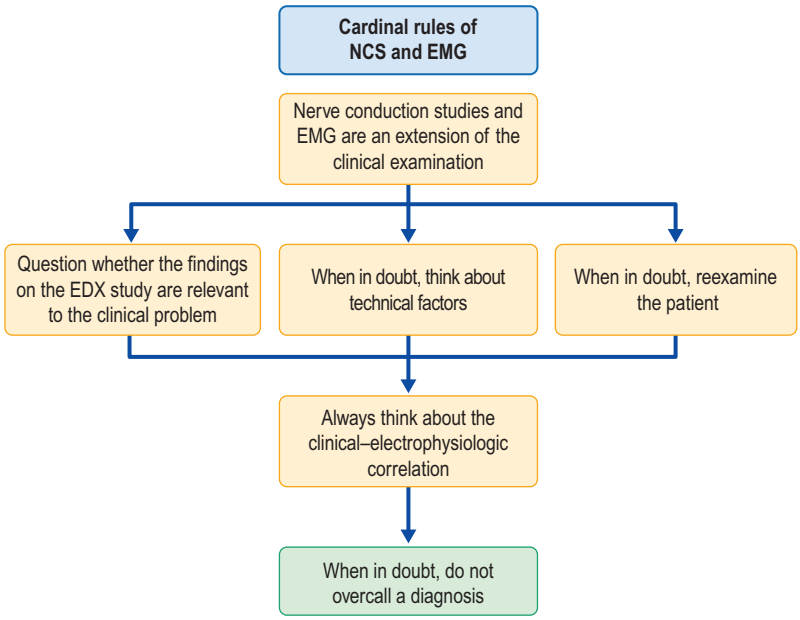

FIGURE 1–6 Cardinal rules of nerve conduction studies and electromyography.

the better the clinical examination, the better the differential diagnosis, and thus the more clearly directed the EDX studies will be.

2. When in doubt, always think about technical factors. EDX studies rely upon collecting and amplifying very small bioelectric signals in the millivolt and microvolt range. Accomplishing this is technically demanding; a large number of physiologic and non-physiologic factors can significantly interfere with the accuracy of the data. Accurate NCSs and EMG depend on intact equipment (e.g., EMG machine, electrodes, and stimulator), as well as correct performance of the study by the electromyographer. Technical problems can easily lead to absent or abnormal findings. Failure to recognize technical factors that influence the EDX study can result in type I errors (i.e., diagnosing an abnormality when none is present), and type II errors (i.e., failing to recognize an abnormality when one is present). Although both are important, type I errors are potentially more serious (e.g., the patient is labeled with an abnormal EDX study result, such as neuropathy, when the "abnormality" on the EDX testing is simply due to unrecognized technical errors). Such faulty diagnoses can lead to further inappropriate testing and treatment. If there is an unexpected abnormal EDX finding that does not fit the clinical examination, the lack of a clinical–electrophysiologic correlation should suggest a technical problem. For instance, if a routine sural nerve sensory conduction study shows an absent potential but the patient has a normal sensory examination of the lateral foot (i.e., sural territory), one should suspect a technical problem (e.g., improper electrode placement or too low stimulus intensity). If the data are not technically accurate, then correct data interpretation can never occur, either at the time of the study or later by the treating physician.
3. *When in doubt, reexamine the patient.* This is essentially an extension of cardinal rule number 1. In the example given with rule number 2, if the sural sensory response is absent after all possible technical factors have been corrected, the clinician should reexamine the patient. If the patient has clear loss of vibration at the ankles, there is less concern about an absent sural sensory response. If the patient's sensory examination is normal on reexamination, the absent sensory response does not fit the clinical findings, and technical factors should be investigated further.
4. *EDX findings should be reported in the context of the clinical symptoms and the referring diagnosis.* In every study, electrophysiologic abnormalities must be correlated with the clinical deficit. Because electrophysiologic studies are quite sensitive, it is not uncommon for the electromyographer to discover mild, subclinical deficits of which the patient may not be aware. For example, a diabetic patient referred to the EMG laboratory for polyneuropathy may show electrophysiologic evidence of a superimposed ulnar neuropathy but have no symptoms of such. Accordingly, the electromyographer should always report any electrophysiologic abnormality in the context of its clinical relevance so that it can be properly interpreted.
5. *When in doubt, do not overcall a diagnosis.* Because electrophysiologic tests are very sensitive, mild, subclinical, and sometimes clinically insignificant findings often appear on EDX testing. This occurs partly because of the wide range of normal values,

which vary with the nerve and muscle being tested. In addition, there are a variety of physiologic and non-physiologic factors that may alter the results of both NCSs and EMG, despite attempts to control for them. These factors, often when combined, may create minor abnormalities. Such minor abnormalities should not be deemed relevant unless they correlate with other electrophysiologic findings and, most importantly, with the clinical history and examination. It is a mistake to overcall an electrophysiologic diagnosis based on minor abnormalities or on findings that do not fit together well. Sometimes, the clinical or electrophysiologic diagnosis is not clear-cut and a definite diagnosis cannot be reached.

Occasionally, NCSs and EMG are clearly and definitely abnormal but a precise diagnosis still cannot be determined. For example, consider the patient whose clinical history and examination suggest an ulnar neuropathy at the elbow. The EDX study often demonstrates abnormalities of the ulnar nerve in the absence of any localizing findings, such as conduction block or slowing across the elbow. Although the referring surgeon usually wants to know whether the ulnar neuropathy is at the elbow, often the only accurate impression the electromyographer can give is one of a non-localizable ulnar neuropathy that is at, or proximal to, the most proximal abnormal ulnar-innervated muscle found on EMG.

6. *Always think about the clinical–electrophysiologic correlation.* This rule combines all of the earlier rules. One usually can be certain of a diagnosis when the clinical findings, NCSs, and EMG abnormalities all correlate well. Consider again the example of the patient with weakness of the hand and tingling and numbness of the fourth and fifth fingers. If NCSs demonstrate abnormal ulnar motor and sensory potentials associated with slowing across the elbow, and the needle EMG shows denervation and reduced numbers of motor unit potentials in all ulnar-innervated muscles and a normal EMG of all non-ulnar-innervated muscles, there is a high degree of certainty that the patient truly has an ulnar neuropathy at the elbow, and the electrophysiologic abnormalities are indeed relevant.

If all three results fit together, the diagnosis is secure. However, if the NCSs and EMG findings do not fit together and, more importantly, they do not correlate with the clinical findings, the significance of any electrical abnormalities should be seriously questioned. Consider a patient with pain in the arm who has an otherwise normal history and examination. If the NCSs are normal except for a low ulnar sensory potential and the EMG demonstrates only mild reinnervation of the biceps, one should be reluctant to interpret the study as showing a combination of an ulnar neuropathy and a C5 radiculopathy. These mild abnormalities, which are not substantiated by other electrophysiologic findings and do not have clear clinical correlates, may have little to do with the patient's pain. In such a case, the patient should be reexamined. If no clinical correlate is found, the studies should be rechecked. If the abnormalities persist, they may be noted as part of the impression but interpreted as being of uncertain clinical significance.

When performed properly, NCSs and EMG can be very helpful to the referring physician. However, the limitations of EDX studies must be appreciated, technical factors well controlled, and a good differential diagnosis established before each study. Otherwise, the study may actually do a disservice to the patient and to the referring physician by leading them astray by way of minor, irrelevant, or technically induced "abnormalities." If the cardinal rules of NCSs and EMG are kept in mind, EDX studies are far more likely to be of help to the referring clinician and the patient with a neuromuscular disorder.