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Radiculopathy and Motor Neuron Disorders

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Summary

Although radiculopathies and motor neuron disorders have vastly different underlying mechanisms and clinical presentations, the electrodiagnostic examination for these disorders demonstrate remarkable similarities. In all of these conditions, the electrophysiological examination reflects motor neuron injury with virtually no involvement of sensory neurons, even in the face of substantial sensory symptoms, as may occur in radiculopathy. The needle examination is a critical part of electrophysiological testing, helping to define the extent and severity of the abnormality, often more effectively than is possible with nerve conduction studies alone. Late responses, including F-waves and the H-reflexes, can also assist in the diagnosis of radiculopathy to some extent. The electrodiagnostic evaluation of motor neuron disease requires special consideration and care.

Key Words: Amyotrophic lateral sclerosis; F-wave; motor neuron disease; myotome; needle electromyography; radiculopathy.

1. INTRODUCTION

The electrodiagnostic (EDX) examination has an established role in the evaluation of radiculopathy and motor neuron disorders (MNDs). An extension of the neurological examination, the EDX examination must always be interpreted in the proper clinical context. Radiculopathy results from injury to nerve roots producing sensory and/or motor symptoms and signs in the distribution of the corresponding dermatomes and/or myotomes. On the other hand, MNDs are characterized by injury and loss of the anterior horn cell, affecting only motor fibers. Although radiculopathies and MNDs are clinically dissimilar, their electrophysiological features are alike, because, in both, the nerve injury occurs proximal to the dorsal root ganglion (DRG). For this reason, they will be discussed together. The fact that polyradiculopathy and MNDs are often indistinguishable from an electrophysiological perspective, yet have dissimilar symptoms and clinical course, underscores the importance of clinical context in assessing EDX findings.

In evaluating radiculopathy, EDX studies are useful in determining the functional consequence of a given structural lesion. They specifically are used to delineate the distribution of the affected muscles, localize the level, and establish the chronicity and extent of the problem. Although EDX studies are generally sensitive and specific, a normal EMG result in the face of signs and symptoms consistent with radiculopathy does not exclude this diagnosis.

In evaluating MND, EDX studies are used to establish objective evidence of lower motor neuron degeneration in multiple body segments and are an essential diagnostic procedure in the workup of these disorders.

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2. ANATOMIC CONSIDERATIONS

Thirty-one pairs of spinal nerves are formed from dorsal and ventral roots (8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal). Ventral roots arise from motor neurons in the anterior and lateral gray columns of the spinal cord. Dorsal roots extend proximally from sensory neurons in the DRG, which lie within the neural foramen (outside the spinal canal). Ventral and dorsal roots join together just distal to the DRG, forming a spinal nerve; on exiting the foramen, the nerve divides into dorsal and ventral rami. The dorsal rami supply the paraspinal muscles and skin overlying the paraspinous region; ventral rami form the plexus, which branches into the individual peripheral nerves that supply the upper and lower limb and the sacral region.

The muscles supplied by a single spinal segment constitute a myotome; the skin region supplied by a single spinal segment is a dermatome. There is significant variability in individual myotomal and dermatomal representation for a particular muscle or skin region. Each muscle receives innervation from multiple contiguous nerve roots, and each dermatome overlaps extensively with neighboring dermatomes.

3. PHYSIOLOGICAL CONSIDERATIONS

3.1. Radiculopathies

The majority of radiculopathies result from nerve root compression, either from disc herniation or as a consequence of spondylotic arthropathy; inflammatory and immunological lesions are less common. The most commonly involved roots are L5 and S1, and C6 and C7 (*see* Table 1 for a list of radiculopathies and associated symptoms and signs). These lesions may affect nerve roots by causing axonal degeneration, focal demyelination, or both. The electrophysiological findings in a patient are determined by the degree to which each of these pathophysiological processes occurs. Regardless of the underlying cause, injury to the roots occurs at a location that is proximal to the DRG. This is a critical point in terms of establishing the electrophysiological pattern of abnormalities, and allows differentiation of radicular lesions from those distal to the DRG. Notably, only a portion of the nerve roots fibers are injured in the majority of cases of radiculopathy, an important factor with regard to the pattern of abnormalities observed on EDX testing. The most commonly used EDX test for radiculopathies, the needle examination of muscle, is used to identify the extent and severity of motor axonal injury in a patient, which is a reflection of the nerve root fiber injury.

3.2. Motor Neuron Disorders

Amyotrophic lateral sclerosis (ALS) is the most common of the MND evaluated in the EMG laboratory. ALS is characterized by upper and lower motor neuron degeneration involving multiple body regions (i.e., cranial, cervical, thoracic, and lumbosacral). The loss of motor neurons usually begins in one area, is asymmetrical, and later becomes evident in other areas. The clinical and electrophysiological findings are dependent on the body segment involved and the severity of involvement. Whereas recognition of upper motor neuron involvement depends on clinical signs, routine EDX studies are of major help in identifying lower motor neuron abnormalities, even before they are clinically recognizable.

A single motor neuron innervates a group of muscles fibers; the motor unit is comprised of the motor neuron, its axon, and all of the muscle fibers innervated by it. The innervation ratio is the number of muscle fibers innervated by a single motor neuron. In ALS, degeneration

Table 1
Neurological Examination Findings in Monoradiculopathies

Root level	*Pain*	*Sensory loss (paresthesias)*	*Motor abnormalities/ weakness*	*Deep tendon reflex abnormalities*
C5	Pain lateral shoulder	Shoulder	Deltoid, supraspinatus, and infraspinatus	Biceps reflex
C6	Neck radiating to the arm	Radial side of the arm to thumb	Brachioradialis, flexor carpi radialis, biceps	Biceps reflex
C7	Neck to the fingers	Between second and fourth finger	Triceps, wrist extensors	Triceps reflex
C8–T1	Neck to the fingers	Ulnar aspect of hand and/or forearm	All hand intrinsics, flexor digitorum profundus	None
L1	Inguinal region	Inguinal region	None	None
L2	Groin, anterior thigh	Anterolateral thigh	Iliopsoas	None
L3	Anterior thigh to knee, anterior leg	Medial thigh and knee	Quadriceps, iliopsoas, hip adductors	Knee jerk
L4	Medial foreleg	Medial lower leg	Tibialis anterior, quadriceps, hip adductors	Knee jerk
L5	Lateral thigh and lower leg, dorsum foot	Lateral lower leg, dorsum foot, great toe	Toe extensors, ankle dorsiflexor, everter and inverter, hip abductors	None, unless S1 involved
S1	Posterior thigh, calf, heel	Sole, lateral foot and ankle, lateral two toes	Toe flexors, gastrocnemii, hamstrings, gluteus maximus	Ankle jerk
S2–S4	Medial buttocks	Medial buttocks, perineal, perianal region	None, unless S1–S2 involved	Bulbocavernosus, anal wink Ankle jerk if S1 involved

of anterior horn cells leads to loss of motor neurons and denervation of muscle fibers that are part of these motor units; nearby, unaffected axons attempt to reinnervate denervated muscle fibers, increasing the innervation ratio in surviving motor neurons. These pathophysiological events are associated with active denervation/chronic reinnervation changes observed on EMG examination, as well as reduced recruitment related to loss of motor units. EDX abnormalities are frequently observed in muscles that are not clinically involved in this disease. Similarly, in polio, another MND, chronic reinnervation and reduced motor unit recruitment is generally more widespread than the clinical examination alone would suggest.

4. ELECTRODIAGNOSIS

4.1. Sensory Nerve Conduction Studies

Sensory nerve conduction study (SNCS) results are nearly always normal in radiculopathy as well as MND. The sensory nerve action potential (SNAP) amplitude is normal even when patients have clinical sensory loss because the lesion occurs proximal to the DRG (i.e.,

is preganglionic) and the peripheral sensory axons are intact. This is the most useful piece of information for differentiating radiculopathies from lesions involving the plexus or individual peripheral nerves. The most common, albeit rare, exception to this rule is involvement of the L5 DRG with L5 radiculopathy caused by a far lateral disc herniation. In MND, the sensory study results are normal because the disorder affects only motor neurons.

There are two essential points that are mostly relevant to radiculopathy with associated sensory symptoms. First, it is most helpful to compare the SNAP from the symptomatic limb with the corresponding SNAP in the contralateral uninvolved limb (with reduction in amplitude of ≥50% considered abnormal) rather than relying purely on reference values for the amplitudes; this is even more essential if there is coexistent polyneuropathy. Second, in evaluating radiculopathy, it is important to attempt recordings from nerves most closely representing the clinically affected dermatome (e.g., superficial peroneal recording for suspected L5 lesions or sural recording for S1 lesions).

4.2. Motor Nerve Conduction Studies

Motor nerve conduction study (MNCS) results are frequently normal in radiculopathy, for several reasons. Myotomal overlap of root innervation to individual muscles makes it likely that, from each muscle, a significant number of uninvolved nerve roots will contribute to maintenance of a normal compound muscle action potential (CMAP); additionally, only a fraction of nerve root fibers are injured in most cases of compressive radiculopathy. If a nerve root lesion causes focal segmental demyelination, the CMAP, which is recorded distal to the lesion, will also be normal. In an injury that is characterized by significant axonal loss, there will be distal axonal degeneration that may result in reduced CMAP amplitude. If degeneration of a large number of motor axons occurs, conduction velocity may be decreased and distal latency prolonged, because of loss of the fast-conducting axons, although, generally, this is mild. All CMAP abnormalities reflect the degree of axon loss and, therefore, are more likely to occur with severe lesions. As with sensory studies, a CMAP should be recorded from a muscle in the clinically relevant myotomes, if possible. This is readily achievable in the legs, where the most common radiculopathies affect L5 and S1 nerve fibers, but less relevant in the arms, where the most common nerve roots involved, C6 and C7, are not generally evaluated with motor nerve conduction studies.

In MND, CMAP may be normal or amplitudes may be reduced in proportion to the loss of motor units. As with radiculopathy, changes in conduction velocity and/or distal latency are generally mild. However, thorough nerve conduction studies are extremely important for identifying peripheral neuropathies that may mimic ALS clinically, such as multifocal motor neuropathy with conduction block. In this disorder, evidence of conduction block is identified, often in unusual segments of nerve (e.g., not at standard compression sites). Despite the prominent conduction block and often some associated axon loss of motor studies, sensory study results are normal or nearly normal. Sometimes the block can be difficult to identify, prompting the electromyographer to pursue proximal testing of nerves, including root stimulation using needle electrodes.

4.3. Late Responses

4.3.1. F-Responses

These late responses are produced by antidromic activation of a subpopulation of motor neurons and are useful because they provide an assessment of proximal motor pathways.

However, F-responses also reflect conduction along the distal motor pathway and may be prolonged if axonal loss or demyelination along any portion of the motor nerve has occurred. Unfortunately, the sensitivity of F-responses in radiculopathy seems low. This may be because F-responses are mediated by more than one nerve root (i.e., L5/S1). It may also be because nerve root injury in most radiculopathies is partial, leaving a reasonable number of motor axons intact, resulting in a normal minimal F-latency. For this reason, a prolonged minimum–maximum latency range (chronodispersion) or evaluating mean F-latency are likely to be more sensitive indicators of radiculopathy. Nevertheless, F-responses also have a low specificity, because axon loss or demyelination anywhere along the entire length of the motor fiber being studied may prolong the F-latency.

In MND, F-responses are generally of normal latency until marked axon loss has occurred, in which case, they are usually only mildly prolonged. Their main usefulness in evaluation of these disorders is in excluding polyneuropathies that may produce a clinical syndrome indistinguishable from ALS, particularly those characterized by proximal conduction abnormalities, such as the multifocal motor neuropathy with conduction block, discussed above.

4.3.2. H-Reflexes

H-reflexes are useful in the evaluation of radiculopathy because they assess both motor and sensory pathways involving the nerve root; however, standard studies evaluate only the S1 root level, a major limitation. H-reflex latency is the most useful parameter to measure. Ipsilateral prolongation (>2 ms longer than the contralateral, uninvolved side) or absence of the H-reflex is observed in unilateral S1 radiculopathy. In bilateral lesions, the reflexes may be prolonged or absent bilaterally. One advantage of the H-reflex over needle EMG is that it becomes abnormal immediately after compression injury of the nerve root, although it remains abnormal thereafter. There are important disadvantages of the H-reflex, including the lack of specificity. They may be abnormal with any lesion that causes depression of the ankle jerks and are generally absent in patients with polyneuropathy. Although uncommonly attempted, an H-reflex can usually be obtained from the flexor carpi radialis in healthy individuals; abnormalities in this response may, thus, be helpful in identifying a C6–C7 radiculopathy.

4.3.3. Needle EMG

Needle EMG is overall the most useful procedure in the electrodiagnosis of radiculopathy. Needle EMG is a sensitive tool for demonstrating axonal loss in motor fibers secondary to nerve root injury; however, EMG is insensitive for demonstrating purely demyelinating lesions unless severe enough to produce substantial reductions in motor unit potential recruitment. The needle EMG in suspected radiculopathies must be extensive and, at the very least, several muscles must be examined. Timing of the EMG in relation to the injury must be considered when analyzing EDX data. Denervation (i.e., fibrillation potentials and positive sharp waves) is expected to develop in paraspinal muscles within 7 to 10 d of a root injury; in the proximal limbs in 2 to 3 wk, and in the distal limbs in 3 to 6 wk, although such abnormalities are often observed sooner. Reinnervation changes generally develop in involved muscles in a similar fashion as the denervation changes (i.e., proceeding distally from the point of injury); usually, these changes take 3 to 6 mo to develop after the acute injury. The evaluation of at least five to seven muscles of the involved extremity, including the paraspinals, is generally required to adequately screen for radiculopathy (Table 2). It is important to verify that muscles in adjacent myotomes are normal, to localize a radiculopathy to a particular level; it is usually not possible to be more precise than to indicate two adjacent root levels of involvement (e.g., C6–C7).

Table 2
Nerves and Spinal Root Supply of Representative Muscles Commonly Tested During Needle Evaluation of Radiculopathy[a]

Nerve	*Muscle*	*Root*
Brachial Plexus		
Spinal accessory nerve	Trapezius	C3–C4
Dorsal scapular nerve	Rhomboid major/minor	C4–C5
Suprascapular nerve	Supraspinatus	**C5**–C6
	Infraspinatus	**C5**–C6
Axillary nerve	Deltoid	**C5–**C6
Musculocutaneous nerve	Biceps brachii	**C5–C6**
Median nerve	Pronator teres	**C6–C7**
	Flexor carpi radialis	**C6–C7**
	Flexor pollicis longus	**C6–C7**
	Abductor pollicis brevis	C8**–T1**
Ulnar nerve	Flexor carpi ulnaris	C7–**C8–**T1
	FDP IV–V	C7–**C8**
	First dorsal interosseous	C8–**T1**
	Abductor digiti quinti	C8–**T1**
Radial nerve	Triceps	C6–**C7–**C8
	Brachioradialis	C5–**C6**
	Extensor carpi radialis	C5–**C6**
Posterior interosseous nerve	Extensor digitorum communis	**C7**–C8
	Extensor indicis proprius	**C8**
Lumbosacral plexus		
Superior gluteal nerve	Gluteus maximus	L5–**S1**
Inferior gluteal nerve	Gluteus medius	**L5–**S1
	Tensor fasciae latae	**L5–**S1
Femoral nerve	Iliopsoas	**L2–L3**
	Quadriceps	L2–**L3–L4**
Obturator nerve	Adductor longus	**L3–L4**
Sciatic nerve	Hamstrings	L5–**S1–**S2
Tibial nerve	Gastrocnemius and soleus	**S1–**S2
	Tibialis posterior	**L5**–S1
Superficial peroneal nerve	Peroneus longus	**L5–**S1
Deep peroneal nerve	Tibialis anterior	L4–**L5**
	Extensor hallucis longus	**L4–L5**

[a]FDP IV–V, flexor digitorum profundus of the fourth and fifth digits.

Characteristic needle EMG findings in radiculopathy include ongoing denervation and/or chronic reinnervation in limb muscles sharing the same root (myotome) distribution but innervated by different peripheral nerves, as well as ongoing denervation in paraspinal muscles. Abnormalities should be sought in distal and proximal limb muscles, although sometimes only distal muscles will be affected. Compromised muscles initially show reduced recruitment followed by fibrillation potentials and/or positive sharp waves, and, in chronic cases, high-amplitude, long-duration motor unit potentials. Understanding of the time frame

for development of these EMG abnormalities in relationship to the clinical nerve root injury is important in interpretation of the findings (*see* preceding paragraphs).

The presence of denervation in paraspinal muscles is an important localizing finding indicating axonal loss in the dorsal rami (i.e., at nerve root level). However, there are several points regarding the paraspinal muscle examination that require further discussion:

1. Paraspinal muscles may be normal in cases of clear-cut radiculopathy.
2. Ongoing denervation, particularly isolated positive sharp waves, may be observed in paraspinal muscles in healthy subjects, particularly those older than the age of 50 yr. Generally, however, abundant denervation changes are not observed in healthy subjects.
3. Paraspinal denervation changes are not specific for compressive radiculopathy and may be observed in inflammatory myopathy and MND, and may be persistent after posterior laminectomy procedures.
4. There is considerable overlap of paraspinal muscle innervation from the dorsal rami; thus, the finding of paraspinal abnormalities at a particular level does not localize the radiculopathy to that level, only limb muscle abnormalities should be used for this purpose. Conversely, paraspinal muscles may require sampling at several adjacent levels for abnormalities to be detected (e.g., examine C6 and C8 paraspinals if C7 paraspinals are normal in a C7 radiculopathy).

In generalized MND, the needle EMG is of critical importance for demonstrating evidence of widespread lower motor neuron degeneration. The findings include ongoing denervation in the form of fibrillation potential, as well as fasciculation potentials, in addition to chronic reinnervation changes. These abnormalities are frequently present in a myotomal distribution (therefore, are identical to polyradiculopathy), but the characteristic that differentiates MNDs from radiculopathy is the finding of abnormalities in multiple body segments: cranial, cervical (either arm and associated paraspinal musculature), thoracic, and lumbar (either leg and associated paraspinal musculature). The evaluation in MND should be focused at demonstrating abnormalities involving more than one nerve as well as more than one root level of abnormality in the various segments with the least discomfort to the patient. This may be possible by examination of only two or three carefully chosen muscles in each of these regions. The finding of fasciculation potentials, although characteristic of MND, is not specific and may also occur with radiculopathy or disorders of peripheral nerve hyperexcitability (e.g., cramp-fasciculation syndrome).

5. SUMMARY OF EDX FINDINGS IN RADICULOPATHY

5.1. Nerve Conduction Studies

1. Sensory: usually normal even if clinical sensory loss is present, an important differentiating feature from nerve and plexus lesions. Care should be taken to record from clinically relevant sensory nerves and to compare with the contralateral side if appropriate.
2. Motor: usually normal even in the presence of weakness. CMAP may be decreased with lesions causing severe axon loss, particularly if multiple, adjacent nerve roots are affected.

5.2. Needle EMG

Overall, needle EMG is the most useful EDX test for evaluating radiculopathy. Timing of the study in relation to symptom onset is very important for interpreting EMG findings. Ongoing denervation takes an average of 2 to 3 wk to develop in affected limb muscles; chronic reinnervation changes take 3 to 6 mo to develop. Paraspinal denervation is useful, although nonspecific, and may be absent in nearly half of all lesions.

6. SUMMARY OF EDX FINDINGS IN MND

6.1. Nerve Conduction Studies

SNCSs: normal.

MNCS: reduced CMAP amplitudes may be observed in muscles experiencing severe axonal loss. In less-involved muscles, CMAP amplitudes may be normal.

6.2. Needle EMG

Ongoing denervation and chronic reinnervation are present in varying degrees in different areas, reflecting abnormalities in multiple nerve and root distributions. The presence of fasciculation potentials should be sought; although they are characteristic of the disorder, fasciculation potentials may be absent in MND and are not specific to MND. Abnormalities should be sought in the most clinically affected body regions, but at least three body regions must be examined, and abnormalities demonstrated in muscles innervated by different peripheral nerves and nerve roots.

SUGGESTED READING

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REVIEW QUESTIONS

1. The best single sensory study to differentiate L5 radiculopathy vs lumbosacral plexopathy is:
   A. Sural nerve.
   B. Saphenous nerve.
   C. Superficial peroneal nerve.
   D. Lateral femoral cutaneous nerve.
   E. None of the above.
2. The sensitivity of F-responses in radiculopathy is generally considered low because:
   A. F-responses are rarely performed.
   B. F-responses are mediated by more than one root.
   C. Nerve injury in radiculopathy is partial.
   D. B and C.
   E. None of the above.
3. The most useful procedure in evaluation of radiculopathy is:
   A. F-responses.
   B. H-reflexes.
   C. Motor nerve conduction studies.
   D. Needle examination.
   E. A and B.
4. The finding of fibrillation potentials in paraspinal muscles:
   A. Clearly localizes the affected root.
   B. Is typical of plexopathy.
   C. Suggests radiculopathy but does not localize the root involved.
   D. Indicate chronic disease.
   E. None of the above.

5. Sensory studies in MND show:
   A. Reduced conduction velocity.
   B. Reduced amplitude.
   C. Prolonged distal latency.
   D. Abnormal morphology.
   E. Normal morphology.
6. Chronic reinnervation on needle examination is characterized by:
   A. Fibrillation potentials.
   B. Positive sharp waves.
   C. Short duration motor unit potentials.
   D. Long duration motor unit potentials.
   E. Nascent motor unit potentials.
7. A 42-yr-old man presents with pain in his lower back radiating down to his toes. You suspect an S1 radiculopathy. Which study will be more likely to be abnormal?
   A. Needle exam of the tibialis anterior.
   B. H-reflex latency.
   C. Peroneal motor response.
   D. Sural sensory amplitude.
   E. None of the above.
8. The following pair of muscles is innervated primarily by the S1 root:
   A. Tibialis posterior and gastrocnemius.
   B. Gastrocnemius and gluteus maximus.
   C. Tibialis anterior and peroneus longus.
   D. Quadriceps and hamstring.
   E. Long head biceps femoris and extensor digitorum brevis.
9. A pure, subacute L5 radiculopathy is more likely to show fibrillation potentials in the following muscles:
   A. Obturator and tibialis anterior.
   B. Vastus lateralis and peroneus longus.
   C. Gastrocnemius and tibialis anterior.
   D. Tibialis anterior and tibialis posterior.
   E. Gluteus maximus and foot intrinsics.
10. The best way to differentiate ALS from a severe ongoing and chronic polyradiculopathy is:
    A. The presence of fasciculation potentials in paraspinal muscles.
    B. The absence of motor unit potentials in abductor pollicis brevis.
    C. The clinical history and neurological exam.
    D. Needle examination of upper and lower extremities.
    E. MRI of the entire spine.

REVIEW ANSWERS

1. The correct answer is C. Sensory nerves tend to be affected in plexopathy and spared in radiculopathy. The saphenous nerve will be abnormal if the L4 plexus is involved and the sural nerve will be abnormal if the S1 branches of the plexus are compromised.
2. The correct answer is D. The sensitivity of F-responses in radiculopathy seems low. This may be because F-responses are mediated by more than one nerve root (i.e., L5/S1). It may also be because nerve root injury in most radiculopathies is partial, leaving a reasonable number of motor axons intact, resulting in a normal minimal F-latency.
3. The correct answer is D. Needle exam is the most useful EDX study to evaluate radiculopathies.
4. The correct answer is C. The finding of paraspinal abnormalities at a particular level dose not localize the radiculopathy to that level, only the limb abnormalities should be used for this purpose.
5. The correct answer is E. Sensory nerve conduction studies are normal in MND.

6. The correct answer is D. Long duration, large amplitude, and polyphasic motor units are sign of chronic reinnervation.
7. The correct answer is B. H-reflexes are useful in the evaluation of radiculopathy because they assess both motor and sensory pathways involving the nerve root; standard studies evaluate only the S1 root level, which is the root involved in this patient.
8. The correct answer is B.
9. The correct answer is D. Tibialis anterior and tibialis posterior are primarily L5 muscles (although tibialis anterior has a substantial contribution from L4 as well).
10. The correct answer is C. ALS and a severe ongoing and chronic polyradiculopathy look almost the same on EDX studies and sometimes can be challenging for diagnosis. The history will be fundamental. MND is painless and does not have associated sensory symptoms. Therefore, clinical history and examination will be the first step in defining the underlying pathology.