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Nerve conduction studies: basic principal and clinical usefulness

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Nerve conduction study (NCS) is an electrophysiological tool to assess the overall function of cranial and peripheral nervous system, therefore NCS has been diagnostically helpful in the identification and characterization of disorders involving nerve roots, peripheral nerves, muscle and neuromuscular junction, and are frequently accompanied by a needle Electromyography. Furthermore, NCS could provide valuable quantitative and qualitative results into neuromuscular function. Usually, motor, sensory, or mixed nerve studies can be performed with using NCS, stimulating the nerves with the recording electrodes placed over a distal muscle, a cutaneous sensory nerve, or the entire mixed nerve, respectively. And these findings of motor, sensory, and mixed nerve studies often show different and distinct patterns of specific abnormalities indicating the neuromuscular disorders. The purpose of this special article is to review the neurophysiologic usefulness of NCS, to outline the technical factors associated with the performance of NCS, and to demonstrate characteristic NCS changes in the setting of various neuromuscular conditions.

Key words: Nerve conduction study; NCS; Peripheral nerve; Electrophysiology; Neuromuscular disorders

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INTRODUCTION

As a fundamental component of the electrophysiological evaluation, nerve conduction study (NCS) is a vital and irreplaceable diagnostic tool to assess the overall condition of the peripheral nervous system and provides valuable quantitative and qualitative insights into neuromuscular function.[1-4] Actually, NCS has been significantly used in the identification and characterization of various neuromuscular disorders, particularly peripheral nerve diseases including nerve roots, peripheral nerves, muscle and neuromuscular junction, and is usually accompanied by a needle electromyography (EMG).[1-4] Among the electrophysiological studies, NCS is one of the most widely used diagnostic tools, however it must be performed and interpreted with careful attention by either an experienced physician or a technologist under the supervision of an experienced physician.

Motor, sensory, or mixed nerve studies can be performed, stimulating the nerve with the recording electrodes placed over a distal muscle, a cutaneous sensory nerve, or the entire mixed nerve, respectively.[3-6] The findings of motor, sensory, and mixed nerve studies often complement one another and yield different types of information associated with distinct patterns of abnormalities, depending on the underlying pathology.[3-6] The contents of this special article are to review the neurophysiologic underpinnings of NCS, to outline the technical factors associated with the performance of NCS, and to demonstrate characteristic NCS changes in the setting of various neuromuscular conditions.

The principals and aim of nerve conduction studies

Peripheral nerves contain many nerve fibers of different diameters, degrees of myelination, and afferent or efferent connections. The NCS studies the fastest parts of these nerve fibers and the aim of the investigation is to document focal or continuous abnormalities in the length of the mixed, motor or sensory nerve.[1-6] Technically, a variety of methods may be used for stimulus or recording, however most NCSs currently are performed with cutaneous, or surface, stimulating and recording electrodes.[1-6] Peripheral nerves may be stimulated through the skin with surface stimulators placed close to a nerve. NCS involves the application of depolarizing electrical waves to the skin over a peripheral nerve, followed by propagated nerve action potential (NAP) recorded at a distant point over the same nerve and a compound muscle action potential (CMAP) arising from the activation of muscle fibers in a target muscle supplied by the nerve.[2-5] These action potentials may be commonly recorded with surface recording electrodes. Surface recording electrodes are designed to give information about the physiologic data for the time taken for the fastest axons to conduct an impulse to the muscle and the size of the response.[4]

Abnormalities of nerve conduction studies may anticipate specific pathologic processes, such as demyelination or axonal loss, and may provide precise localization of focal nerve lesions. More specifically, the conduction velocity, latency and amplitude of reactions are assessed in the NCS.[1-7]

The general preparation for the NCS

The physicians should provide explanation of the examination to the patient so that they understand the examination, and notify the patient that electric stimulation may induce slight pain to help with the completion of the examination in a more cooperative manner. The physicians would help the patient to relax and put them in a comfortable position for the examination.

The physicians may measure the skin temperature using a thermometer on the EMG machine or skin thermometer. Motor and sensory nerve conduction velocities are reduced by 1.3-2.4 m/s as the skin temperature decreases by 1°C.[2-9] Nerve conduction velocities can be appropriately measured when the temperatures of the examination room and the patient's skin are 26°C and 30-36°C, respectively.[2-9] If the examination site feels cold, skin temperature should be measured prior to the examination, and the appropriate treatment (i.e., fan heater or warm water) should be given to raise the skin temperature. However, if a skin temperature controller or warm water are unavailable, skin temperature must be accurately measured and recorded so that the NCS results can be better interpreted.[2-9]

It is crucial to minimize the impedance as much as possible; in fact, the impedance during the examination should remain below 5 kΩ.[2-9] Typically, gel on the electrode or tape to hold the electrodes on the skin are used. In rare cases, the skin is rubbed with alcohol or acetone, needles, or sandpaper to reduce the impedance between the electrode and the patient's skin. When electrode impedance is at its minimum, there is no interference or noise at 60 Hz.[2-9] Even if the

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effects from interference are negligible for motor NCSs, they can be an issue during sensory NCSs or combined NCSs, especially if the sensitivity is set below 5 μV.[2-9]

And the ground electrode should be attached to the limbs to be examined, with the ideal position between the stimulation and recording electrodes. Having the current path run through the frontal chest should be avoided if possible. This can occur when performing an NCS on the left arm and putting the ground electrode on the right arm. In order to minimize noise after stimulation, the ground electrode should be placed in the appropriate position between the stimulation site and recording electrodes. However, changing the position of the ground electrode for different examination sites is inconvenient, and it is, therefore, recommended that the ground electrode is placed at a set location on the arm or leg to be examined. This is the most appropriate method in most NCS cases. Nevertheless, if noise from stimulation hinders clear measurement of complex muscle or nervous action potentials, the ground electrode should be positioned between the stimulation and recording electrodes.

Often, infants have small and short limbs, and therefore, specific electrodes for infants should be used. This prevents the stimulation from spreading to other nerves and ensures an adequate distance between the two stimulation areas to calculate nerve conduction velocity.

Unexpected stimulation can also induce sudden movement during the examination, which can sometimes result in the detachment of the electrodes. Therefore, informing the patient prior to stimulation can help the patient to prepare for any pain associated with the stimulation. Additionally, in order to minimize pain, the shortest possible stimulation time and weakest intensity to induce a supramaximal response in the recorded muscle or nerve should be used. The patient can best endure the pain when stimulation is given at a rate of one stimulation per second. In healthy people, 0.05 ms of stimulation is sufficient to induce a supramaximal response. However, certain EMG machines have a minimum stimulation time greater than 0.05 ms, and therefore, the stimulation time should be set accordingly. Patients with neurological conditions often require longer stimulations to induce a supramaximal response. In sensory and combined NCSs, these patients may not exhibit any increase in the amplitude of compound nerve action potentials even with stimulation duration above 0.2 ms. In motor NCSs, the stimulus duration must be increased up to 1.0 ms, in some cases, to obtain a response. These findings suggest that patients with neurological disorders exhibit a lower level of nervous system activity assuming that the stimulation and recording electrodes are appropriately positioned.[4-9]

The machine settings for NCSs should be fixed to default, unless alterations are needed. It is important to observe overall responses on the oscilloscope monitor. The latency, compound muscle action potentials, and compound nerve action potentials should all be clearly observable. Often, the settings for sensitivity and sectional velocity need to be changed; for example, if the latency, amplitude, and duration of a compound muscle action potential are 40 ms, 1,500 μV, and 40 ms, respectively, the sensitivity and sectional velocity should be respectively changed to 500 μV and 10 ms.[4-9] The two most important machine settings for NCSs are the stimulus duration and sectional velocity. Supramaximal stimulation should be obtainable after an appropriate adjustment of stimulation duration and intensity. Changing the sectional velocity can result in an inaccurate measurement of latency. Because sensory and combined nervous action potentials have small amplitudes, the patient must be completely relaxed to accurately record these. With the audio monitor on, the patient hears the noise and can, therefore, be more relaxed.

The procedure of motor NCS

Motor conduction study is performed by electrical stimulation of a nerve, and recording the CMAP from surface electrodes overlying a muscle supplied by a stimulated nerve. The recording electrodes are placed over the skin overlying the target muscle using adhesive conductive skin electrode. The active electrode (known as G1) is placed over the muscle belly and the reference electrode (known as G2) over an electrically inactive site such as usually the muscle tendon.[1-5] A ground electrode is also placed somewhere between the stimulating and recording electrodes providing a zero voltage reference point. The stimulator then is placed over the nerve that supplies the muscle, with the cathode placed closet to the recording electrode. In most electrodiagnostic studies, routine motor NCS of the arm include median nerve (recording the abductor pollicis brevis muscle) and ulnar nerve (recording the abductor digiti minimi muscle), and in the leg, the tibial nerve (recording the abductor hal-

lucis muscle) and peroneal nerve (recording the extensor digitorum brevis muscle). Proximal stimulation sites can be added to address specific clinical questions (e.g., stimulating the ulnar nerve above and below the elbow, or common peroneal nerve above and below the fibular head to assess for evidence of demyelination). In many cases these routine studies must be supplemented to adequately assess an area of potential injury. In the arm, motor studies of the radial nerve (recording the brachioradialis, extensor digitorum communis, or extensor indicis proprius muscles), ulnar nerve (recording the first dorsal interosseous muscle), musculocutaneous nerve (recording the biceps muscle), or axillary nerve (recording the deltoid muscle) may be indicated.[10]

The CMAP is the summation of all underlying individual muscle fiber action potentials. The latency of the CMAP is the time from stimulus to the initial CMAP deflection from the baseline and is a biphasic potential with an initial upward deflection (negativity) followed by a smaller downward deflection (positivity). The CMAP amplitude is measured from baseline to negative peak which is demonstrated by an upward deflection and measured in millivolts (mV) (Fig. 1).[1-9]

To record the CMAP, the stimulating current (mA) is slowly increased from a baseline 0 mA, usually by 5-10 mA, until a point is reached where an increase in stimulus produces no increment in CMAP amplitude. It is only at this supramaximal stimulation that reproducible values for CMAP amplitude and the latency between the stimulus and the onset of the CMAP can be recorded accurately. The nerve is then stimulated at a more proximal site according to nerve pathway.

In the normal state, stimulation of the median nerve at the wrist and the elbow results in two CMAPs of similar shape and amplitude because the same motor axons innervating the muscle fibers build up the response.[9,10] However, the latency will be greater for elbow stimulation compared with wrist stimulation because of the longer distance between the stimulating and recording electrodes.[9,10] The difference in latency represents the time taken for the fastest nerve fibers to conduct between the two stimulation points as all other factors involving neuromuscular transmission and muscle activation are common to both stimulation sites (Fig. 1). If one measures the distance between the two sites then the fastest motor nerve conduction velocity (NCV) can be calculated as follows: NCV (m/s) = distance between stimulation sites (mm) / (proximal latency-distal latency [ms]).[9,10]

The procedure of sensory NCS

The sensory nerve action potential (SNAP) is obtained by electrically stimulating sensory fibers and recording the nerve action potential at a point along the same nerve. In the sensory NCS, technical factors and electrical noise assume more importance, because most sensory responses are very small. And, once again the stimulus must be supramaximal. A pair of recording electrodes (G1 and G2) are placed in line over the nerve at an interelectrode distance of 3 to 4 cm, with the active electrode (G1) placed closest to the stimulation. Recording the SNAP orthodromically refers to distal nerve stimulation and recording more proximally; the direction in which physiological sensory conduction oc-

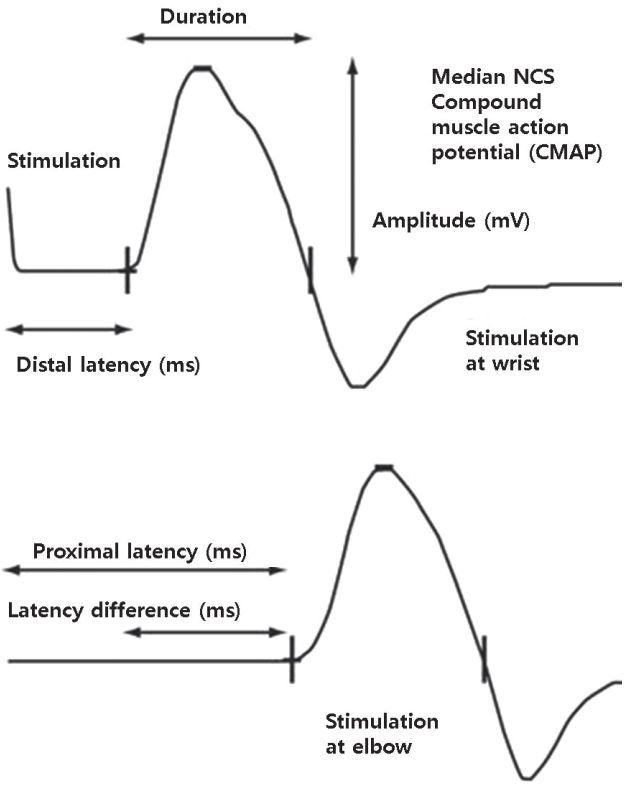

Fig. 1. Compound muscle action potential (CMAP) in median motor nerve conduction study (NCS). Active recording electrode is over the abductor pollicis brevis (APB) muscle, with stimulation at the wrist, elbow, axilla, and brachial plexus. The more proximal stimulation is performed at a measured distance from the first. The difference between the proximal latency (PL) and distal latency (DL) in milliseconds reflects the conduction time along the fastest nerve fibers between the sites, eliminating the travel time from the distal site and across the neuromuscular junction (NMJ), as well as muscle fiber depolarization time. The distance between the sites in millimeters divided by the nerve conduction time (PL minus DL) is known as the conduction velocity.

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curs.[1-9] Antidromic testing is the reverse. The sensory latency and the peak to peak amplitude of the SNAP are measured. The velocity correlates directly with the sensory latency and therefore either the result may be expressed as a latency over a standard distance or a velocity. Only the largest diameter and fastest conducting sensory fibers are tested using conventional sensory studies functionally supplying fine touch, vibration, and position sense. However, in the cases of small fibers neuropathies with prominent neuropathic pain, conventional sensory nerve conduction studies may be normal, therefore quantitative sensory testing and autonomic testing will be required.[9,10]

The procedure of F waves and H reflex

F waves are a type of late motor response that occurs after the CMAP. When a motor nerve axon is electrically stimulated at any point an action potential is propagated in both directions away from the initial stimulation site.[11] The distally propagated impulse gives rise to the CMAP. However, an impulse also conducts proximally to the anterior horn cell, depolarizing the axon hillock and causing the axon to backfire. This leads to a small additional muscle depolarization (F wave) at a longer latency. Unlike the M response, F waves vary in latency and shape because different populations of neurons normally backfire with each stimulus. The most reliable measure of the F wave is the minimum latency of 10-20 firings. F waves allow testing of proximal segments of nerves that would otherwise be inaccessible to routine nerve conduction studies. Usually, F waves examine long lengths of nerves while motor NCS evaluates shorter segments. Therefore F wave abnormalities can be a sensitive indicator of peripheral nerve pathology, particularly if sited proximally. The F wave ratio which compares the conduction in the proximal half of the total pathway may be used to determine the site of conduction slowing, particularly, to distinguish a root lesion from a patient with a distal peripheral neuropathy.

Furthermore, the circuity of the H reflex involves the Ia muscle spindles as sensory afferents and the alpha motor neurons and their axons as efferents. If a low submaximal stimulus with a long duration is applied to a nerve, it is possible to selectively activate the Ia fibers. The gain must be increased initially to 200 to 500 uV. The typical H reflex latency is approximately 30 ms, so the sweep speed must be increased to 10 ms. The recording montage consist of G1 placed over the soleus and the reference electrode (G2), placed over the Achilles tendon. The H reflex can be useful in a couple of situations. First, the response is the electrically correlated with the tendon ankle reflex.[10,11] If the ankle reflex is present clinically, an H reflex should always present. Any lesion that might decrease the ankle reflex also might prolong the H reflex.[10,11] Thus one may see a prolonged H reflex in polyneuropathy, proximal tibial and sciatic neuropathy, lumbosacral plexopathy, and lesions of the S1 nerve roots.[10,11]

Motor NCS in neuromuscular disorders with axonal loss

The most specific abnormality of motor NCS is a reduction in CMAP amplitude which shows decreased functioning motor axons connected to muscle fibers. Since myelin is unaffected and the remaining axons conduct normally, the latencies and conduction velocities will be normal. However, with increasing motor axon loss some of the largest fastest conducting fibers will be lost. Therefore distal motor latency may be mildly prolonged (< 120% of normal limit) and conduction velocity may be slightly decreased (> 80% of normal limit).[2-10]

The dynamics and timing of an axonal insult can affect the results of NCS. Immediately after traumatic complete transection of the nerve, the portion of the nerve distal to the lesion will be normal as there has not been time for axonal degeneration to occur.[2-10]

The CMAP amplitude will only start to fall a few days later. Conversely, if there is a very slow loss of axons in a generalized neuropathy, the remaining unaffected axons may have time to sprout new connections to muscle fibers (collateral reinnervation) and the CMAP may remain within the normal amplitude range even though the total number of nerve axons is smaller.[2-10] However, the immature regenerating fibers have slower velocities due to the effect of the short internodal distances and this produces a more dispersed CMAP.

Motor NCS in neuromuscular disorders with demyelination

With loss of myelin structure, saltatory conduction fails, therefore the latency of NCS is prolonged and the conduction velocity of NCS is slowed.[8-10] NCS shows severely prolonged motor latencies and markedly slowed conduction

velocities. The precise changes seen depend on the site and extent of demyelination. If demyelination is very proximal then distal motor latency and conduction velocity may be normal in which case only F waves may show abnormalities. Conduction block or temporal dispersion both result in a reduction in CMAP amplitude (Fig. 2). The CMAP area is also used to assess the contribution of these two processes. To demonstrate segmental demyelination on motor nerve conduction study, a combination of conduction block, temporal dispersion, prolonged distal latencies or markedly slow conduction velocities must be seen. In the demyelinating cases of conduction block, the CMAP area or amplitude with stimulation proximal to site of conduction block is smaller compared with distal stimulation (proximal/distal CMAP area ratio < 0.5 and proximal/distal CMAP amplitude ratio < 0.7) (Fig. 2).[2-10] In temporal dispersion (proximal/distal CMAP duration > 1.15), there is a loss of synchrony in the nerve action potentials resulting in a loss of CMAP amplitude because the positive part of one muscle fiber action potential cancels out the negative part of another (phase cancellation).[2-10]

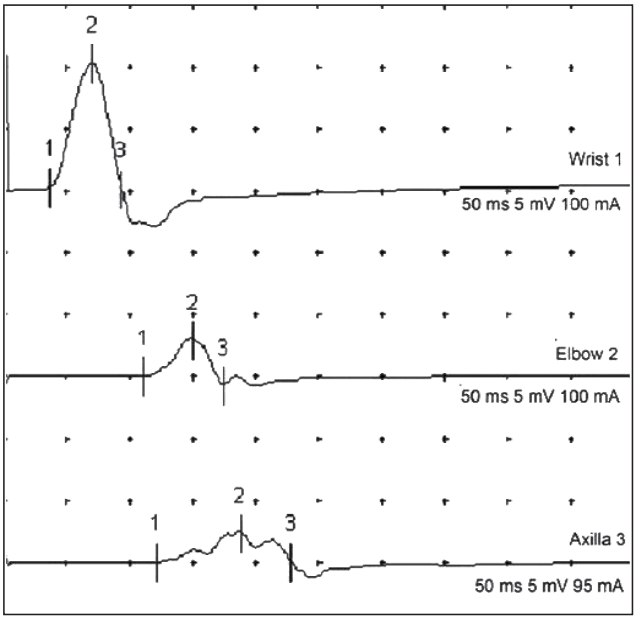

Fig. 2. Conduction block in median motor nerve conduction study (NCS). In the demyelinating cases of conduction block, the compound muscle action potential (CMAP) area or amplitude with stimulation proximal to site of conduction block is smaller compared with distal stimulation (proximal/distal CMAP area ratio < 0.5 and proximal/distal CMAP amplitude ratio < 0.7).

Sensory NCS in neuromuscular disorders

In both axonal and demyelinating pathologies, the SNAP amplitude will be reduced by different reasons. Sensory axonal loss will result in a smaller SNAP. Demyelination also produces small SNAP but with prolonged durations. As they are of much shorter duration than CMAP they are more susceptible to phase cancellation.

The distribution of sensory NCS abnormalities may be helpful in determining etiology. For example, the loss of SNAP in the lower limbs is common in an axonal dying back neuropathy related to chemotherapy agents such as vincristine; whereas equal involvement of upper and lower limb SNAP will suggest the possibility of a sensory ganglionopathy.[10]

In proximal nerve trauma, maintenance of the sensory potential depends on the intact cell bodies in the dorsal root ganglia. Thus sensory NCS is extremely useful in localizing a peripheral nerve lesion as either preganglionic or post-ganglionic. In a patient with a clinically suspected C8, T1 root lesion and with appropriate anesthesia in that dermatome, the absence of the ulnar and medial antebrachial cutaneous sensory potential places the lesion distal to the dorsal root ganglion (DRG) in the lower trunk of the brachial plexus and not at root level. Of course, further needle EMG can then be used to define this clinical situation.[8]

F waves in neuromuscular disorders

F waves are sensitive to all forms of generalized peripheral neuropathy with their absence or a prolonged latency occurring early. For example, in Guillain-Barre syndrome (GBS) where demyelination may be segmental, proximal and patchy, F wave abnormalities may be the only electrophysiological abnormality seen in the early time. In axonal pathology, F wave latencies may also be mildly prolonged in keeping with the motor conduction velocity slowing secondary to the loss of the fastest conducting motor axons. In the motor neuron diseases such as amyotrophic lateral sclerosis (ALS), prolongation of any F wave latency is strong evidence, and the possibility of other pathological process such as multifocal motor neuropathy would be thought less likely.[10,11]

F waves may be absent in focal peripheral nerve or anterior spinal disorders. They were initially also thought to be very useful in identifying individual root distribution abnormalities, and the F wave ratio may be useful for distinguish-

ing the presence of a distal or proximal lesion.[10,11]

General reports of NCS

Before interpretation of the outcome, factors such as electromagnetic interference, inadequate environment, or the temperature in the room that may affect the examination outcome must be carefully considered. The outcomes of NCS should include the nerves tested, areas of stimulation and recording, the time between recordings, and the conduction velocities, latencies, and amplitudes of responses. The physician must fully understand each component of the report and recognize the importance of each component in order to make a more accurate diagnosis. Furthermore, a detailed report including technique used, distance, examination room reference values, and temperature measurements should be included in the final report or standard manual in each examination room.

The outcomes of each NCS should be reported using the following methods. In motor NCS, the physician would record the examined nerve, stimulation area, the distance between peripheral stimulation area and recording area, and report the amplitude of complex muscle action potentials for each stimulation and recording area, the latency when stimulating the farthest peripheral area and nerve conduction velocity. In sensory NCS, the physician would record the examined nerve, stimulation area, and the distance between stimulation and recording areas, and report the amplitude of sensory nerve potentials for each stimulation and recording area, and the velocity obtained from the peak latency of the SNAP. Of course, if possible, normal reference value for NCS outcomes should be suggested so that physicians from other centers can confirm. If normal reference values are not included in the final report, abnormal outcomes must be clearly noted. When performing NCS or repeated nerve stimulation studies, the physicians should confirm that the temperature of the examined hand or foot was continuously monitored.[9] Prolonged peripheral latency of sensory or motor nerves during a NCS can be due to reduced hand or foot temperatures. For repeated nerve stimulation tests, patients who should show abnormalities can produce healthy outcomes if the temperature of hand or foot is not maintained. Often any issues would be recorded, from the patient's inability to tolerate electrical stimulation to technical limitations from technical factors such as thickness of subcutaneous tissue and swelling of the limbs that can affect the completion and outcome of the NCS. Waveforms from NCS should be included to assist with quantitative understanding of the outcome.

CONCLUSION

In neuromuscular disorders, NCS can be clinically useful both in localizing lesions and determining the pathological processes. Also, the major advantages of NCS include easy performance, lesion localization, and assessment of severity, pathophysiological determination of demyelination or axon loss and identification of clinical diagnosis.

However it is inappropriate to use a uniform standardized NCS for all patients without any prior neurological examinations or history takings. It is very important to carry out tests accurately and reproducibly and to develop an investigation strategy based on the patient's symptoms, signs and the differential diagnosis rather than a fixed protocol. And, the physicians should report the results clearly and then place them in the context of the clinical situation. In conclusion, the diagnostic approach with using NCS is crucial for the physician to diagnose the neuromuscular diseases and determine further diagnostic tests; furthermore the integrated analysis of NCS, neurological examinations and patient's manifestations should be performed simultaneously to obtain the satisfactory outcomes.

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