Chapter 5
Electrodiagnostic Testing of the Peripheral Nerves

Thomas Schelle

5.1 Introduction

Electrodiagnostic examination (EDX) consists of two major parts: nerve conduction studies (NCS), including long latency reflex testing (F-waves), and needle electromyography (EMG). In addition, somatosensory evoked potentials and magnetic stimulation motor evoked potentials are needed sometimes, but the two latter techniques are outside the scope of this chapter. NCS and EMG are usually performed together. In contrast to nerve imaging such as magnetic resonance imaging (MRI) and high-resolution ultrasound (HRUS) (see Chap. 6), EDX provides functional information about the electrical properties of the peripheral nerves. EDX should only be carried out by specially trained staff, such as by a certified physician, or under his or her direct supervision [1].

What does EDX do? It extends the clinical examination. It can differentiate between disorders of the peripheral nerves, the neuromuscular junction, and the muscle itself. In a peripheral nerve disease in particular, EDX provides useful data regarding the localization of focal involvement (e.g., anterior horn cell,

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nerve root, nerve plexus, peripheral nerve), the type (e.g., demyelinating or axonal), the severity (incomplete versus complete), the duration (subacute or chronic), and the prognosis (reinnervation or no reinnervation) [2, 3].

What is EDX not able to do? It cannot replace a careful anamnesis survey and clinical examination by a neurologist experienced in the field of peripheral nerve disorders [4, 5]. Furthermore, EDX is unable to depict the underlying pathological features of a peripheral nerve disease. For instance, a carpal tunnel syndrome is usually caused by compression of the median nerve owing to narrowness within the carpal tunnel, but it may also occur because of compression by a mass lesion such as a ganglion cyst, an intraneural hematoma, or a peripheral nerve tumor. In all these cases, EDX provides the same result. Only imaging techniques (see Chap. 6) are able to demonstrate the underlying pathological features in those cases [6].

In the next sections, we will focus on the basics of EDX in disorders of the peripheral nerve only. The scope of this book does not include diseases of the muscles and the neuromuscular junction. For a more detailed description, please refer to specialist literature [2, 3].

5.2 Types of Nerve Fibers Assessable with EDX

According to the classification of Erlanger and Gasser, there are three different types of nerve fibers: large myelinated A-alpha fibers, small myelinated A-delta fibers, and unmyelinated C fibers [7]. A very important fact is that conventional EDX can only assess the largest, fast-conducting, and well-myelinated A-alpha fibers of the motor, sensory, and "mixed" peripheral nerves, including efferent motor fibers and afferent sensory fibers mediating the sense of touch, position, and vibration.

Slow conducting A-delta and C fibers mediating pain, cold, and warm sensations are only measureable with special techniques, such as heart rate variability test or sympathetic skin response test, which are discussed elsewhere [2, 3]. This fact explains why some painful conditions, such as small fiber neuropathy, cannot be examined using conventional EDX [4, 8].

5.3 Motor Nerve Conduction Studies

5.3.1 Technique and Parameters

In a motor NCS, the peripheral nerve is stimulated with a transcutaneous depolarizing square wave electrical pulse (stimulation electrode) of very short duration. The stimulus generates a muscle contraction in the target muscle, and its intensity must be supramaximal in order to excite all A-alpha fibers. Furthermore, a ground electrode is also necessary, providing a zero-voltage reference point. With two self-adhesive surface recording electrodes that are placed on the muscle belly (pick-up electrode) and on the tendon of the target muscle (reference electrode), the compound muscle action potential (CMAP) arising from the activated muscle fibers is recorded. The stimulation can be carried out proximally to the recording electrodes at different sites of the nerve course (e.g., wrist, forearm, elbow, upper-arm, and Erb's point) [9].

In the case of deeply situated peripheral nerves, such as the lumbar plexus, stimulation is also possible with needle electrodes or, alternatively, by means of transcutaneous magnetic stimulation (TMS). This also applies to deeper lying muscles, where the CMAP can also be recorded with needle electrodes. However, these special techniques are discussed elsewhere [2, 3].

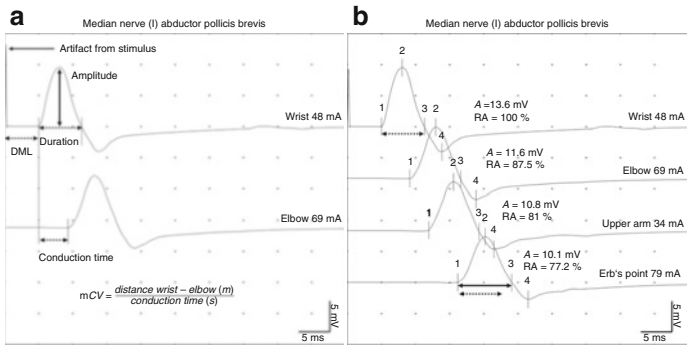


Fig. 5.1 (**a**) Important parameters derived from motor nerve conduction studies and calculation of the motor nerve conduction velocity. (**b**) Physiological "temporal dispersion." Note the amplitude decay (RA, relative amplitude) and the prolonged duration of the compound muscle action potential (CMAP) recorded after proximal stimulation compared with the CMAP obtained after distal stimulation

Neurophysiological convention specifies that negative voltage results in an upward deflection of the CMAP. Taking this fact into account, the routine technique described above allows a couple of parameters derived from the CMAP, that are used in the diagnosis of peripheral nerve diseases to be measured and calculated (Fig. 5.1a) [9–12]:

Distal motor latency (*DML*) is the time between stimulus onset and onset of the negative peak of the CMAP. It reflects the time required for conduction through the distal axons (fastest A-alpha fibers), the neuromuscular transmission time, and the time needed to generate a muscle action potential. It is measured in milliseconds.

CMAP Amplitude is measured from the baseline to the negative peak of the CMAP. It is determined by the number of activated muscle fibers. It is measured in millivolts.

Duration is defined as the time from the onset of the CMAP to the return to baseline at the end of the CMAP. It reflects the range of conduction velocities within the nerve. It is measured in milliseconds.

Conduction time is measured in milliseconds on the basis of the difference between the motor latencies after proximal and distal stimulation.

Motor nerve conduction velocity is calculated for every nerve segment after distal and proximal stimulation by determining the quotient of the distance between the two stimulation points over the conduction time. It is measured in meters per second. The minimum distance between the two stimulation points should be at least 10 cm to avoid inaccuracy [9–12].

Note that the larger the distance between the stimulation and recording electrodes, the longer the duration of the CMAP owing to an increased range of conduction velocities. This phenomenon is additionally characterized by an increasing decay of the amplitude of the CMAP, also called *temporal dispersion* (Fig. 5.1b) [13, 14].

Age-matched normal values for NCS, including motor nerve conduction velocity, distal motor latency, and the CMAP amplitude of every single peripheral nerve are either derived from studies in the laboratories or obtained from related literature [2, 3, 9, 15].

There are many physiological factors affecting nerve conduction. Only a few are addressed here. Generally, nerves of the upper extremity conduct faster than those of the lower extremity. Moreover, the nerve conduction velocity in proximal nerve segments is faster than in the distal parts of a peripheral nerve [16]. The most important factors influencing NCS in the clinical routine are age and skin temperature. In infants and patients of advanced age, nerve conduction velocities are diminished. Furthermore, a decrease in skin temperature also decreases the conduction velocities [17–19]. Therefore, standardization and

documentation of the skin temperature during electrodiagnostic testing is mandatory. In the case of low skin/room temperatures, a hot water bath or ceiling-mounted radiant heaters can be effective in raising the skin temperature of the limbs.

5.3.2 Demyelinating Disorders

Demyelinating disorders of the peripheral nerve result in impairment of conduction owing to the focal or generalized pathological features of the myelin sheath [11]. As a consequence, EDX demonstrates a slowing of the motor nerve conduction velocities and/or a prolongation of distal motor latencies. Depending on the type of nerve involvement, different patterns of motor nerve conduction velocity deterioration can be observed [2, 3, 9–12, 15]:

- Focal: affecting only one nerve segment (e.g., in the early stages of entrapment in ulnar neuropathy at the elbow). An example is shown in Fig. 5.3a.
- Multifocal: affecting certain nerve segments in one or more different peripheral nerves (e.g., multifocal motor neuropathy, acute and chronic inflammatory demyelinating neuropathy).
- Generalized: affecting all nerve segments in different nerves (e.g., hereditary sensorimotor neuropathy type 1).

If only the distal nerve segment is affected, prolongation of the distal motor latency will result, whereas nerve conduction velocity and CMAP amplitude are normal. This applies in particular to the early stages of carpal tunnel syndrome, tarsal tunnel syndrome, and Guyon's canal syndrome. In contrast to focal entrapments, a generalized demyelinating neuropathy leads to prolongation of the distal motor latencies in addition to a slowing of the nerve conduction velocities (Fig. 5.2). Distal motor latency is used for evaluation because

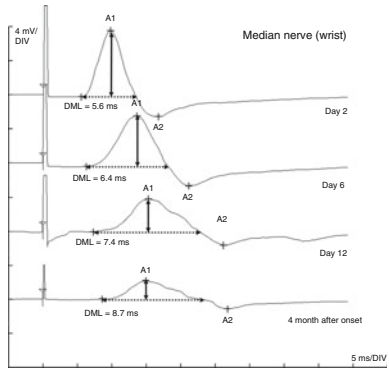


Fig. 5.2 Distal CMAP and distal motor latency (DML) of the median nerve in a patient with acute inflammatory demyelinating neuropathy 2, 6, 12 days, and 4 months after onset of the clinical symptoms. Note the prolonged DML due to the distal nerve segment being affected and pathological "temporal dispersion"

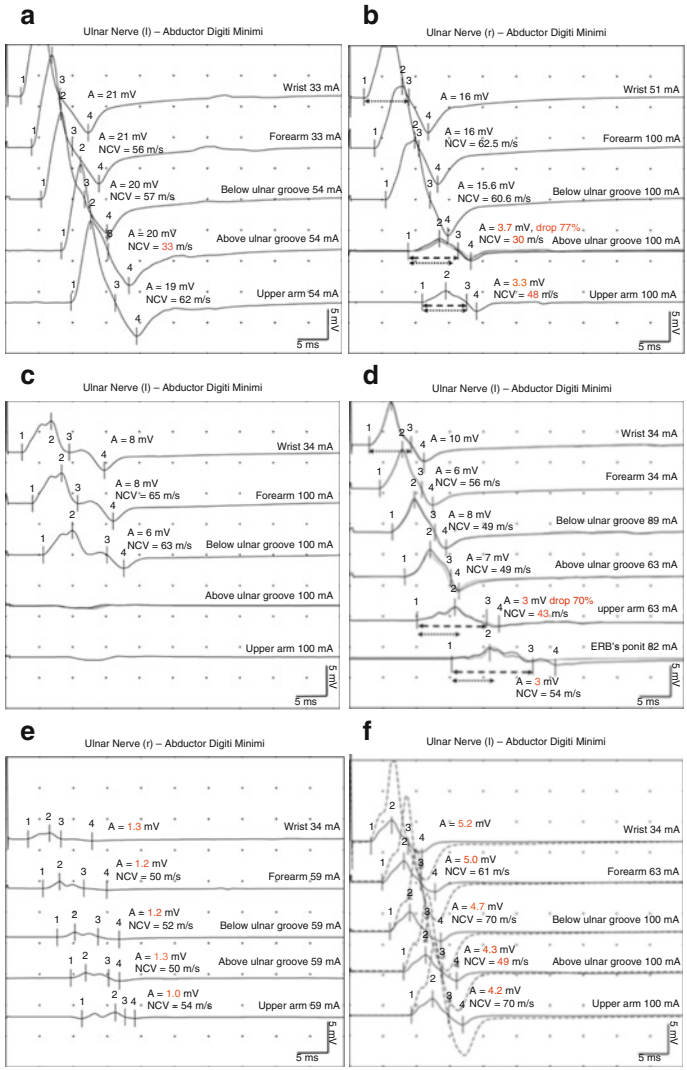
the nerve conduction velocity of distal nerve segments cannot be calculated. DML can therefore be explained by the fact that the exact distance between the stimulation electrode and the endplate region of the supplied muscle is unknown. Moreover, distal motor latency contains the indeterminable time needed for neuromuscular transmission and the generation of muscle contraction (CMAP) [2, 3, 9–12, 15].

Apart from prolonged distal motor latencies and lowered conduction velocities, there are two other conditions that typically occur in demyelinating nerve disorders, referred to as "abnormal temporal dispersion" and "conduction block" [13, 14]. As mentioned above, in a healthy peripheral nerve the duration of the CMAP after proximal stimulation normally increases and the CMAP amplitude decreases compared with the CMAP recorded after distal stimulation. This feature is termed "temporal dispersion." In the case of a demyelinating disorder, temporal dispersion is further increased because of the lowered conduction velocity

and increasing heterogeneity of the motor nerve conduction velocities of different A-alpha fibers generating the CMAP. Consequently, besides the prolonged duration of CMAP and the decay of its amplitude, it appears to be split at and above the site of the lesion, whereas the distal CMAP remains normal (Fig. 5.3d) [9–12]. In scientific studies, different consensus criteria regarding the "abnormal temporal dispersion" have been published. According to the American Academy of Neurology, temporal dispersion is abnormal "if the CMAP obtained after proximal stimulation shows more than a 20 % decay of the amplitude and more than a 15 % increase of the duration compared with the CMAP obtained after distal stimulation" [13]. In contrast, the criteria of the American Association of Neuromuscular and Electrodiagnostic Medicine assume an abnormal temporal dispersion "if the duration of the proximal CMAP is prolonged by more than 30 % compared with the duration of the distal CMAP." It is assumed that segmental demyelination over longer distances is responsible for this phenomenon [14].

On the other hand, a short segmental demyelination is attributed to a "conduction block." If the conduction block is complete, a normal CMAP can be recorded after distal stimulation, whereas stimulation proximal to the lesion will generate no CMAP (Fig. 5.3c). An incomplete conduction block is assumed if the CMAP amplitude (or area under the curve) after proximal

Fig. 5.3 Different types of demyelinating lesions on the example of ulnar neuropathy at the elbow obtained with fractionated motor nerve conduction studies. (**a**) Segmental slowing of the motor nerve conduction velocity. (**b**) Incomplete conduction block. (**c**) Complete conduction block. (**d**) Abnormal "temporal dispersion." For details please refer to the text. (**e**) Pure axonal loss. The site of the lesion is not detectable with use of a motor nerve conduction study. (**f**) Both axonal loss and focal demyelination. *Dotted line*: CMAP of the ulnar nerve of the healthy side


a
Ulnar Nerve (l) – Abductor Digiti Minimi
A = 21 mV
Wrist 33 mA
A = 21 mV
NCV = 56 m/s
Forearm 33 mA
A = 20 mV
NCV = 57 m/s
Below ulnar groove 54 mA
A = 20 mV
NCV = 33 m/s
Above ulnar groove 54 mA
A = 19 mV
NCV = 62 m/s
Upper arm 54 mA
5 mV
5 ms
b
Ulnar Nerve (r) – Abductor Digiti Minimi
A = 16 mV
Wrist 51 mA
A = 16 mV
NCV = 62.5 m/s
Forearm 100 mA
A = 15.6 mV
NCV = 60.6 m/s
Below ulnar groove 100 mA
A = 3.7 mV, drop 77%
NCV = 30 m/s
Above ulnar groove 100 mA
A = 3.3 mV
NCV = 48 m/s
Upper arm 100 mA
5 mV
5 ms
c
Ulnar Nerve (l) – Abductor Digiti Minimi
A = 8 mV
Wrist 34 mA
A = 8 mV
NCV = 65 m/s
Forearm 100 mA
A = 6 mV
NCV = 63 m/s
Below ulnar groove 100 mA
Above ulnar groove 100 mA
Upper arm 100 mA
5 mV
5 ms
d
Ulnar Nerve (l) – Abductor Digiti Minimi
A = 10 mV
Wrist 34 mA
A = 6 mV
NCV = 56 m/s
Forearm 34 mA
A = 8 mV
NCV = 49 m/s
Below ulnar groove 89 mA
A = 7 mV
NCV = 49 m/s
Above ulnar groove 63 mA
A = 3 mV drop 70%
NCV = 43 m/s
upper arm 63 mA
ERB's ponit 82 mA
A = 3 mV
NCV = 54 m/s
5 mV
5 ms
e
Ulnar Nerve (r) – Abductor Digiti Minimi
A = 1.3 mV
Wrist 34 mA
A = 1.2 mV
NCV = 50 m/s
Forearm 59 mA
A = 1.2 mV
NCV = 52 m/s
Below ulnar groove 59 mA
A = 1.3 mV
NCV = 50 m/s
Above ulnar groove 59 mA
A = 1.0 mV
NCV = 54 m/s
Upper arm 59 mA
5 mV
5 ms
f
Ulnar Nerve (l) – Abductor Digiti Minimi
A = 5.2 mV
Wrist 34 mA
A = 5.0 mV
NCV = 61 m/s
Forearm 63 mA
A = 4.7 mV
NCV = 70 m/s
Below ulnar groove 100 mA
A = 4.3 mV
NCV = 49 m/s
Above ulnar groove 100 mA
A = 4.2 mV
NCV = 70 m/s
Upper arm 100 mA
5 mV
5 ms

stimulation is reduced only when with the CMAP after distal stimulation [9]. Depending on the affected nerve, there are again different criteria defining an incomplete conduction block. According to the American Association of Neuromuscular and Electrodiagnostic Medicine, a "drop of more than 50 % in proximal CMAP compared with CMAP obtained after distal stimulation in the median and ulnar nerves and more than 60 % in the tibial and peroneal nerves is considered as pathological, while CMAP duration increases by no more than 30 %" [14]. In contrast, the criteria of the American Academy of Neurology require a "20 % drop of the (proximal) CMAP area or amplitude compared after distal and proximal stimulation" [13].

Unfortunately, the diagnosis process for demyelinating disorders of the peripheral nerves can become very challenging. Primary axonal loss is sometimes accompanied by secondary demyelination (Fig. 5.3f). This explains why slowed conduction velocities and prolonged distal motor latencies can occur in an axonal disorder [12]. Moreover, during the first few days after severe axonal nerve damage this condition will present a complete or incomplete conduction block because Wallerian degeneration has nor been completed yet and the segment distal to the damage is still conducting. This phenomenon has frequently been referred to as a "pseudo-conduction-block" [20]. Therefore, different criteria have been suggested, considering motor conduction velocities, distal motor latencies, and F-wave latencies. For instance, Van den Bergh and Pieret assume inter alia a motor conduction velocity slowing of <70 % of the lower limit of normal and a prolonged distal motor latency of >150 % of the upper limit of normal to be characteristic of a demyelinating condition [21].

5.3.3 Axonal Disorders

Axonal loss leads to a reduction of the activated muscle fibers and is thus paramount to a reduction of CMAP amplitude. In a fractionated motor nerve conduction study this applies to all

generated CMAPS – distally and proximally. As a consequence, and in contrast to focal demyelinating disorders, a localization of the lesion with motor NCS is impossible (Fig. 5.3e) [10–12]. This important lack of diagnostic power can be solved by needle electromyography and nerve imaging (see Sect. 5.6 and Chap. 6) [6, 22]. Furthermore, at an early stage (days 0–14) after onset of an axonal injury, this presentation can be misdiagnosed as a conduction block (see Sect. 5.3.2) [20]. If axonal loss also includes the fastest conducting A-alpha fibers, motor nerve conduction velocities may also be reduced. However, the extent of conduction slowing is less than following nerve fiber demyelination, and it usually ranges above 70 % of the lower limits of normal [2, 3, 21].

5.4 Sensory Nerve Conduction Studies

5.4.1 Technique and Parameters

As in a motor NCS, the peripheral nerve is stimulated with a transcutaneous depolarizing square wave electrical pulse (stimulation electrode) of a very short duration. However, a lower stimulation intensity is required than in a motor NCS. In contrast to motor NCS, a self-adhesive recording electrode can be placed either distally (antidromic recording) or proximally (orthodromic recording) to the stimulus site because the evoked electrical activity propagates in both directions. Furthermore, a ground electrode is also necessary [9]. In clinical practice, antidromic recordings are preferred, mainly because the amplitude of the sensory nerve action potential (SNAP) is larger than that obtained by orthodromic recordings [10–12]. Sensory nerve conduction studies can also be performed with needle electrodes; however, these special techniques are discussed elsewhere [2, 3]. Compared with CMAPs, SNAPs are smaller and measured in microvolts. Therefore, an averaging of several

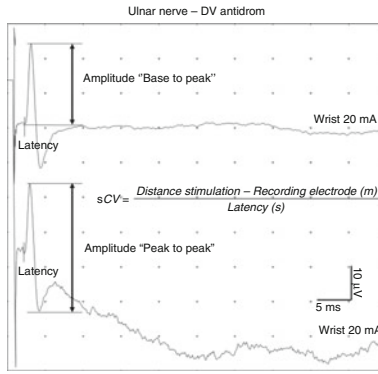


Fig. 5.4 Important parameters derived from sensory nerve conduction studies and calculation of the sensory nerve conduction velocity

SNAPs is required to improve the signal-to-noise ratio (SNR). Most important parameters derived from sensory NCS are as follows (Fig. 5.4) [10–12]:

SNAP amplitude reflects the number of the largest activated sensory nerve fibers (A-alpha). It is measured (base to peak or peak to peak) in microvolts.

SNAP conduction velocity is easily calculated using only a single site measurement because the distance between the recording and stimulating electrodes and the sensory latency is directly measurable. It is measured in meters per second.

As mentioned above, only the largest and fastest conducting sensory A-alpha fibers, which functionally supply senses of touch, position, and vibration senses, can be assessed using sensory NCS. Usually, small fiber neuropathies affecting C-fibers mediating pain do not show any abnormality in conventional sensory NCS [4, 8]. Quantitative sensory testing and autonomic testing or skin biopsy are necessary to provide the

correct diagnosis in this situation. These special techniques are described elsewhere [2, 3].

5.4.2 Demyelination Disorders

As in motor NCS, the primary feature of demyelination is a reduction of sensory nerve conduction velocity [10–12]. Additionally, the duration of SNAP increases owing to an enlarged range of nerve conduction velocity. It leads to "temporal dispersion" and "phase cancellation" (Fig. 5.5). Consequently, the SNAP amplitude will also drop in a demyelinating disorder [10–12, 23].

5.4.3 Axonal Disorders

Axonal disorders will primarily reduce the amplitude of the SNAP generated after electrical stimulation, whereas its duration is normal. As in motor NCS, further axonal loss of the fastest conducting fibers will also lead to a modest slowing of the sensory nerve conduction velocities (Fig. 5.5) [10–12, 21, 23].

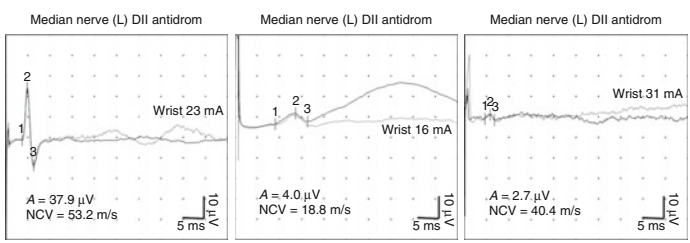


Fig. 5.5 Sensory nerve conduction studies of the median nerve. *Left*: physiological. *Middle*: demyelinating disorder with slowing of motor nerve conduction velocity and "temporal dispersion." *Right*: pure axonal loss

Sensory NCS are useful to determine whether the site of the nerve lesion is pre- or postganglionic. In the case of a preganglionic lesion the connection between the cell bodies of the dorsal root ganglion and the peripheral nerve remains intact. Consequently, a normal SNAP and conduction velocity can be obtained by sensory NCS, despite anesthesia in the dermatome supplied by that root. However, an absent or pathologically changed SNAP indicates a postganglionic lesion either of the nerve plexus or of a single peripheral nerve [24]. Apart from this electrophysiological dogma, in some recent studies it has been shown that – in a small percentage of subjects (2.4–12.1 %) with preganglionic lesions due to a L5 or S1 radiculopathy – the SNAP amplitude was abnormal. This exception may be due to dorsal root ganglion compression proximal to the spinal foramen or intra-spinally, and should be always kept in mind [25, 26].

5.5 Long Latency Reflexes (F-Waves)

5.5.1 Technique and Parameters

F-waves are a type of late motor response. Their name is derived from the foot, where they were first described. With a reversed stimulation electrode, F-waves can be recorded in the same setting as stated in Sect. 5.3.1 concerning motor nerve conduction studies [9]. If a nerve is electrically stimulated above its final segment the action potential propagates in both directions.

The orthodromic propagated action potential generates CMAP, also known as an M-response. On the other hand, the antidromic propagated action potential reaches the anterior horn cell body and depolarizes the axon hillock. As a result, a

small portion of the alpha-motor neurons backfire and a second orthodromic action potential reaches the muscle. This causes a late muscle depolarization that involves only a small portion of the muscle fibers, referred to as an F-wave [27–31]. Recording F-waves will therefore allow the electrodiagnostic testing of long and proximal nerve segments (e.g., the lumbosacral plexus or nerve roots) which are inaccessible to conventional electrical nerve stimulation [29]. In contrast to the M-response, F-waves usually vary in latency and shape because different populations of motor neurons backfire with each stimulus. Therefore, normally, "10–20 consecutive stimulations will be needed and the most reliable measure of the F-wave is its minimum latency of 10–20 firings" [29, 31]. It strongly depends on the body height, which should be taken into account. Moreover, the "F-wave persistence" is commonly used and represents the number of F-waves obtained per number of stimulations [27–31]. Regarding other parameters (*dispersion*, *amplitude-ratios*) derived from F-wave studies please refer to specialist literature [29].

5.5.2 Clinical Application

In generalized demyelinating nerve disorders (e.g., chronic and acute inflammatory demyelinating neuropathy) the proximal nerve segments or nerve roots are often affected by focal demyelination. This fact leads to decreased F-wave persistence or even to their absence (Fig. 5.6). Furthermore, the minimum F-latency is prolonged [32, 33]. F-waves may also be found to be pathological in other proximal axonal or demyelinating peripheral nerve disorders. Discussion of the value of F-wave studies in detecting radiculopathies has, however, been controversial [29]. Early studies reported lower sensitivity (50–80 %),

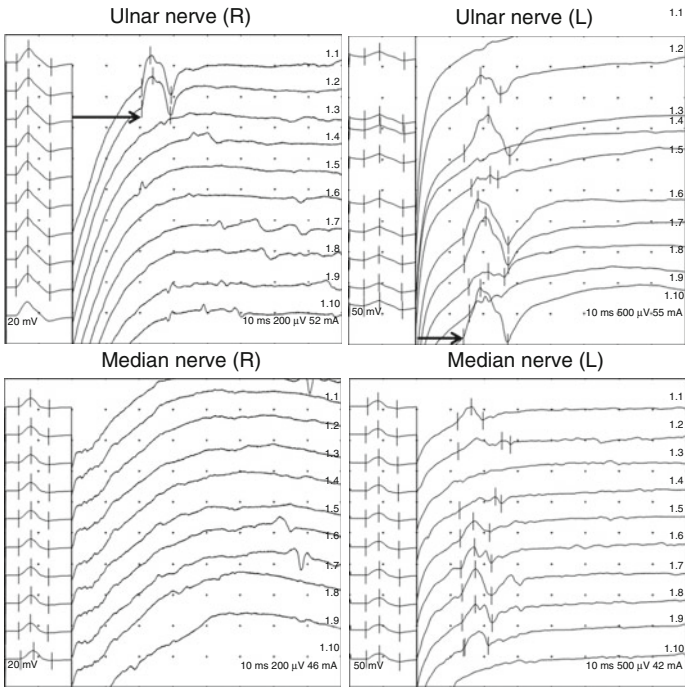


Fig. 5.6 F-waves in a patient with a lesion of the lower brachial plexus at the right side. Note the prolonged F-latency (*arrow*) and the decreased persistence in the right ulnar nerve and the absent F-waves in the right median nerve

whereas recent studies in patients with L5/S1 radiculopathies, considering not only latencies but also additional parameters such as persistence, dispersion, and amplitude ratios, reported sensitivities (90 % for L5 and 80 % for S1 radiculopathy), comparable to needle EMG [29, 34, 35]. Unfortunately, few data exist to evaluate the diagnostic value of F-waves in cervical radiculopathies. A recent study reported low sensitivity of only 55 % [36].

5.6 Needle Electromyography

5.6.1 Technique and Parameters in Healthy Subjects

Needle electromyography is commonly used to assess axonal nerve lesions, thereby delivering complimentary information to nerve conduction studies. In pure demyelinating disorders, however, no or only a few additional findings can be obtained by myography [22, 37–39]. In this section, we focus on the basic application of needle electromyography in disorders of the peripheral nerve. For special techniques such as single fiber electromyography, macro-electromyography, turns–amplitude analyses, application on myopathies, and disorders of the neuromuscular junction, please refer to specialist literature [2, 3].

A concentric needle electrode is inserted into the target muscle and the electrical activity of its muscle fibers is recorded during rest and periods of voluntary muscle contraction with minimal and maximal force. As in nerve conduction studies, a self-adhesive ground electrode is placed somewhere on the skin to provide a zero voltage reference point [9].

5.6.1.1 Normal Findings at Rest

The needle insertion in the muscle belly leads to a mechanical irritation of muscle fibers close to the tip of the needle electrode. As a result every forward movement of the needle produces bursts of electrical activity that vary in shape. This activity is also referred to as "*insertional activity*, never lasting longer than 300 ms" (Fig. 5.7a) [9, 22]. Accidentally hitting the endplate area of the target muscle, which is rather unpleasant for the patient, can irritate terminal axons, and results in two other types of spontaneous activity known as "endplate spikes" and

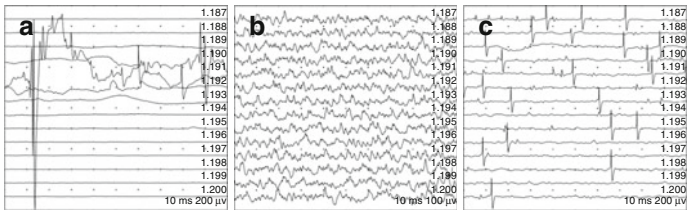


Fig. 5.7 Normal activity during needle electromyography at rest. (**a**) Insertional activity followed by electrical silence. (**b**, **c**) Endplate noise and endplate spikes (note the initial upward deflection and irregularity)

"endplate noise," also referred to as "endplate potentials" (Fig. 5.7b, c). Endplate spikes are biphasic potentials characterized by a negative (upward) onset and an irregular discharge frequency, whereas endplate noise is monophasic and of lower amplitude, but also shows a negative onset and an irregular discharge frequency [40].

5.6.1.2 Normal Findings During Voluntary Muscle

Contraction of Minimal Force

Voluntary muscle contraction leads to activation of several "motor units". A motor unit is represented by a single α-motor neuron in the spinal cord and all the individual muscle fibers it innervates [41–43]. As the extent of voluntary muscle contraction increases, more and more motor units are recruited. The potentials generated by a motor unit (motor unit action potential, MUAP) can be recorded using modern EDX equipment. However, with conventional needle electrodes it is impossible to assess the whole territory of a motor unit. Only the muscle fibers close to its tip (located within the recording radius of the needle electrode) generate the MUAP. Special techniques ("Macro-EMG") will allow the entire motor unit to be recorded [2, 3, 22].

Typically, motor units do not fire rhythmically, which means with the same discharge frequency, in contrast to pathological spontaneous activity (see Sect. 5.6.2.1). In healthy muscles these discharges of a single motor unit never exceed 20–50 Hz [42, 43]. The most important parameters of a MUAP are (Fig. 5.9a):

Amplitude is related to the size and density of the muscle fibers within the recording radius of the needle electrode [44–46].

Duration is determined by the number and size of muscle fibers of a particular motor unit close to the recording electrode. Furthermore, the spatial dispersion of the terminal axons and differing conduction velocities within the terminal axons can influence it [46].

Phases determine the number of baseline crossings of the MUAP. Up to four phases are considered normal. MUAPs with more than four phases are called "polyphasic." In healthy individuals polyphasic MUAPs should never exceed 10 % of all recorded and analyzed MUAPs of an individual muscle. In the case of asynchronous firing muscle fibers within the entire motor unit, which occurs in both neuropathic and myopathic disorders, the number of polyphasic MUAPs is increased. This also holds true for an increased number of *turns* – defined by changed direction of the MUAP without crossing the baseline [22, 46, 47].

Stability: individual MUAPs of healthy individuals do not change their morphology or shape. They are stable. Unstable MUAPs indicate diseases of the neuromuscular junction (e.g., myasthenia gravis), or they occur secondary to neuropathic or myopathic disorders [22].

Factors that influence the MUAP amplitude and duration are the type of muscle and the age. The latter may be explained by

an increasing loss of anterior horn cells in individuals of advanced age. This leads to an incorporation of denervated muscle fibers into surviving motor units, resulting in an increase in the amplitude of the MUAP [22]. Normal values for MUAP amplitude and duration for individual muscles are either derived from studies in the laboratories or obtained from related literature [2, 3, 9].

5.6.1.3 Normal Findings During Voluntary Muscle Contraction of Maximal Force

As explained above, as the force of the muscle contraction increases, more and more motor units, and finally the largest ones, are recruited. Greater voluntary activity will also increase their discharge frequency. In a healthy individual this process proceeds gently and continuously. Accordingly, a dense "interference pattern" appears and the individual MUAPs can no longer be differentiated from each other [9, 22].

5.6.2 Needle Electromyography in Focal and Generalized Neuropathies

5.6.2.1 Findings at Rest

Except for insertional activity and endplate potentials (see Sect. 5.6.1.1), no other type of electrical activity should be observed in healthy muscle tissue. This means that in the absence of a forward movement of the needle electrode the normal muscle is electrically silent in its resting state. Pathologically altered insertional activity is characterized by a "prolonged insertional activity" lasting longer than 300 ms after the forward movement of the needle and/or "pathological spontaneous activity." On the other hand, a diminished or absent insertional

activity occurs in muscles affected by an acute compartment syndrome, whereas additional increased needle insertion resistance is typical of a late stage of axonal loss where muscle parenchyma is replaced with connective tissue owing to absent reinnervation [9].

In the case of axonotmesis, the affected muscle fibers mainly show two patterns of pathological spontaneous activity: "fibrillations" and "positive sharp waves." Both appear approximately 10–14 days after onset of an axonal loss because the Wallerian degeneration needs to be completed first. In contrast to MUAPs, they always fire with the same discharge frequency. Compared with normal endplate potentials, biphasic fibrillations (Fig. 5.8a) and monophasic positive sharp waves (Fig. 5.8b) are characterized by an initial positive (downward) deflection. They result in the separation of muscle fibers from the degenerated axons. The extent of denervation is measurable semi-quantitatively by the frequency of occurrence of spontaneous activity within different muscle areas. Additionally, the distribution of the denervation pattern within different individual muscles allows localization of the underlying pathology as well as differentiation between focal and generalized axonal disorders. Either with successfully completed incorporation of muscle fibers in surviving motor units or with their death because of failed reinnervation, fibrillations and positive sharp waves will disappear again [22, 48–50]. "Complex repetitive discharges" are complex waveforms consisting of fibrillations and positive sharp waves. If they are observed in a neuropathy, they indicate a chronic denervation process where denervation is followed by reinnervation and subsequent denervation. They are characterized by an abrupt beginning and end (Fig. 5.8c) [22, 51, 52]. "Fasciculations" are spontaneous and not voluntarily activated MUAPs (Fig. 5.8d). They can be observed in healthy subjects (benign fasciculations). If they occur along with fibrillations, positive sharp waves or abnormally changed MUAPs, they are considered to be pathological and indicate a neuropathic disorder. Anterior

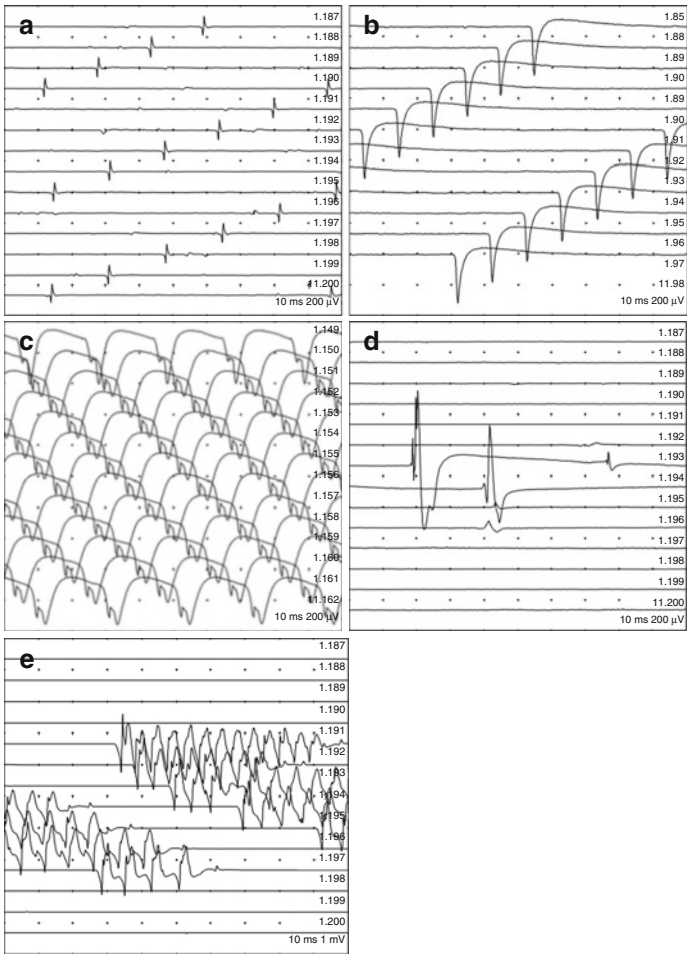


Fig. 5.8 Different abnormal findings (spontaneous activity) during needle electromyography at rest in neuropathies. (**a**) Fibrillations. (**b**) Positive sharp waves (note the initial downward deflection and the regular discharging frequency). (**c**) Complex repetitive discharges. (**d**) Fasciculations with the same appearance as motor unit action potentials (MUAPs). (**e**) Myokymic discharges

horn cell diseases also show the above-mentioned combination of different types of pathological spontaneous activity. Groups of two, three or more fasciculations, also known as "doublets, triplets and multiplets," have the same clinical significance [53]. "Myokymic discharges" are characterized by repetitive bursts of MUAPs (Fig. 5.8e) and occur along with radiculopathies and radiation neuropathies [54].

5.6.2.2 Findings During Voluntary Muscle Contraction of Minimal Force

At an acute stage of complete axonal loss, there is no voluntary muscle contraction and no individual MUAPs can be recorded. If the axonal damage is incomplete the remaining motor units generate MUAPs with normal duration, amplitude, and number of phases at this time. However, a decreased recruitment pattern in weak muscles – owing to the loss of motor units – and an increased discharge frequency of the remaining motor units can indicate an early incomplete lesion. In contrast, this finding does not occur when there is insufficient cooperation from the patient during examination nor in the case of central paralysis where the second neuron is unaffected. If muscles clinically appear completely paralyzed, e.g., in the case of a neuropathy, needle electromyography can demonstrate that the function of some individual motor units is preserved [9, 55].

Based on the intactness of anterior horn cells, nerve connective tissue, and the continuity of the epi- and perineurium respectively, and not on a disrupted or inadequately surgically repaired nerve, reinnervation of muscle fibers starts along the original nerve fiber tracts with a growth rate of about 1–2 mm/day [56]. A long distance between the injured nerve segment and its target muscle only leads to incomplete reinnervation because a restructuring of connective tissue first has to take place, or, as mentioned in Sect. 5.3.2, resulting fibroses may additionally hinder the sprouting process of axons. In the case

of a preceding complete denervation, the ingrowing axons initially reach only a small number of surviving muscle fibers; thus, the corresponding MUAPs appear with a short duration, low amplitude, reduced recruitment, and increased number of phases owing to the "spatial dispersion" of endplates, as usually seen in myopathies (Fig. 5.9b) [22]. With reinnervation

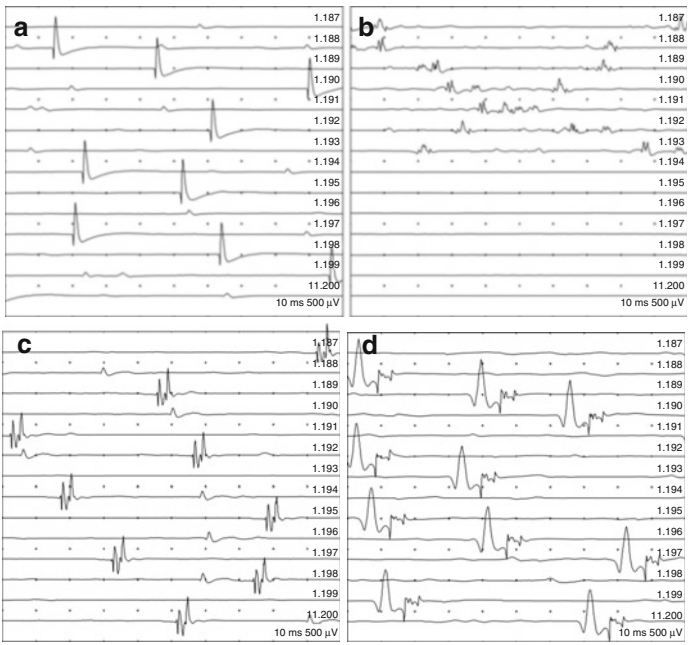


Fig. 5.9 Electromyographic findings during voluntary muscle contraction at minimal force in neuropathies. (**a**) Normal MUAPs. (**b**) Early reinnervation. MUAPs appear small and polyphasic as in a myopathy. (**c**, **d**) Reinnervation with polyphasic MUAPs and late components. Note the prolonged duration and increased amplitude. (**e**) Late stages of reinnervation. Finally, the polyphasic components will disappear, although amplitude increases further

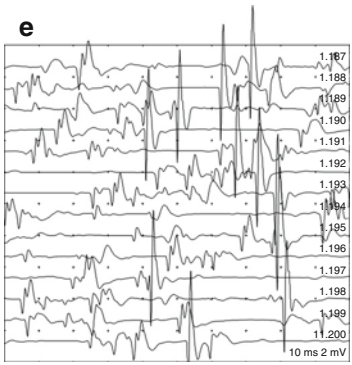


Fig. 5.9 (continued)

proceeding in the absence of fibrosis or inadequate nerve reconstruction, the territory of the motor unit increases in size because more and more muscle fibers become incorporated. The same process occurs in chronic partial denervation, where surviving motor units incorporate – by means of collateral axonal sprouting – muscle fibers from dead ones. Therefore, the number of muscle fibers supplied by such a "neuropathic" motor unit can be higher than in normal individuals [57]. Thus, the resulting "neuropathic" MUAPs appear with a longer duration together with increased amplitude (Fig. 5.9c). Because of slowed conduction along the newly-formed terminal axons and increased "spatial dispersion" of the endplates, these MUAPs also have more phases – and sometimes satellite potentials (Fig. 5.9d). In the late stages, polyphasic changes of the MUAP will disappear again. In addition to that, increasing conduction velocities and lowered "spatial dispersion" also occur; however, the amplitude remains larger than it usually appears in healthy subjects [22]. An example is shown in Fig. 5.9e.

5.6.2.3 Findings During Voluntary Muscle Contraction of Maximal Force

Because of the smaller total number of motor units, the density of the interference pattern is thinned out. In severe cases, individual MUAPs will then be visible. If reinnervation takes place the remaining motor units increase their territory by incorporating denervated muscle fibers. Accordingly, the amplitude of interference pattern is also increased [22, 37–39].

5.7 Limitations and Pitfalls

Both nerve conduction studies and needle electromyography may be unpleasant for some patients. While nerve conduction studies with surface electrodes are non-invasive, repeated needle electrode insertion occasionally leads to complications such as bleeding, infection or nerve injury in individuals undergoing electromyography [58]. The literature states that needle electromyography is relatively contra-indicated in patients treated with antiplatelet agents and anticoagulants [9]. However, in recent studies there has been no statistically significant difference between muscle hematoma occurrence following needle electromyography in patients undergoing therapy with warfarin or antiplatelet agents and in nontreated individuals. Only a small amount of subclinical muscle hematoma was observed in the group receiving blood-thinning medication [59, 60]. Furthermore, nerve conduction studies may theoretically impair the function of implanted biomedical devices such as pacemakers or cardiac defibrillators. In some recent studies, though, it was demonstrated that, in nerve conduction studies at routine sites, no electrical impulses could be detected by the sensing systems of these devices [61, 62]. It has therefore been suggested that the current guidelines restricting nerve conduction

studies in such patients should be subject to revision [62]. Even repetitive nerve stimulation is safe in patients with implanted cardiac defibrillators, and it appears safe in patients with implanted pacemakers using bipolar sensing. Caution is only recommended in pacemaker patients with unipolar sensing systems [63].

The correctness of results provided by EDX substantially depends on the experience of the investigator. Many pitfalls can arise such as false evaluation due to anomalous innervation, improper machine settings, and insufficient patient preparation (skin temperature). For a detailed overview please refer to specialist literature [64].

5.8 Conclusions

Electrodiagnostic examination provides clinically important information on both focal and generalized disorders of the peripheral nervous system. On the other hand, it cannot be overemphasized that EDX is only an extension of our clinical examination and anamnesis survey and, although we never neglect it, it will not replace either the clinical examination or an anamnesis survey. Nerve conduction studies facilitate differentiation between axonal and demyelinating disorders, and between a focal and generalized affection of the peripheral nerve. With fractionated motor nerve conduction studies or inching techniques, a demyelinating process can be located: first, by means of focal conduction velocity slowing or prolongation of distal motor latency; second, by evaluating a conduction block; and third, by signs of abnormal temporal dispersion. Moreover, sensory nerve conduction studies allow preganglionic lesions to be distinguished from postganglionic lesions in the majority of cases. Long latency reflexes (F-waves) provide a way of examining the proximal parts of the peripheral nervous system

(plexus and root segments) that are otherwise inaccessible to conventional electrical nerve stimulation. In all types of axonal loss (acute, subacute, chronic), needle electromyography, along with nerve conduction studies, provides information on their extent, localization, and acuity. Additionally, needle electromyography provides a highly reliable assessment of an important question – whether reinnervation takes place or not – which will help to determine the prognosis of a focal peripheral nerve disorder.

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