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Clinical Motor Nerve Conduction Studies

by

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Abstract

Nerve conduction studies are an essential part of an EMG examination. The principles of motor nerve conduction studies are described. The different parameters are defined and their significance is discussed. The methods for individual motor nerves are illustrated and the reference values are given.

Keywords: *Motor nerve conduction studies, motor conduction velocity, F waves, A waves, H reflex.*

Introduction

The clinical usefulness of nerve conduction studies in the diagnosis of diffuse and local neuropathies has been thoroughly validated (Hodes et al. 1948, Gilliatt and Thomas 1960, Johnson and Olsen 1960, Lambert 1962, Lewis and Sumner 1982). The findings reflect the functional state of the myelinated motor nerves, the neuromuscular transmission and the muscle fibres. Many reviews and manuals for nerve conduction studies have been published (Kaeser 1970, Goodgold 1972, Rosenfalck and Rosenfalck 1975, Ma and Liveson 1983, Oh 1984, DeLisa et al. 1987).

The exact details of the investigation procedures vary considerably from one laboratory to another. Many laboratories use methods and reference values that have been described in the literature, often with local modifications. Only a few laboratories have possibilities to obtain their own reference values for all nerves studied. Rigorous standardization of the methods can significantly reduce the variability at the laboratory and enable reference values to be transferred

from one hospital to another. Rational use of reference values can also considerably increase the sensitivity of the measurements without a decrease in specificity.

An initiative to agree on basic principles and methods for specific nerves was undertaken by three Nordic departments in 1986-89. The participants were the Department of Clinical Neurophysiology at University Hospital in Uppsala, Sweden, the Department of Clinical Neurophysiology at the University Hospital of Turku, Finland, and the Department of Informatics at the University of Aalborg, Denmark. The aims of this collaboration were to find uniform, standard methods for nerve conduction measurements and establish a large common reference value database (Falck et al. 1991).

In the following, we will outline the general principles of motor nerve conduction studies and give detailed descriptions of methods for most individual motor nerves that are studied.

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Stimulation of Nerves

Stimulation Sites and Nerve Segments

The nerve should be stimulated at points where it is easy to find and superficial enough for transcutaneous stimulation. These points are called *stimulation sites* (Fig. 1a). The part of the nerve between two stimulation sites is called a *nerve segment* (Fig. 1a). Most motor nerves can be stimulated with surface electrodes at several different sites.

Measurement of Distance

The length of a nerve segment is measured from the centre of the cathode at one stimulation site along the nerve to the center of the cathode at the next stimulation site. It is important that the limb is in a standardized position during the recording of the signal as well as when the distances are measured.

Type of Stimulator

Both constant-current and constant-voltage stimulators may be used, although the former is preferred since the stimulus intensity around the nerve is better controlled. The use of magnetic stimulation to investigate the motor nerve conduction is limited. The exact point of stimulation is not well defined because the magnetic fields are widespread and the currents spread to other nearby nerves (Odderson and Halar 1991). Magnetic stimulation cannot currently be recommended as a useful alternative to electrical stimulation in nerve conduction studies.

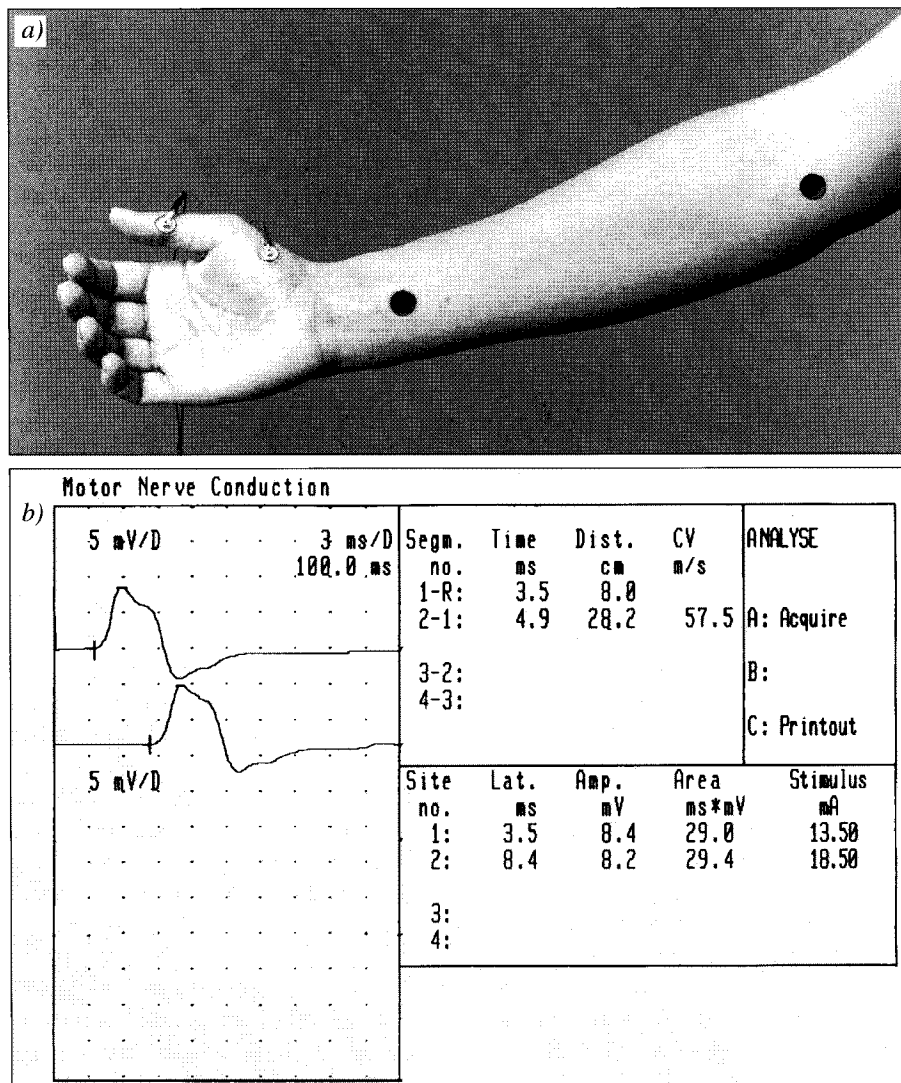


Fig. 1. Illustration of the measurement of motor nerve conduction of the median nerve. a) Placement of the electrodes, stimulation sites at elbow and wrist. The distance from the recording electrode over the thenar muscles to the cathode of the stimulating electrode is 80 mm. b) Recorded traces.

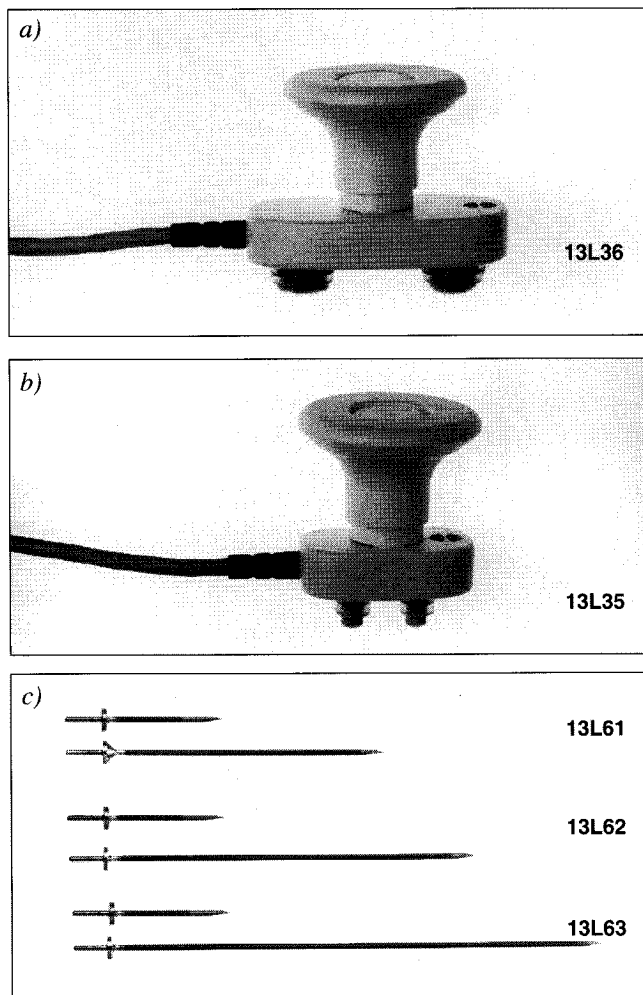


Fig. 2. Electrodes used for stimulation in motor nerve conduction studies.

a) A stimulation electrode with a fixed interelectrode distance of 23 mm between the centre of the anode and cathode (DANTEC 13L36); this electrode is used in adults as well as children.

b) Small stimulation electrode that can be used in small children (DANTEC 13L35).

c) Near-nerve needle electrodes used for stimulation (DANTEC 13L61, 13L62, 13L63).

Stimulating Electrodes

Both surface and needle electrodes can be used for stimulation (Fig. 2). The choice of stimulation electrodes depends on the nerve segment studied. In segments where the nerve runs superficially, surface electrodes are preferable. Most commercially available surface-stimulating electrodes (DANTEC 13L36, 13R45, 13R74) are recommendable in adults and children. In neonates, an electrode with a smaller surface and a smaller interelectrode distance, 10 mm, can be used (DANTEC 13L35). Stimulation with small electrodes is usually more painful because the local current density is higher than with large electrodes.

For stimulation of deeply located nerves, and sometimes when very short consecutive segments are studied ("inching"), monopolar needle electrodes (DANTEC 13L61, 13L62, 13L63) may be preferable. Using needle electrodes, the exact

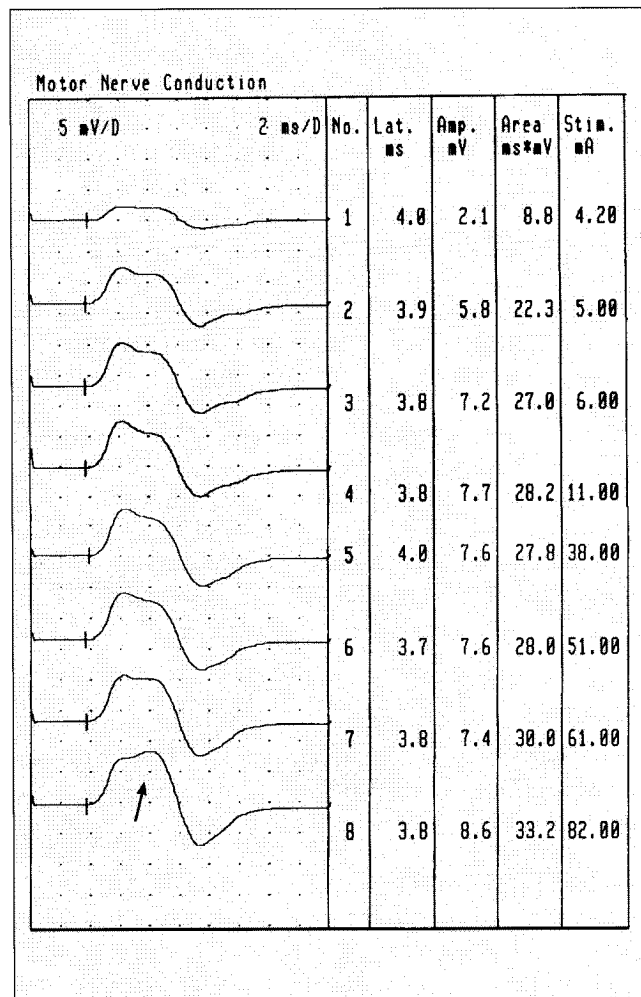


Fig. 3. The effect of the stimulus intensity on the M wave. Median nerve stimulated at the wrist, recording electrode over the thenar muscles. Initially, the amplitude increases and the latency decreases with increasing stimulus intensity (traces 1-3). After supramaximal stimulus intensity has been reached (trace 3), a moderate increase in intensity does not alter the amplitude or latency traces (4-7). A large increase in the stimulating current (trace 8) will also stimulate the ulnar nerve (↑) and alter the shape of the M wave.

stimulation point can be more accurately defined. The proximity of the electrode to the nerve can be determined by the stimulus current needed to evoke maximal response.

Stimulus Duration and Intensity

Most laboratories use a square-wave stimulus with a duration of either 0.1 or 0.2 ms. There is no significant difference in the measurements made with these stimulus durations. If maximal response cannot be obtained, a duration of 0.5 ms or even 1 ms should be used (Panizza et al. 1989). These longer stimuli may increase the latencies. The same stimulus duration should be used for all stimulation sites in a given study.

The stimulus intensity must be high enough to excite all alpha motor neurons in the nerve, but not so high as to cause unnecessary pain and current spread along the nerve. In this

way, the point of stimulation will be poorly defined due to "cathodal escape" (Fig. 3). Furthermore, a high stimulus current may also spread to other nearby nerves and excite muscles innervated by them. We recommend an intensity that is 10-25% above the intensity necessary for a maximal M wave.

Placement of Stimulating Electrodes

Usually, the cathode is placed directly over the nerve and the anode proximal to it along the nerve. To reduce the stimulus artifact, it may be an advantage to rotate the anode obliquely over the nerve.

When the H reflexes are measured, it is often recommended that the cathode be placed proximal to the anode to avoid anodal block (Kimura 1989). For F wave measurements, our recommendation is to keep the same electrode position as for studies of motor conduction velocity (MCV). With the stimulus intensities used, there is no anodal block in motor axons (Winkler and Stålberg 1988).

At the most distal stimulation sites, the cathode of the stimulating electrode should be placed at a fixed distance of 80 mm from the recording electrode if possible. This reduces the variability of the DLAT, AMPL and DUR (see under Parameters to measure) measurements.

If needle electrodes are used for stimulation, the cathode should be placed close to the nerve and the anode subcutaneously proximal or lateral to the cathode. A surface electrode may also be used as anode. The position of the cathode is good when a threshold response is obtained with an intensity of 0.5 mA (Trojaborg 1992), but acceptable recordings can still be obtained with thresholds of up to 2 - 3 mA.

Recording of the M Wave

Generation of the M Wave

The M wave (also called the compound motor action potential, CMAP) represents the activity generated by individual muscle fibres innervated by the stimulated motor axons. The shape and size of the M wave depend on the number and size of the activated muscle fibres and on the temporal dispersion of their action potentials. The amplitude and area of the M wave may be reduced by loss of alpha motor neurons, conduction block between the stimulating electrode and the muscle and by neuromuscular transmission block. The temporal dispersion of the action potentials may have a complex influence on the summation of the action potentials; in principle, increased temporal dispersion prolongs the duration of the M wave and reduces its amplitude.

The M wave of the hand muscles is often preceded by a small potential (Fig. 4) which is an antidromic compound sensory nerve action potential generated by the sensory palmar digital nerve branches in the hand (Simpson 1964, Buchthal and Rosenfalck 1966). This potential is seen only if a high gain is used and should be discarded in the determination of motor latencies.

Recording Electrodes

Surface electrodes

Most motor nerves can be studied with surface electrodes (Fig. 5). The electrodes are painless for the patient and less selective than needle electrodes.

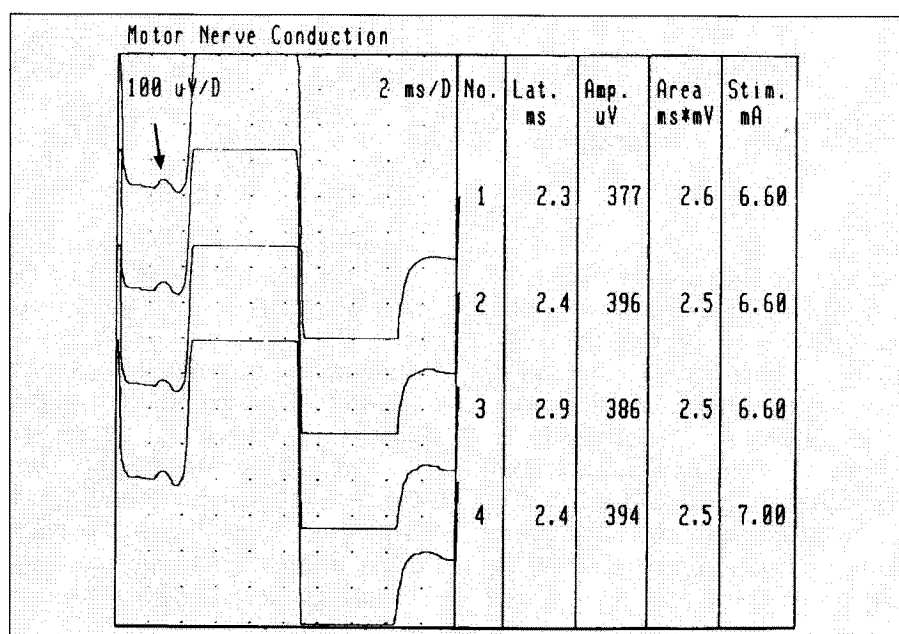


Fig. 4. A small compound nerve action potential (\downarrow) precedes the M wave recorded from the thenar muscles following stimulation of the median nerve at the wrist. The nerve action potential is probably generated by the palmar digital nerves to the thumb. This nerve action potential is not included in the motor nerve measurements.

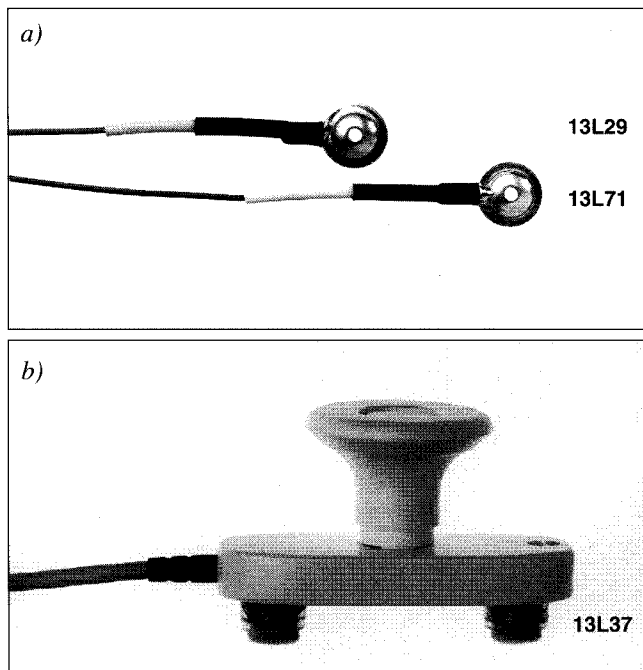


Fig. 5. Recording electrodes.
 a) A pair of stainless steel cup electrodes with a diameter of 11 mm (DANTEC 13L29 and 13L71).
 b) Surface electrode with a fixed (37 mm) interelectrode distance (DANTEC 13L37).

Silver, silver/silver chloride or stainless steel electrodes can be used. Usually, the diameter of the electrodes is 5-11 mm (Fig. 5) (DANTEC 13L29 or 13L71).

Some commercially available electrodes that can be used for recording have a fixed interelectrode distance (DANTEC 13L37), usually less than 20-40 mm. The interelectrode distance is too small for these electrodes to be recommended if AMPL and AREA are measured.

Needle electrodes

Intramuscular needle electrodes are not recommended for most studies and definitely not for amplitude and area measurements. A serious drawback to using needle electrodes, especially concentric electrodes, is their selectivity. They record activity only from the muscle fibres closest to the electrode tip, not the global activity of the muscle. Therefore, the findings represent only a subpopulation of axons. Another problem is that muscle contractions often displace the electrode and the shape of the M wave varies from one stimulus to the next.

Sometimes, subcutaneous needle electrodes are used, for instance during surgical monitoring. In certain situations intramuscular needle electrodes have to be used. For instance when the suprascapular nerve is studied, the M wave is recorded from the infraspinatus muscle, which lies beneath the trapezius muscle.

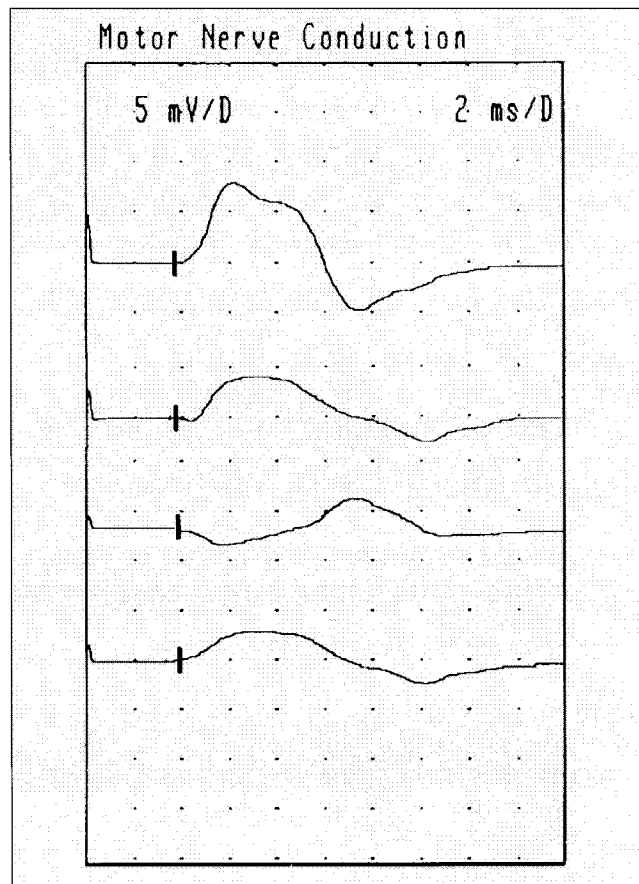


Fig. 6. Effect of the placement of the recording electrode on the M wave. The median nerve is stimulated at the wrist and the M wave is recorded from the thenar muscles. The electrode is placed correctly over the end-plate zone of the muscle, the onset is in the negative direction (trace 1). The electrode is placed outside the end-plate zone; there is a small positive wave preceding the main negative component (traces 2-3). Note that the onset of the first deflection from the baseline is identical in both recordings. The duration of the small positive wave is proportional to the distance from the end-plate zone.

Electrode Placement

When differential amplifiers are used, both the "recording" and "reference" electrodes contribute to the recorded signal. The placement of the electrodes in relation to the muscle is therefore important.

Active electrode

The recording electrode should be placed over the end-plate region of the muscle, usually over the middle of the muscle belly. If the recording electrode is placed properly, the onset of the M wave is in the negative direction (Fig. 6). If an initial positive deflection is recorded at stimulation of the most distal stimulation site, the electrode is probably not directly over the end-plate zone and should be repositioned.

When the nerve is stimulated at proximal sites, there may be other muscles that generate the initial small positive deflection preceding the main part of the M wave. This positive deflection should not be included in latency measurements (Fig. 7).

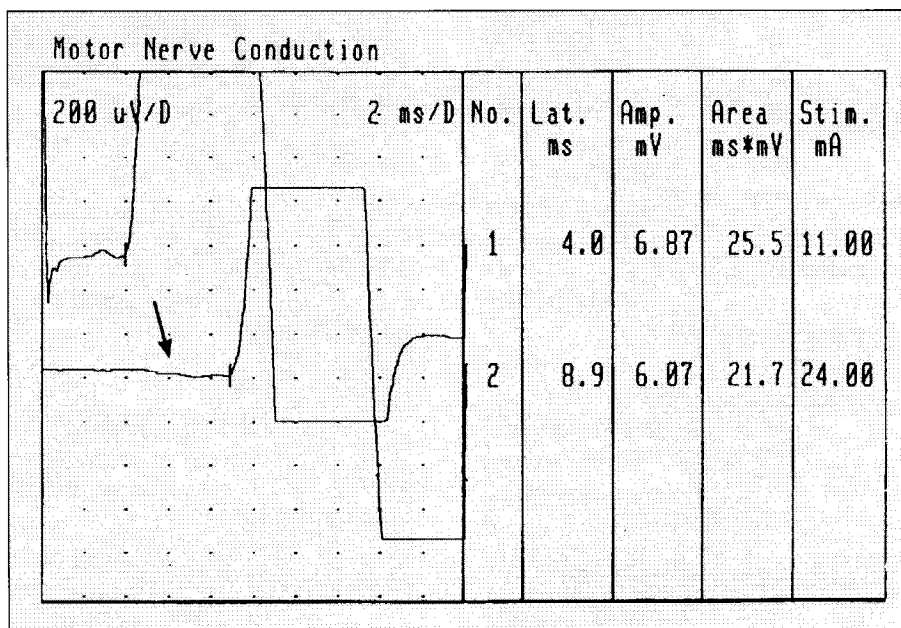


Fig. 7. The effect of volume-conducted activity from proximal muscles. The M wave is recorded from the thenar muscles following stimulation at the wrist (trace 1). The M wave deflection is upwards, in the negative direction. When the median nerve is stimulated at the elbow (trace 2) there is a smooth positive potential preceding the negative deflection. This slow initial deflection is a far-field potential generated by the forearm muscles innervated by the median nerve.

Reference electrode

The reference electrode should be placed over an area which is as inactive as possible so as not to influence the shape of the M wave. The reference electrode should preferably be placed entirely outside the muscle or tendon. Often, the reference electrode is placed over the tendon of the muscle, but this region is not inactive (Gutjahr and Ferber 1984, Taylor 1991).

Ground electrode

In most motor nerve conduction studies, the stimulus artifact is insignificant and the ground electrode may be placed wherever convenient.

Recording Electrode Impedance and Equipment Input Impedance

The impedance between the skin and the electrode should be 20 kOhms or less. Most modern EMG equipment has an input impedance of 1 MOhm or more. The higher the input impedance of the equipment, the less sensitive the measurements are to high electrode-skin impedances.

Filter Settings

The high-pass filter (low-frequency band) should be set at a frequency that does not significantly distort the shape of the M wave. Our reference values have been collected with a 20 Hz high-pass filter. The low-pass filter is typically set to 10 kHz.

Sweep Speed and Time Resolution

The usual sweep speed is 2 ms/div; acceptable settings vary between 1 ms/div and 5 ms/div. The sweep should have a time resolution of at least 0.1 ms. The responses must be repeated to make sure that the consecutive M waves do not vary.

Position of Limbs

In nerve segments running across joints, the position of the joint influences the length of the measured nerve segments. In extreme joint positions, the nerve is stretched, which affects the measured length of the nerve segment and alters the conduction velocity. The most important segment in this respect is the ulnar nerve across the elbow. Various recommendations have been given, ranging from extended elbow (Jebsen 1967, Chang and Chen 1980, Harding and Halar 1983, Håkansson 1956) to 135° degree flexion (Gutjahr and Ferber 1984, Kinkaid et al. 1986). Bielawski and Hallett (1989) showed that the yield of abnormal findings was not related to the elbow position, although the reference values for each elbow position were different. To avoid luxation of the ulnar nerve over the medial epicondyle during recording we recommend a 15 - 35° flexion of the elbow.

The position of the limb also influences the length of the muscle that generates the M wave. If the muscle is shortened, DUR decreases and AMPL increases. It is important to maintain a neutral relaxed position of the distal hand and foot joints. No attempt should be made to extend or flex joints.

Parameters to Measure

Distal Latency (DLAT)

This is the time from the stimulus to the onset of the M wave. The latency is measured from the stimulus to the first deflection of the signal from the baseline (Fig. 8).

Manual measurement of latency is dependent on the gain used (Maynard and Stolow 1972). We suggest that a gain of 200 $\mu\text{V}/\text{div}$ should be used for all manual latency measurements, although part of the signal will overflow.

Conduction Time (CT)

The conduction time is the difference in the proximal and distal latencies (Fig. 8). In calculating the conduction time, it may sometimes be convenient to use the first positive or negative peak instead of the distal latency for both the proximal and the distal M waves.

Maximal Motor Conduction Velocity (MCV)

MCV is calculated as the length of the nerve segment divided by the conduction time. It corresponds to the conduction velocity of the fastest alpha motor nerves.

Methods for measurement of the slower conducting fibres (Hopf 1962) and the cumulative distribution of the motor conduction velocities (Ingram et al. 1988) have been described. These methods are routinely used only in a few laboratories and are not dealt with here.

Amplitude (AMPL)

The AMPL of the M wave is measured from baseline to highest negative peak (Fig. 8). If there is a preceding positive deflection, the AMPL is still measured from the baseline to the highest negative peak.

Duration (DUR)

The DUR of the M wave can be defined in several ways: (1) from onset to first negative to positive baseline crossing, (2) from onset to last positive peak. Because the endpoint of the M wave is difficult to define, our suggestion is to measure the duration from onset to the first negative to positive baseline crossing (Fig. 8).

Area (AREA)

The AREA is the integrated area between the signal and the baseline over the DUR (Fig. 8).

Decay

Even in normal nerves, the motor conduction velocities in the different axons range from 30 to 60 m/sec. (Hopf 1962, Rosenfalck and Rosenfalck 1975, Gutjahr and Ferber 1984). Because of this, there will be increasing temporal dispersion of the nerve action potentials and of the evoked motor unit potentials with increasing conduction distance. The AMPL at distal stimulation is higher than at proximal stimulation. This

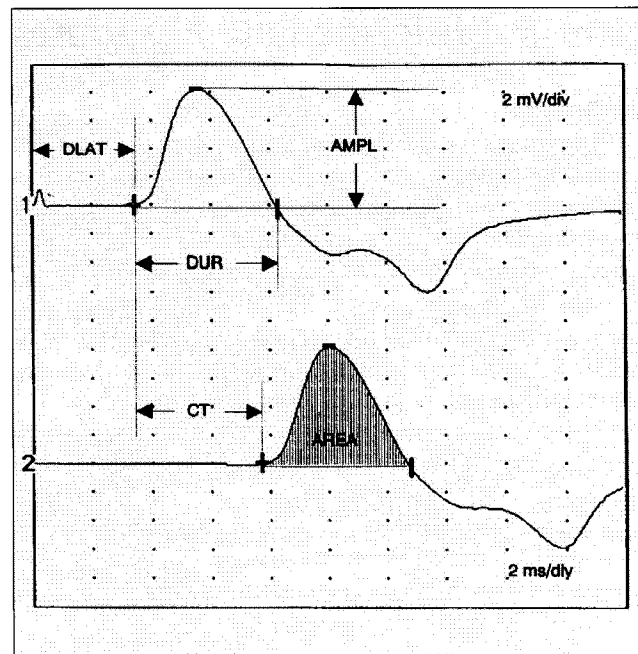


Fig. 8. Parameters to measure. If the latency is measured manually, this should be done at a gain of 200 $\mu\text{V}/\text{div}$. See text for explanations. AMPL = amplitude, AREA = area, CT = conduction time, DUR = duration, DLAT = distal latency.

change in amplitude following stimulation at different sites along the nerve is expressed as proportional values. The amplitude change, DECAY, and area decay (AREADECAY) are calculated as follows (Olney, Budingen and Miller 1987).

$$\text{DECAY} = 100 * (\text{AMPL}_{\text{dist}} - \text{AMPL}_{\text{prox}}) / \text{AMPL}_{\text{dist}}$$

$$\begin{aligned} \text{AMPL}_{\text{dist}} &= \text{AMPL recorded at distal stimulation} \\ \text{AMPL}_{\text{prox}} &= \text{AMPL recorded at proximal stimulation} \end{aligned}$$

$$\text{AREADECAY} = 100 * (\text{AREA}_{\text{dist}} - \text{AREA}_{\text{prox}}) / \text{AREA}_{\text{dist}}$$

$$\begin{aligned} \text{AREA}_{\text{dist}} &= \text{AREA recorded at distal stimulation} \\ \text{AREA}_{\text{prox}} &= \text{AREA recorded at proximal stimulation} \end{aligned}$$

Dispersion

The proportional change in duration, DISPERSION, is calculated in a similar way. However, there is a slight but significant difference: the distal duration is subtracted from the proximal duration. This is to maintain the logical connection of the parameter with its pathophysiological significance. Increased dispersion of the conduction velocities will also give increased DISPERSION.

$$\text{DISPERSION} = 100 * (\text{DUR}_{\text{prox}} - \text{DUR}_{\text{dist}}) / \text{DUR}_{\text{dist}}$$

$$\begin{aligned} \text{DUR}_{\text{dist}} &= \text{DUR recorded at distal stimulation} \\ \text{DUR}_{\text{prox}} &= \text{DUR recorded at proximal stimulation} \end{aligned}$$

Late and Intermediate Responses

H reflex

The H reflex is a monosynaptic reflex elicited by electrical stimulation of the muscle spindle afferents. The reflex is obtained at weak stimulus strength and is maximal at a stimulus strength above threshold for the M wave. At higher stimulus strength, the H reflex is blocked by antidromic impulses in the motor axons. The H wave is more easily obtained with a stimulus duration of 0.5 or 1.0 ms (Panizza et al. 1989). The reflex is habituated with repetitive stimulation and the stimulation frequency should not exceed 0.5 Hz.

The latency of the H reflex is measured from the stimulus to onset of the H wave (Fig. 9). Usually, the H reflex is recorded from the gastrocnemius or soleus muscles, this reflex arc is mediated mainly via the S1 root. An H reflex may also be recorded from the flexor carpi radialis mediated mainly by the C7 root (Deschuytere et al. 1976).

Reference values are usually given as the H latency minus the M latency with stimulation at popliteal fossa. Voluntary activation of the investigated muscle or Jendarssic's manoeuvre will enhance the H reflex amplitude and shorten the latency. These procedures to enhance the H reflex are, however, not recommendable.

F waves

The F wave is a recurrent discharge of an antidromically activated motor neuron. The F wave follows the M wave (Fig. 10). The recurrent discharges occur in each motor unit only in 0-5% of the stimuli. Several stimuli must be given to obtain a sample from several axons. Different numbers of stimuli have been recommended; our recommendation is to use 20 stimuli. The following parameters may be measured:

Minimum F wave latency (F-LAT) is the shortest F wave latency of 20 consecutive stimuli minus DLAT.

F wave frequency is the number of times an F wave was obtained divided by the total number of stimuli.

F wave amplitude may be expressed as the mean F amplitude in relation to the M wave amplitude.

F wave dispersion (chronodispersion) is the difference between the longest and shortest F wave latencies among the first F waves in each trace (Panayatopoulos 1979). We have not found this parameter as useful as minimum F wave latency and frequency.

A Waves

These are intermediate responses with a latency longer than the M wave and usually, but not always, shorter than F waves (Fig. 11). The A wave appears at a critical stimulus intensity and has a constant shape at consecutive stimulations. The A wave is not a late component of the M wave. When the stimulating electrode is moved proximally, the latency of the A wave is decreased. A waves are common in tibial nerves of

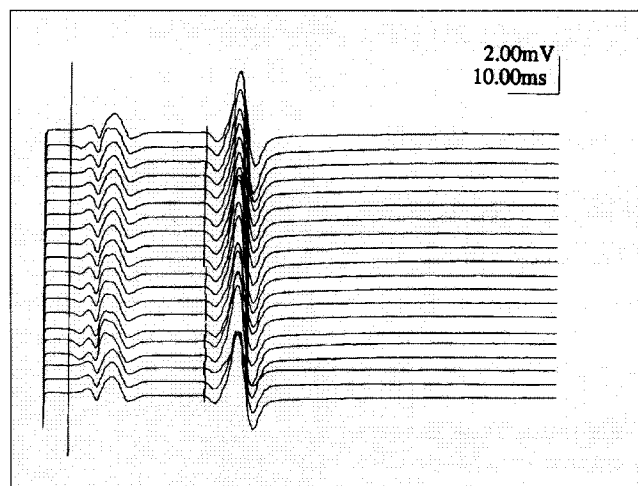


Fig. 9. H waves. In contrast to the F waves, the shape and latency of the H wave remains constant.

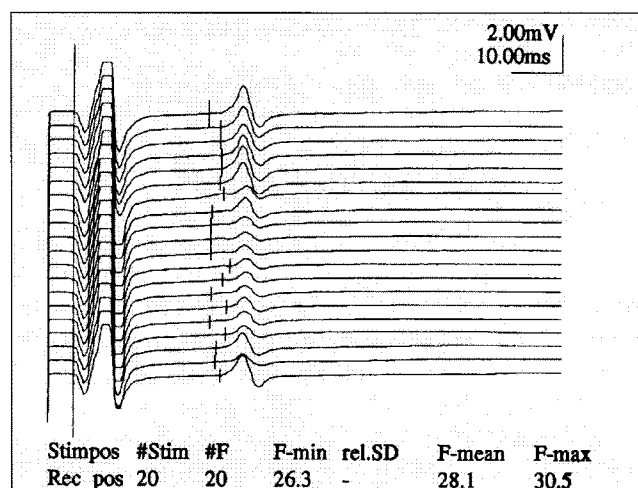


Fig. 10. F waves. The F minimum, mean and maximum latencies are indicated.

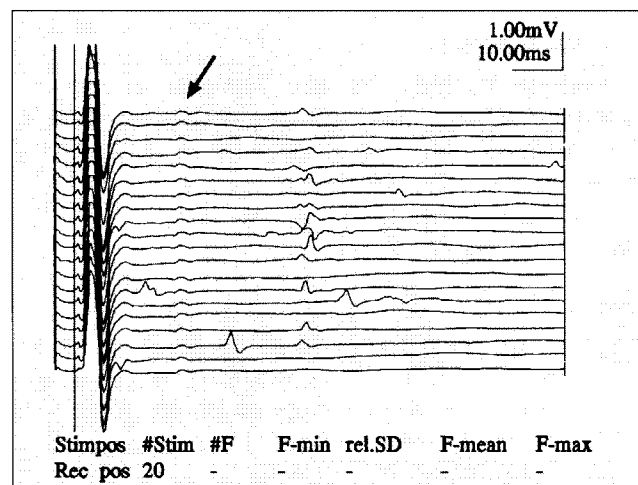


Fig. 11. A waves. The A waves have a constant shape and latency; at high stimulus intensity, they tend to disappear.

healthy subjects but uncommon in other motor nerves. The presence of A waves should be reported, because they suggest an abnormality, usually caused by an extra discharge in a hyperexcitable zone of the axon.

Anomalies

The most common anomaly is the Martin-Gruber anastomosis. In the Martin-Gruber anastomosis, there is one or more branches from the median nerve that cross over to the ulnar nerve in the forearm. The presence of anomalous innervation can be detected if there are unexpected changes in the M wave from the distal to the proximal stimulation site. In a typical subject with a Martin-Gruber anastomosis, the M wave amplitude recorded from the thenar muscles at distal median nerve stimulation is significantly lower than at proximal stimulation. At proximal stimulation, the M wave also shows an early positive deflection. At ulnar nerve stimulation, a low response is obtained from hypothenar muscles at elbow stimulation but is normal at wrist stimulation. Conventional motor conduction studies in a nerve segment with an anomaly are unreliable. Using special double stimulus techniques, nerve conduction can be measured (Kimura 1989).

Another common anomaly is the accessory superficial peroneal nerve, a branch from the superficial peroneal nerve to the extensor digitorum brevis muscle (EDB). Here, a low M wave amplitude is obtained from the EDB muscle at distal stimulation compared to proximal stimulation. A good M wave is, however, obtained at stimulation behind the lateral malleolus.

Causes of Variability

To optimize the sensitivity of the measurements, all variables that may influence the results must be considered. Some variables are biological, related to the subject, and others are physical, related to the physical state of the nerve and muscle.

Biological factors

Age

Age is probably the most important biological factor. In preterm neonates, the conduction velocities are very slow: at 25 weeks' gestational age, the MCV of the ulnar nerve is 12 m/s and of the tibial nerve 6 m/s (Schultke et al. 1968, Blom and Finnström 1971). In full-term neonates, the MCV is around half the adult values, 25 - 30 m/s in the upper extremity (Gamstorp 1965, Gamstorp and Shelbourne 1965, Edebol Eeg-Olofsson 1992). The MCV increases to almost adult values by the age of three to five years. Adult values are reached in the teens (Gamstorp and Shelbourne 1965, Rosenfalck and Rosenfalck 1975, Lang et al. 1985). Above the age of 20, there is a slight reduction in the nerve conduction velocity with increasing age (Wagman and Lesse 1952, Buchthal and Rosenfalck 1966, Lucci 1969, Nielsen 1973, Gutjahr and Ferber 1984, Rivner et al. 1990, Falck et al. 1991, Stetson et al. 1992). On average, the MCV decreases by 0.5 - 1.8 m/s per 10 years of age.

The AMPL of the response from M. extensor digitorum brevis decreases significantly with age in adults (Falck et al. 1991), but the AMPL of the thenar muscles on median nerve stimulation does not change significantly with age.

DLAT does not depend on age (Falck et al. 1991, Taylor 1991).

Height

Many authors (LaFratta and Smith 1964, Lang and Björqvist 1971, Campbell, Ward and Swift 1981, Soudmand et al. 1982, Gutjahr and Ferber 1984, Rivner et al. 1990, Falck et al. 1991, Taylor 1991, Stetson et al. 1992) have shown that taller subjects have slower conduction velocities than short subjects. Height explains more variability than age in several motor nerves. The conduction velocity decreases 2-3 m/s per 10 centimetres increase in height.

Gender

Some authors have demonstrated that women have slightly slower conduction velocities, 2-4 m/s, than men (LaFratta and Smith 1964, Lang and Björqvist 1971, Gutjahr and Ferber 1984, Stetson et al. 1992).

Physical Factors

Temperature

The most important physical factor affecting the parameters is temperature. Temperature has a dual effect on nerve conduction measurements (Lang and Puusa 1981). There is a *local* effect on the M wave and DLAT and a *segmental* effect on the MCV.

AMPL increases with decreasing local temperatures down to 18°C (Ricker, Hertel and Stodieck 1977). The increase in amplitude is 1.7% per °C decrease in local temperature (Hopf and Maurer 1990).

A decrease in temperature of a *nerve segment* decreases the conduction velocity by 1.2 m/s/°C to 2.4 m/s/°C (Henriksen 1956, Zysno and Reichsmüller 1968, Bolton et al. 1982, Gutjahr and Ferber 1984, Dioszeghy and Stålberg 1992), causing reduction in M wave amplitude. The local and segmental temperature effects on the amplitude interact and cancel each other. Therefore, there is no significant relationship between temperature and AMPL (Bolton, Sawa and Carter 1981, Falck et al. 1991).

Most of the motor nerve segments are embedded in muscles. Only extreme variations in skin temperature will significantly affect the near nerve temperature of the motor nerves. The skin temperature overlying the median nerve in the forearm and the peroneal nerve in the leg is only partially correlated with the temperature around the nerve. According to Gutjahr and Ferber (1984) the skin temperature explained only 3% of the conduction velocity variability of motor nerves. At skin temperatures above 30°C, Falck et al (1991) found no significant relationship between the skin temperature and motor nerve conduction velocity of the median and peroneal nerves. Preheating every motor nerve with an infrared heater is not practical and is far too time-consuming for clinical studies.

Our recommendation is to heat the limbs with hot water, paraffin, infrared heater or hot pack for at least 10 minutes if

the skin temperature of the dorsal side of the hand is less than 28°C and if the dorsal side of the foot is less than 27°C.

Length of Segment

The conduction velocity is faster in the proximal segments of a nerve (Trojaborg 1964). Because of this, long nerve segments tend to have higher conduction velocities (Gutjahr and Ferber 1984). The DECA Y increases a little with increasing length of the nerve segment (Kimura et al. 1986).

In local nerve lesions, a slight focal conduction delay may not be detected if the measurements are made over long segments. On the other hand, if the segment length in motor nerve conduction studies is below 80 mm, the relative measurement error of the distance is going to be quite large. An optimal segment length for detection of focal conduction abnormalities in entrapment neuropathies is roughly 100-120 mm.

Sometimes, it is desirable to use "inching" over a segment, stimulating the nerve at short 10 - 20 mm intervals (Kimura 1979, Campbell et al. 1992). This is useful in the ulnar nerve at the elbow and peroneal nerve at the fibular head.

Measurement Errors

In calculating the MCV, the two main sources of measurement error are determination of latency and measurement of distance. The latency can usually be measured with an accuracy of 0.1 - 0.2 ms at each point. The error due to latency measurement is around 2 - 3% (Buchthal and Rosenfalck 1966, Gutjahr and Ferber 1984, Taylor 1991). The distance can be measured with an accuracy of 2 - 8 mm, making the error in the distance measurement 3 - 5% (Buchthal and Rosenfalck 1966, Gutjahr and Ferber 1984, Taylor 1991). The measuring tape should be made of material which does not stretch easily.

Variability between Laboratories

In our own reference value databases, there were only few significant differences between the two departments that participated (Falck et al. 1991). Also, comparison between our reference values and a Japanese study with the same methods did not show any significant differences (Arimura et al. 1990). We believe that with rigorous standardization of methods, reference values could be transferred from one laboratory to another.

Variability of Repeated Measurements (Reliability)

MCV measurements vary between 2% and 5% (Bergmans 1971, Bleasel and Tuck 1991, Taylor 1991, Halonen, Falck and Puusa in preparation). Any change in conduction velocity from one examination to another greater than 5% should be considered significant.

Reference Values and Reporting of Findings

Reference Values

Analysis of our own data shows that linear regression models can be used. Many parameters depend on one to three independent variables, which makes it difficult to deal with the reference values in simple tables of reference limits. The reference values are given as regression equations and a standard deviation. The regression equations have the general format $y = \text{constant} + x_1 \times \text{age} + x_2 \times \text{height}$. The measured results should be compared with expected values calculated from the regression models. The difference between the measured and expected value is described by the Z-score: the measured value minus the expected value divided by the standard deviation. A Z-score between -2 and +2 will be considered normal, while values outside this range are abnormal.

Side Differences

In healthy subjects, the mean values show no significant side differences between nerve segments (Gutjahr and Ferber 1984). In the diagnosis of local nerve lesions, it may sometimes be helpful to compare the results of the affected side with the healthy side. There are few reports that indicate the magnitude of a significant side difference. In our experience, a side difference of more than 10 - 12 m/s is significant.

Reporting

The results must be reported in an accurate and comprehensive way. The report for internal use within the EMG department should contain the following: latency, amplitude, segment length, conduction velocity, decay, dispersion, stimulation intensity, maybe gain and even filter settings and reference values (Fig. 12). The referring clinician, on the other hand, should be able to extract the main findings without an in-depth knowledge of neurophysiology. For him, a graphic report with only the essential findings may be preferable and give a quick view of the results (Fig. 13).

MOTOR NERVES:		dLat	SD	dAmp	SD	CV	SD	F-M	SD	Amp%	SD
Right Medianus											
Wrist - Ab Elb		5.2	5.4	11.6	0.6	57.4	0.3	20.8	0.2	-7	0.1
Left Medianus											
Wrist - Ab Elb		3.9	1.5	12.6	1.0	57.6	0.3	21.7	1.1	-2	0.5
Right Ulnaris											
Wrist - Bel Elb		3.0	0.3	10.3	-0.6	57.4		20.6	-0.0	-6	
Bel Elb - Ab Elb		5.7		9.7		62.5	15.5			-1	-18.8
Left Ulnaris											
Wrist - Bel Elb		2.7	-0.7	8.6	-1.3	62.5		21.7	0.9	-7	
Bel Elb - Ab Elb		5.5		8.0		50.0	3.0			-3	-21.0
SENSORY NERVES:		^a Lat	SD	Amp	SD	CV	SD				
Right Medianus											
Palm - Wrist		2.9	5.9	43		—					
Dig II - Wrist		4.3	3.1	13		—					
Dig III - Wrist		4.6	4.0	6.3		—					
Left Medianus											
Palm - Wrist		2.5	3.6	42		—					
Dig II - Wrist		3.7	1.8	14		—					
Dig III - Wrist		3.9	2.5	10		—					
Right Ulnaris											
Palm - Wrist		1.6	-1.7	37		—					
Dig IV - Wrist		2.8	-0.0	9.4		—					
Dig V - Wrist		2.6	-0.4	12		—					
Left Ulnaris											
Palm - Wrist		2.0	0.6	16		—					
Dig IV - Wrist		3.1	0.5	4.4		—					
Dig V - Wrist		2.8	0.1	6.6		—					

Fig. 12. A complete report for internal use contains all the relevant numbers and the Z-score distance from the expected mean of the reference values (SD).

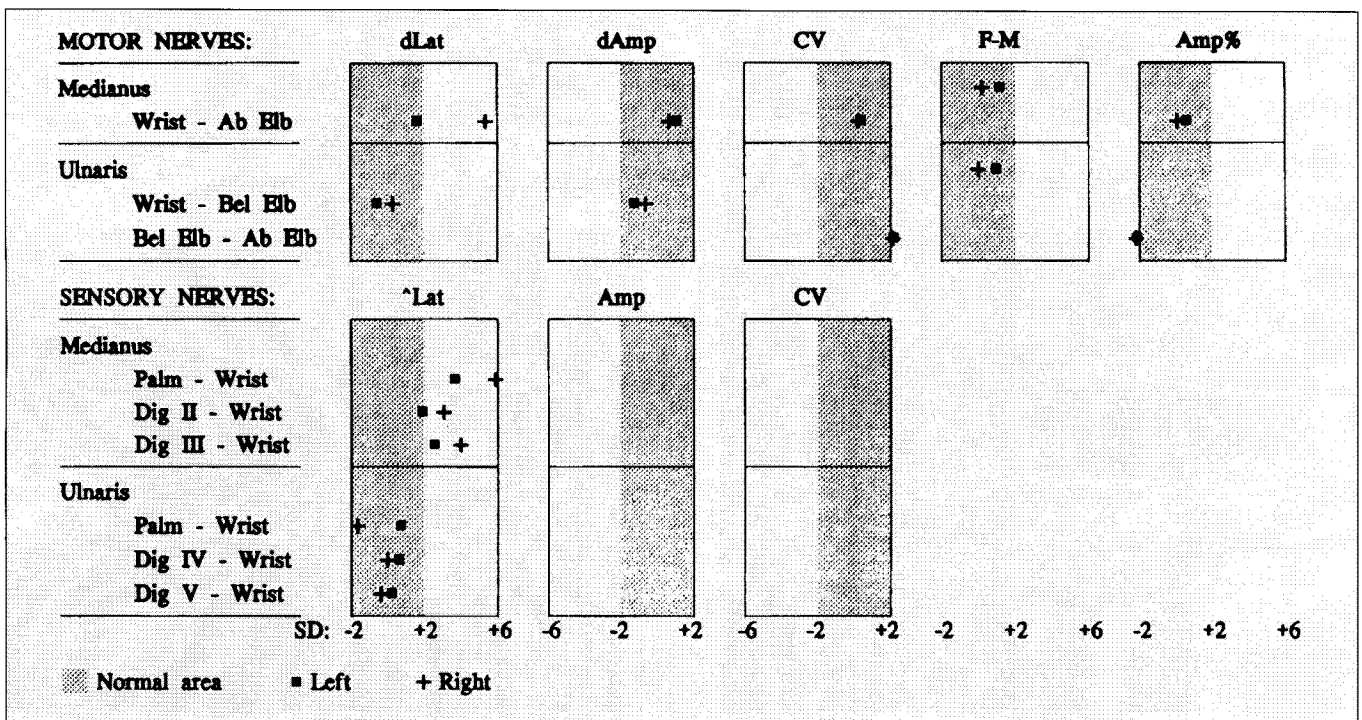


Fig. 13. A graphic report for the referring clinician contains the Z-score distance from the expected mean values. The right side is indicated by + and the left side by ■. The normal range is shaded and the abnormal area (2 SD outside) is not shaded.

Methods for Motor Nerve Conduction Studies

N. MEDIANUS (Fig. 14)

Position of limb: patient supine, sitting or reclining. Elbow extended or slightly flexed, forearm supinated (palm of the hand facing upwards), wrist in a neutral position. Fingers in a neutral, relaxed position, slightly flexed.

Type of recording electrodes: surface electrodes.

Placement of recording electrode: at the midpoint of a line drawn from the first metacarpophalangeal joint and the insertion of the tendon of m. flexor carpi radialis.

Placement of reference electrode: at the distal interphalangeal joint.

Stimulation sites:

1. Palm
2. Wrist, 80 mm proximal to the recording electrode (measured obliquely, along the course of the nerve)
3. Elbow
4. Upper arm
5. Supraclavicular region

Anomalies: the Martin - Gruber anomaly occurs in 15% of normal subjects. If a Martin - Gruber anomaly is present, special techniques are required to measure the conduction velocity.

N. MEDIANUS, H reflex

Position of limb: patient supine, sitting or reclining. Elbow extended or slightly flexed, forearm supinated.

Type of recording electrodes: surface electrodes.

Placement of recording electrode: over m. flexor carpi radialis 6-8 cm distal to the medial epicondyle.

Placement of reference electrode: over the lateral epicondyle.

Stimulation site: elbow.

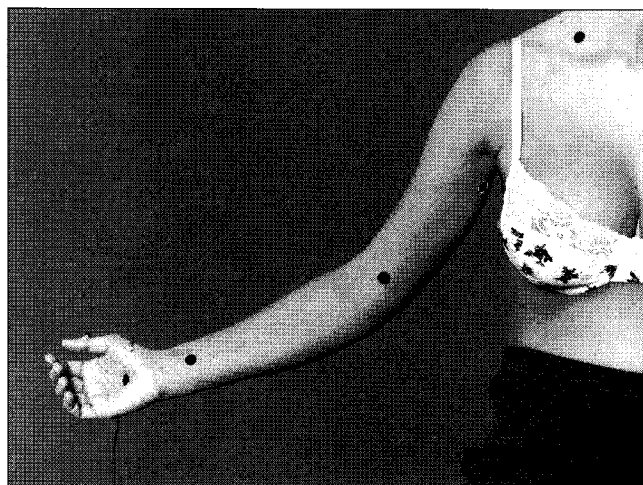


Fig. 14. N. medianus. Stimulation sites are indicated by large black dots. See text for details.

N. INTEROSSEUS ANTERIOR

Position of limb: patient supine, sitting or reclining. Elbow extended or slightly flexed, forearm midway between supination and pronation (thumb pointing upwards).

Type of recording electrodes: concentric needle.

Position of recording electrode: m. pronator quadratus. Needle inserted between the ulnar and radial bones from the dorsal side of the forearm 2-3 cm proximal to the radial styloid process.

Stimulation site: elbow.

Note: Only the conduction time is measured.

N. ULNARIS (Fig. 15)

Position of limb: patient supine, sitting or reclining. Elbow slightly flexed (15° - 30°). The forearm is rotated outwards, the palm faces upwards. The fingers are relaxed in a neutral position, slightly flexed.

Type of recording electrodes: surface electrodes.

Position of recording electrode: at the midpoint of a line between the fifth metacarpophalangeal joint and the piriform bone.

Position of reference electrode: on the middle phalanx of digit V.

Stimulation sites:

1. Wrist, 80 mm proximal to the recording electrode
2. Middle of forearm. Below elbow, around 10 mm distal to the medial epicondylus
4. Above elbow, around 90-120 mm proximal to medial epicondylus
5. Axilla
6. Supraclavicular region

Anomalies: Martin - Gruber anomaly.

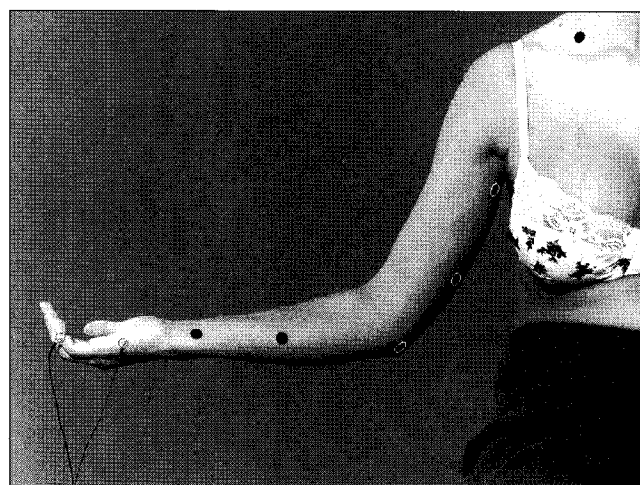


Fig. 15. N. ulnaris. Stimulation sites are indicated by large black dots. See text for details.

N. RADIALIS (Fig. 16)

Position of limb: patient supine, sitting or reclining. Elbow extended, palm facing downwards.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over the middle of m. extensor indicis proprii.

Position of reference electrode: over the fifth metacarpal bone.

Stimulation sites:

1. Forearm. At the junction of the proximal and middle third of the forearm, in the groove between m. extensor digitorum communis and m. extensor carpi ulnaris
2. Elbow, between the tendon of m. biceps brachii and m. brachioradialis.
3. Upper arm, in the radial groove
4. Axilla (not shown in Fig. 16)
5. Supraclavicular region

Note: It may be necessary to use needle stimulation electrodes in the forearm and elbow. At these points, the nerve is located beneath muscles and may be difficult to stimulate. Calipers should be used to measure the distance in the segment from the elbow to the forearm.

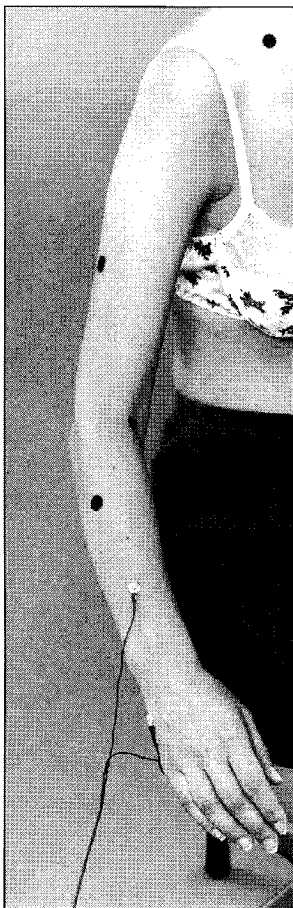


Fig. 16. *N. radialis*. Stimulation sites are indicated by large black dots. See text for details.

N. MUSCULOCUTANEUS

Position of limb: patient supine, sitting or reclining.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over the middle of the belly of the long head of the brachial biceps muscle.

Position of reference electrode: over the lateral epicondylus.

Stimulation sites:

- (1. Axilla, just above the tendon of m. latissimus dorsi)
2. Supraclavicular region

Measurement of distance: distance should be measured with calipers.

N. AXILLARIS (Fig. 17)

Position of limb: patient supine, sitting or reclining. Elbow extended and forearm supinated.

Type of recording electrodes: surface electrodes.

Position of recording electrode: in the middle of the lateral side of m. deltoideus.

Position of reference electrode: in the lower third of the upper arm.

Stimulation sites:

1. Supraclavicular region

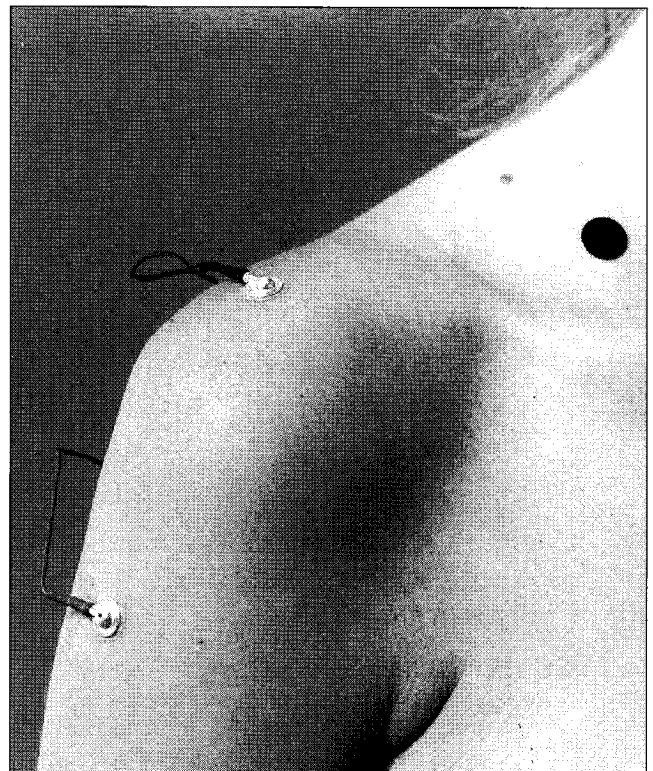


Fig. 17. *N. axillaris*. Stimulation site is indicated by a large black dot. See text for details.

N. SUPRASCAPULARIS

Position of patient and limb: patient prone, arm alongside the trunk.

Type of recording electrodes: needle or surface electrodes.

Type of stimulating electrodes: needle or surface electrodes.

Position of recording electrode: m. infraspinatus.

Stimulation sites:

- [1. Below the scapular spine (needle electrodes required)]
- [2. Just distal to incisura scapulae (needle electrodes required)]
3. Supraclavicular region

N. THORACICUS LONGUS (Fig. 18)

Position of limb: patient prone, sitting or reclining. Arm abducted 90 degrees.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over m. serratus anterior in the midaxillary line over the sixth or seventh rib.

Position of reference electrode: over the sixth or seventh rib in the mamillary line.

Stimulation sites: supraclavicular region.

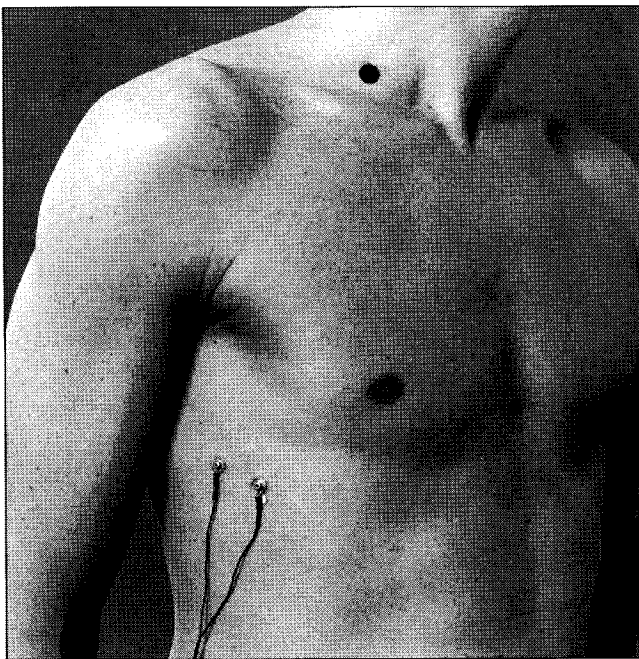


Fig. 18. *N. thoracicus longus*. Stimulation site is indicated by a large black dot. See text for details.

N. THORACODORSALIS

Position of limb: patient prone, sitting or reclining.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over m. latissimus dorsi in the posterior midaxillary line.

Position of reference electrode: over the sixth or seventh rib in the midaxillary line.

Stimulation sites: supraclavicular region.

N. DORSALIS SCAPULAE

Position of limb: patient prone, sitting or reclining.

Type of recording electrodes: needle or surface electrodes.

Position of recording electrode: over m. rhomboideus medial to the scapula at the level of spina scapulae.

Position of reference electrode: over the scapula.

Stimulation sites: supraclavicular region.

N. PHRENICUS (Fig. 19)

Position of patient: patient supine, sitting or reclining.

Type of recording electrodes: surface electrodes.

Position of recording electrode: in the 8th intercostal interspace in the anterior axillary line.

Position of reference electrode: over the xiphoid process.

Stimulation site: the phrenic nerve is stimulated percutaneously at the posterior border of m. sternocleidomastoideus, at the lower border of the thyroid cartilage.

Note: Stimulation should be performed during expiration.

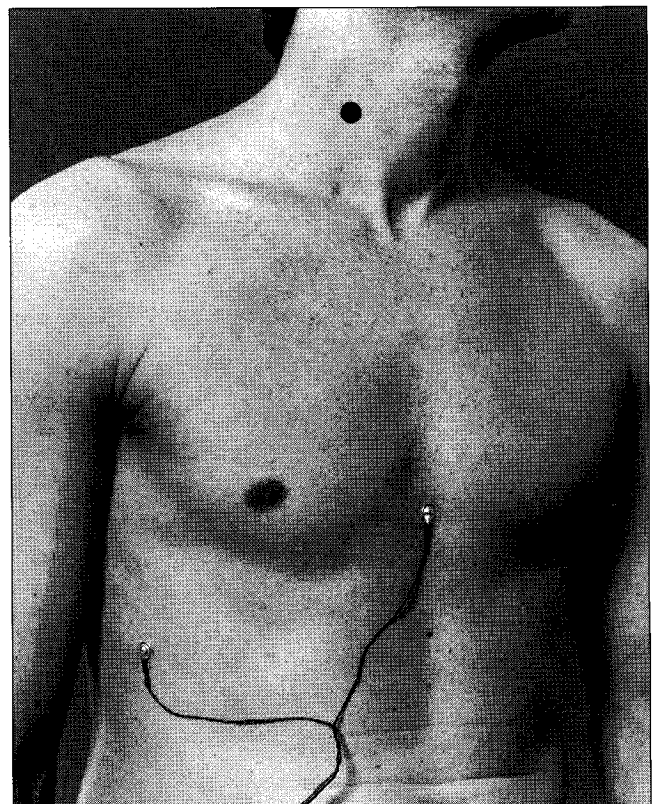


Fig. 19. *N. phrenicus*. Stimulation site is indicated by a large black dot. See text for details.

N. ACCESSORIUS (Fig. 20)

Position of patient: patient supine, sitting or reclining. Head turned 45 degrees to the side contralateral to the measurement.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over the upper part of m. trapezius, at the junction of the middle and lateral third of the upper border of the muscle.

Position of reference electrode: over the acromio-clavicular joint.

Stimulation sites:

1. At the base of the skull immediately in front of the insertion of m. sternocleidomastoideus
2. Posterior triangle of the neck, behind m. sternocleidomastoideus

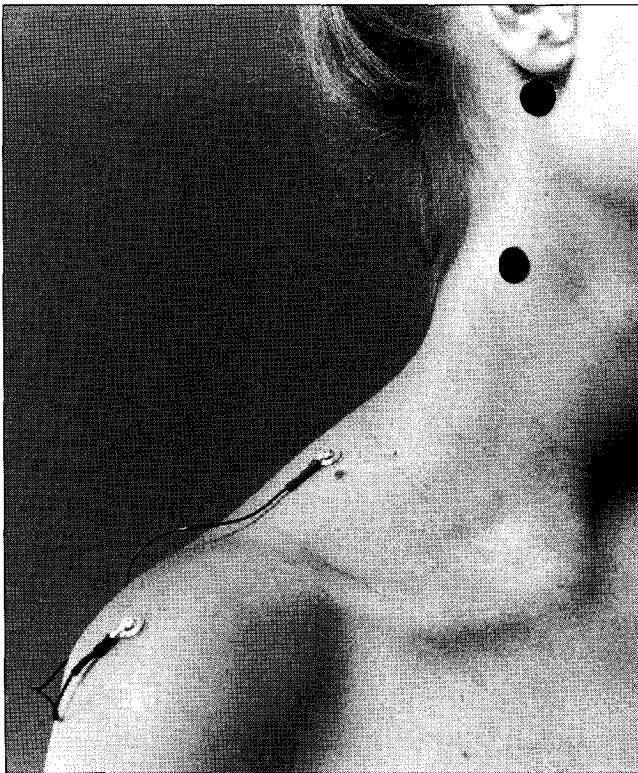


Fig. 20. *N. accessorius*. Stimulation sites are indicated by a large black dot.

N. FACIALIS (Fig. 21)

Position of patient: supine, sitting or reclining.

Type of recording electrodes: surface electrodes.

Position of recording electrode: depends on the branch of the facial nerve studied.

1. R. temporalis: m. frontalis, 20 mm above the eye
2. R. zygomaticus: m. nasalis, below the canthus of the eye
3. R. buccalis: m. orbicularis oris, on the lateral side of the lip
4. R. mandibularis: m. depressor anguli oris, 20 mm above the margin of the mandible
5. R. cervicalis: m. platysma (not shown)

Position of reference electrode: on tip of nose.

Stimulation sites: immediately below and anterior to the pinna of the ear. The individual branches may be stimulated more distally if necessary.

Anomalies: the branching of the facial nerve is highly variable.



Fig. 21. *N. facialis*. See text for details.

N. HYPOGLOSSUS

Position of patient: supine, sitting or reclining.

Type of recording electrodes: surface electrodes.

Position of recording electrode: below the chin, overlying m. genioglossus.

Position of reference electrode: over the same muscle on the contralateral side.

Stimulation sites: the posterior angle of the mandible.

N. PERONEUS PROFUNDUS (Fig. 22)

Position of limb: patient supine, sitting or reclining. The ankle joint in a relaxed, neutral position.

Recording electrodes: surface electrodes.

Position of recording electrode: in the middle of m. extensor digitorum brevis.

Position of reference electrode: at the fifth metatarsophalangeal joint.

Stimulation sites:

1. Ankle, 80 mm proximal to the recording electrode, lateral to the tendon of m. tibialis anterior
2. Below the knee, 20-50 mm distal to the proximal part of caput fibulae
3. Above the knee, 50-90 mm above caput fibulae, medial to the tendon of m. biceps femoris

Anomalies: m. extensor digitorum brevis is innervated by n. peroneus profundus alone in most subjects. In some subjects, there may be an accessory branch from n. peroneus superficialis to m. extensor digitorum brevis.

Note: The distance in the segment across the knee should be at least 100 mm.

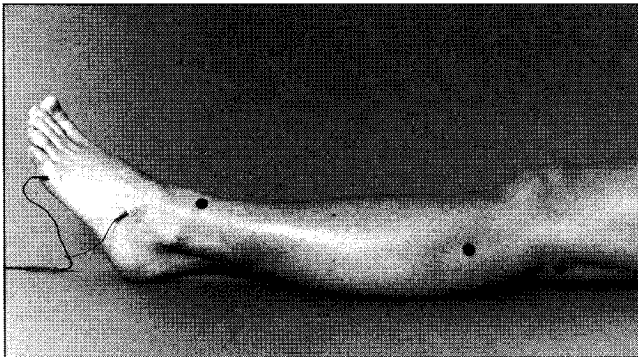


Fig. 22. *N. peroneus profundus*. Stimulation sites are indicated by large black dots.

N. PERONEUS SUPERFICIALIS

Position of patient and limb: patient supine, sitting or reclining. Leg extended.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over the belly of m. peroneus longus

Position of reference electrode: lateral malleolus.

Stimulation sites:

1. Below the knee, 20-50 mm distal to the proximal part of caput fibulae.
2. Above the knee, 50-90 mm above caput fibulae, medial to the tendon of m. biceps femoris

Note: The distance of the segment across the knee should be at least 100 mm.

N. PUDENDUS (Fig. 23)

Position of patient and limb: patient supine, preferably on a gynaecological examination table.

Type of recording and stimulating electrodes: special electrode mounted over a glove on the forefinger. At the tip is a pair of stimulating electrodes, at the base a pair of recording electrodes (St Mark's pudendal electrode, DANTEC 13L40).

Position of recording electrodes: sphincter ani externus; additional electrodes may be placed in the urethral sphincter.

Position of reference electrode: sphincter ani externus.

Stimulation site: laterally over the ischial tuberosity.

Note: Only DLAT and AMPL are measured.

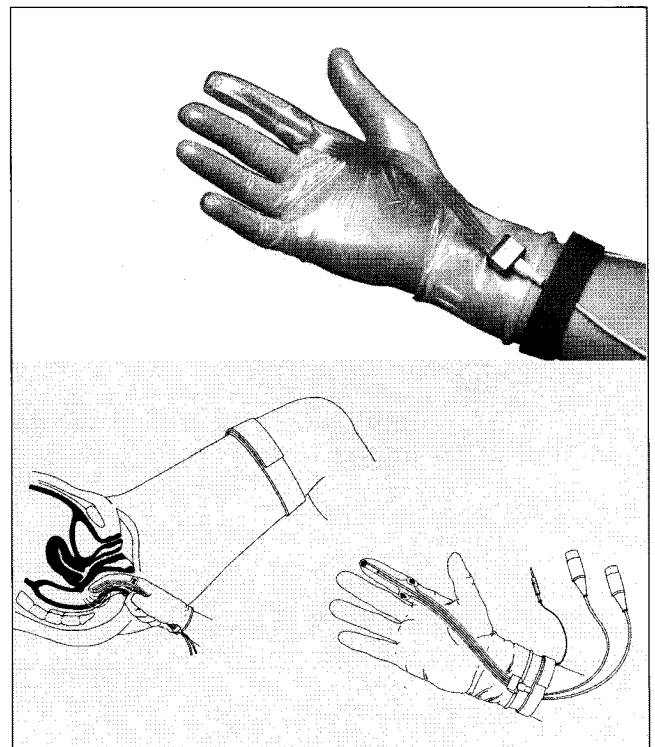


Fig. 23. *N. pudendus*. See text for details.

N. TIBIALIS (Fig. 24)

Position of patient and limb: patient prone or reclining. Legs extended.

Type of recording electrodes: surface electrodes.

Position of recording electrode: the site of the recording electrode depends on the distal branch studied:

1. *N. plantaris lateralis:* over middle of the m. abductor digiti minimi, on the lateral side of the foot
2. *N. plantaris medialis:* over the middle of m. abductor hallucis; this is 10 mm below the posterior part of the navicular bone

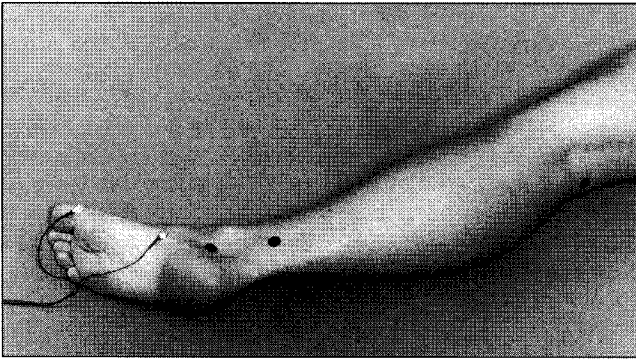


Fig. 24. *N. tibialis*. Stimulation sites are indicated by large black dots.

Position of reference electrode:

1. Over the proximal phalanx of digit V
2. Over the proximal phalanx of digit I

Stimulation sites:

1. Below medial malleolus (about 50 mm below the middle of the malleolus)
2. Above medial malleolus (about 50 mm above the middle of the malleolus)
3. Knee, in the fossa poplitea

N. TIBIALIS, H reflex (Fig. 25)

Position of patient and limb: patient prone or reclining. Legs extended.

Type of recording electrodes: surface electrodes.

Position of recording electrode: over m. soleus halfway between knee and ankle.

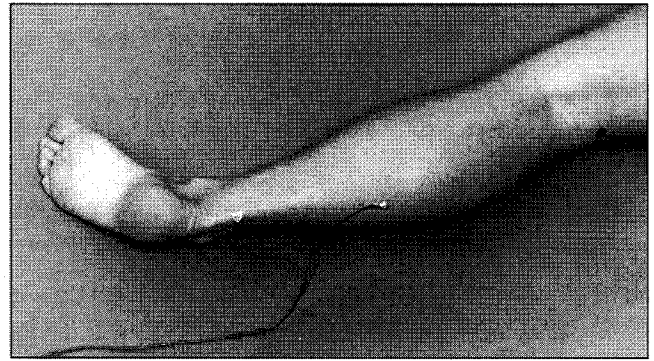


Fig. 25. *N. tibialis*, H reflex. See text for details.

Position of reference electrode: over the Achilles tendon.

Stimulation sites: knee, in the fossa poplitea.

N. FEMORALIS

Position of patient and limb: patient supine, sitting or reclining. Hip and knee extended.

Type of recording electrodes: surface electrodes.

Position of recording electrode: electrode is placed over m. vastus medialis.

Position of reference electrode: below the medial epicondylus of the knee.

Stimulation site: surface or needle electrode below the inguinal ligament.

Note: Only the conduction time from the inguinal ligament to m. vastus medialis is measured. Conduction velocity cannot be calculated.

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Appendix: Reference Values for Motor Nerve Conduction Velocities

Nerve	constant	age	height	SD	R2
Median motor elbow – wrist					
CV	66.22	-0.09	-0.03	3.39	0.10
DL	0.61	0.007	0.016	0.33	0.17
lnAMPL	1.13	-0.002	-0.0005	0.14	0.04
DECAY	-5.68	-0.74	0.009	11.73	0.01
FLAT	-5.46	0.04	0.16	1.06	0.06
Ulnar motor below elbow – wrist					
CV	75.93	-0.08	-0.08	4.67	0.06
DL	0.36	0.005	0.015	0.32	0.16
lnAMPL	1.25	-0.001	-0.0009	0.96	0.03
DECAY	1.13	-0.09	-0.03	8.83	0.02
FLAT	-9.67	0.04	0.184	1.21	0.61
Tibial nerve knee – ankle					
CV	90.15	-0.11	-0.22	3.99	0.26
DL	-0.91	0.001	0.03	0.73	0.16
lnAMPL	1.57	-0.007	-0.001	0.16	0.29
FLAT	-14.45	0.09	0.32	2.41	0.62
Peroneal nerve below knee – ankle					
CV	102.59	-0.13	-0.29	3.40	0.42
DL	2.51	-0.001	0.01	0.69	0.03
lnAMPL	0.23	-0.003	0.003	0.20	0.08
DECAY	8.92	-0.004	-0.10	17.34	0.00
FLAT	-17.71	0.07	0.34	2.41	0.63

The reference values are given in a multiple linear regression equation, which defines the expected mean reference value for a given age and height and which has the general format:

$$Y = \text{constant} + \text{age} \times X_1 + \text{height} \times X_2,$$

Age is in years and height in centimetres (cm);
SD gives the standard deviation.

The Z-score (the distance of the measured value from the expected mean) is calculated as follows:

$$Z = (Y - \text{measured value}) / \text{SD}$$

For instance, in a 40-year-old man who is 180 cm, the measured median nerve CV is 48 m/s. The Z-score of this value is calculated as follows:

$$\text{Expected value} = 66.22 - 0.09 \times 40 - 0.03 \times 180 = 57.22$$

$$Z = (57.22 - 48) / 3.39 = 2.72$$

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