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The motor nerve simulator

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Abstract

Objective: The aim of the study was to develop a mathematical model of the motor nerve and the action potentials generated from its axons, in order to simulate conditions seen in neurography. The model should be used for the detailed study of the relationship between various nerve characteristics and the electrophysiological recordings obtained.

Methods: The model was developed as a software tool. The signals from individual motor units were real recordings using conventional surface electrodes. There was good agreement between the constructed compound muscle action potential and the one recorded live for the subject from whom the individual signals were obtained.

Result: A number of physiological characteristics can be changed, including the number of axons, their conduction properties, excitability properties, degree of proximo-distal velocity slowing. F-waves and A-waves can be generated.

Conclusion: The model gives a good similarity to findings obtained in live recordings. A number of physiological characteristics can be studied individually, something that cannot be done in live recordings. The model can be used in teaching and in research studies of the relationship between nerve properties and neurography parameters. © 2001 Published by Elsevier Science Ireland Ltd.

Keywords: Simulation; Nerve-muscle disease; Neurography; Conduction block; Excitability; Neuropathy

1. Background

The myelinated nerve axon conducts impulses in a saltatory fashion with depolarization at the nodes (Tasaki and Takeuchi, 1942). The currents are prevented from penetrating the membrane between the nodes in the normal nerve due to an isolating myelin sheath. This means that the impulse propagation is much faster compared with continuous depolarization. The conduction velocity is also dependent on the axonal diameter and the properties of the membrane (Waxman, 1977). A normal axon conducts with a speed of 35–60 m/s (Rosenfalck and Rosenfalck, 1975). The velocity is reduced if the myelin is defective due to pathological changes; if the ion-channels at the nodal areas are blocked; or if the axon diameter is smaller than normal. Velocity is also positively dependent on temperature.

Once the correlation between neurophysiological and morphological characteristics was established, the nerve conduction study became an important method used in clinical routines (Hodes et al., 1948; Gilliatt and Thomas, 1960; Lambert, 1962). Such studies have been performed in most electromyography (EMG) laboratories since the 1960's and since then have become more sophisticated, sensitive and specific.

The aim of our effort is to:

- Simulate a motor nerve conduction study as closely as possible, based on available information;
- Determine the effect on the evoked response after changing the stimulation and nerve characteristics;
- Study the relationship between anatomical and physiological nerve characteristics that cannot easily be investigated in live recordings; and
- Develop a teaching tool for motor nerve conduction studies.

This work is a presentation of the model and of the first results obtained with this method.

2. Procedures for motor conduction studies

The procedures for nerve conduction studies are standardized, and the principles for motor conduction studies (MCS) used in our laboratory, have been summarized elsewhere (Falck and Stålberg, 1995). Most of these are relatively similar for all neurophysiological laboratories worldwide. Standard measurements will not be summarized here

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but the reader is referred to the literature. Parameters that are quantified are indicated in Fig. 1. Calculations, briefly summarized below, are made from the measured values.

2.1. Calculated parameters

2.1.1. Conduction velocity

The conduction velocity (CV) is calculated by dividing the length of the nerve segment between the two stimulation points by the difference between the proximal and distal latency (Falck and Stålberg, 1995).

$$\text{CV (m/s)} = \text{distance (mm)}/(\text{LAT}_{\text{prox}} - \text{LAT}_{\text{distal}}) \text{ (ms)}$$

The calculated motor conduction velocity reflects the fastest motor axons when the latency is measured to the onset of the compound muscle action potential (CMAP).

2.1.2. Temporal dispersion

Since nerve fibres have different conduction velocities, a longer conduction distance (using a more proximal stimulation site) will give an increased duration of CMAP. The change in duration with a proximal stimulation site is called temporal dispersion and is calculated as follows:

$$\text{DISPERSION} = 100 \times (\text{DUR}_{\text{prox}} - \text{DUR}_{\text{distal}})/\text{DUR}_{\text{distal}}$$

In healthy subjects, the maximum dispersion in the ulnar nerve between elbow and wrist is 10–15% (Lewis and Sumner, 1982; Brown and Feasby, 1984; Olney et al., 1987). In long nerve segments the CV may be lower and the dispersion higher than that seen in short segments (Taylor, 1993).

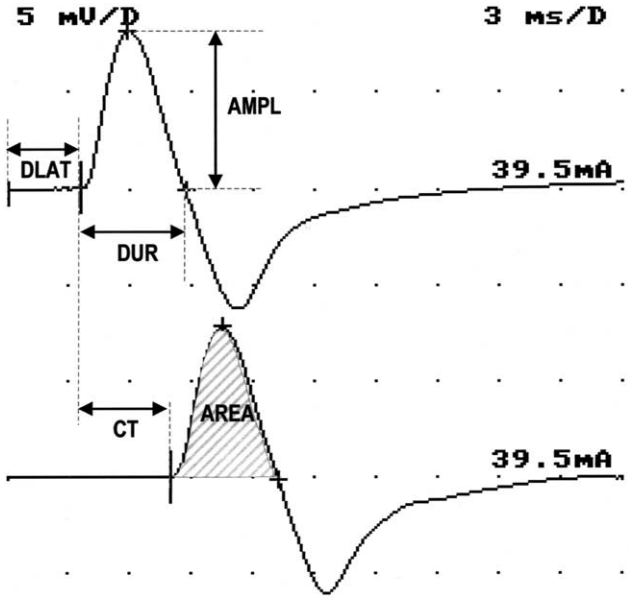

Fig. 1. Live recordings showing nerve conduction study of median nerve in a healthy subject. Measured parameters of the CMAP are indicated. Distal (trace 1) and proximal (trace 2) stimulations are shown. Latency difference measured to take-off for the two, conduction time (CT), is used for calculating conduction velocity.

2.1.3. Physiological amplitude and area decay

With proximal stimulation, when the duration of the CMAP gets longer due to the temporal dispersion, the amplitude and the area of the CMAP changes.

DECAY is calculated as shown in these formulas:

$$\text{AMPLDECAY} = 100 \times (\text{AMPL}_{\text{distal}} - \text{AMPL}_{\text{prox}})/\text{AMPL}_{\text{distal}}$$

$$\text{AREADECAY} = 100 \times (\text{AREA}_{\text{distal}} - \text{AREA}_{\text{prox}})/\text{AREA}_{\text{distal}}$$

In healthy subjects, the mean value of the AMPLDECAY is 4.5–6.2% in the ulnar nerve (Olney et al., 1987; Taylor, 1993) and 5.6–7.7% in the median nerve (Falck et al., 1992).

2.1.4. Definitions of motor conduction block

One of the abnormal findings in nerve conduction studies concerns the presence of impulse conduction block (CB). A conduction block is the failure of an action potential to propagate throughout the length of a structurally intact axon.

There have been several attempts to define criteria for conduction block (Cornblath et al., 1991). To discriminate between ‘pure’ demyelination and a conduction block, the following criteria has been suggested (ad hoc Subcommittee of the American Academy of Neurology AIDS Task Force 1991):

Conduction block is present if there is:

>20% AMPLDECAY or AREADECAY and <15% DISPERSION or if there is

>50% AMPLDECAY or AREADECAY, independent of DISPERSION.

It has been (Lange et al., 1992) demonstrated that both these criteria are equally sensitive in detecting CB.

Our own modifications of these rules are:

>25% (arm nerves) or >40% (leg nerves) AMPLDECAY and <15% DISPERSION or if there is

>50% AMPLDECAY, independent of DISPERSION (in this case there is a combination of CB and demyelination). By using this model, it will be possible to study the validity of this definition.

The other finding which indicates CB is the frequency of occurrence of F-waves (persistence). In cases of proximal CB, there may be no drop in amplitude in the distal part of the nerve, but a reduction in the occurrence of F-waves. The normal frequency of F-waves varies for different motor nerves.

The number of F-responses should always be reduced when conventional MCS has shown a conduction block; otherwise a technical error should be suspected.

2.2. Other motor parameters

2.2.1. F-waves

When the motor nerve is stimulated, nerve action potentials propagate both in the distal direction to evoke a muscle response, and in the proximal direction as a non-physiological event. Occasionally, depolarization of the motor neurons may evoke a recurrent response by stimulating the first node distal to the neurons. There is only a small chance that the timing of the depolarization/repolarization will allow this to happen. Normally a recurrent response is evoked in 0.5–5% of stimulations, with some differences between nerves and changes with pathology.

The F-waves travel from the stimulation point on the nerve to the neuron and back to the muscle. By subtracting the distal latency, the time taken from the stimulus point to the neuron and back again to the stimulus point can be obtained. This time depends on the conduction distance involved.

Since each normal nerve contains hundreds of motor axons, it is usual to obtain 5–15 different F-waves from 20 stimulations. They differ in latency and shape since they normally represent activity from different motor units. The frequency of occurrence is reduced when there is a conduction block anywhere along the nerve. F-wave measurements thus reflect conduction along the entire nerve and are therefore particularly useful in the study of polyneuropathies, especially those that involve more proximal nerve segments.

2.2.2. A-waves

A-waves are responses usually occurring between the CMAP and the F-wave (Fig. 2). They have a constant shape and latency and are found with most stimulations when present. In order to characterize a constant late component as an A-wave we have required a frequency of occurrence of at least 7 per 20 stimulations. In normal conditions they are sometimes seen in the tibial nerve but rarely in other nerves (Bischoff et al., 1996). They are seen in various pathological conditions but are not specific for any particular diagnosis. An A-wave may be generated as an extra discharge in the stimulated axon (intermediate double discharges, IDD) (Magistris and Roth, 1992), or be due to ephaptic transmission between two axons. They may sometimes arise as an axon reflex (which gave rise to the name of A-waves) in which case a weak stimulation activates two branches of the axon in antidromic and ortodromic direction respectively. In a proximal branching of one axon the distally initiated impulse turns in ortodromic direction to the muscle and a late response occurs (Fullerton and Gilliatt, 1965). It may also represent the response from one axon with exceptionally slow conduction velocity, which we call M-satellites.

2.3. Summary of parameters

The most common motor neurography parameters are summarized in Table 1.

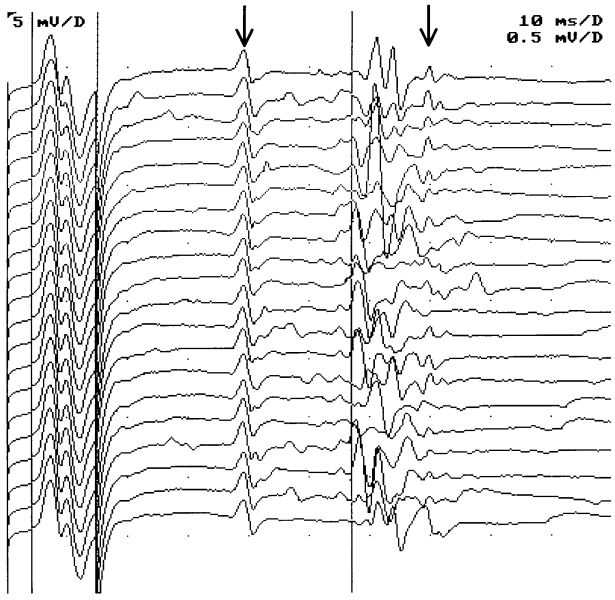

Fig. 2. Studies in tibial nerve of a patient with normal conduction velocity. F-waves to the right seen as signals of variable shape at consecutive traces. A-waves both before and after F-waves (arrows). The vertical lines indicate from left: distal M latency, position for changed amplifier gain and normal upper limit for shortest F-wave latency. The number of F-waves is normal.

3. The model

An anatomical nerve model for motor conduction studies was constructed for alpha motor axons and their muscle fibres. A similar approach was described earlier (Lee et al., 1975). A number of nerve characteristics were incorporated in the model according to the description in the next section. The default parameters are summarized in Table 2.

3.1. Anatomical characteristics

3.1.1. Number of axons

The axons are positioned randomly in a circular cross section simulating the nerve. There is no grouping of axons in fascicles, which might influence some of the detailed studies performed at submaximal stimulation. The maximal number of axons (motor units) is 300. This value is based on values obtained from estimated motor unit counts in various nerves. For reasons discussed in the Results section, a value of 85 was chosen as default. This is close to the minimal number of axons reported in estimations of number of motor units (McComas, 1995).

3.1.2. Length of axons

Axon length has importance for F-response latency and for relative conduction velocity along the nerve, which is linearly decreased in proximo-distal direction (Gilliatt and Thomas, 1960). A mean length of 750 mm was chosen as the default setting a value between an approximate length of 600 mm for adult arm nerves and 1100 for leg nerves.

Table 1
Common neuropathy parameters

Parameter	Significance	Usually measured as
CMAP		
Ampl	# Axons, synchronisation	Neg. amplitude (mV)
Area	# Axons, synchronisation	Neg. area (mV *ms)
Dur	Synchronisation	Neg. peak duration (ms)
Ampl decay	Cond. block + dispersion	% Reduction in amplitude
Dispersion	Axonal velocity dispersion	% Increase in duration
CV	Velocity of fastest axons	Latency diff/distance. (m/s)
Distal latency	Velocity of fastest axons	Time to waveform onset (ms)
F-waves		
Latency	CV of axons along entire nerve	Lat (min, mean in ms)
Dispersion	Axonal velocity dispersion	Min and max lat (ms)
Persistence	# Axons and MN excitability	# F-waves/20 stimuli
Amplitude	MUP shape + # F-waves, not often used	Peak-peak ampl (μV)
A-waves		
Presence	Abnormal excitability of axons or	
Slowly conducting axons (M satellite)	Present or not	

3.1.3. Size of axons

The mean diameter as well as the variation (which is approximated to a Gaussian distribution for alpha motor axons) can be set (Lee et al., 1975). Modification of the distribution can only be changed if the diameter of each axon is given a separate diameter value. The population under study may be restricted to a certain diameter population with upper and lower limits. A mean diameter of 9.5 μm (SD 1.3) was chosen as the default which means that most of the axon diameters were between 7 and 12 μm, a value close to 8.3–11.8 μm used by Lee et al (Lee et al., 1975).

3.2. Physiological characteristics

3.2.1. Excitability of individual axons

The excitability for stimulation is dependent on the distance to the surface of the nerve and on the axon diameter, with larger axons being more excitable than smaller individual axons. The relative diameter dependent excitability was given an arbitrary value between 0 and 10.

For a given situation, the excitability of each axon is fluctuating (membrane noise) expressed as current (in mA).

3.2.2. Conduction velocity of individual axons

The default situation was a mean axon diameter of 9.5 μm (see Results; the model) and a CV linearly dependent on axon diameter, with a linear increase in the velocity of 5.7 m/s per μm increase in diameter (see review Dumitru, 1995). The mean velocity may be decreased to simulate a generalized polyneuropathy by giving a percentile value of normal CV. This can also be done for selected populations of axons. Furthermore CV and diameter can be changed independent of each other for individual axons.

Table 2
Summary of parameters and default settings

Parameter	Range	Default settings
Anatomical parameters		
Number of axons	1–300	85
Size of axons	1–20	9.5 ± 1.3 μm
Length of axons	100–1500	750 mm
Physiological parameters		
Excitability of individual axons in relation to diameter	0–10	5 (0 = no dependence, 10 = max)
Membrane noise	0–20	± 5 mA
Mean conduction velocity for individual axons	1–200	54 ± 14 m/s
Proximal-distal relationship on conduction velocity	−99–100	−10% (slower in distal segment)
F-response probability	0–100	0.9%
Central delay for F wave	0–10	500 μs
A-waves present		No
Focal changes in conduction velocity	0–100%	No
Conduction block (% of axons)	0–100%	No
Electrode parameters		
Stimulation electrode (one distal, one proximal)		Point stim beneath the cathode
Position of electrodes	Nerve length	Dist = 80 mm, prox 300 mm
Stimulation parameters		Single stim, no dur, no anodal stim
Recording electrode (silver discs, 1 cm)		Belly-dist interphalangeal joint, fixed

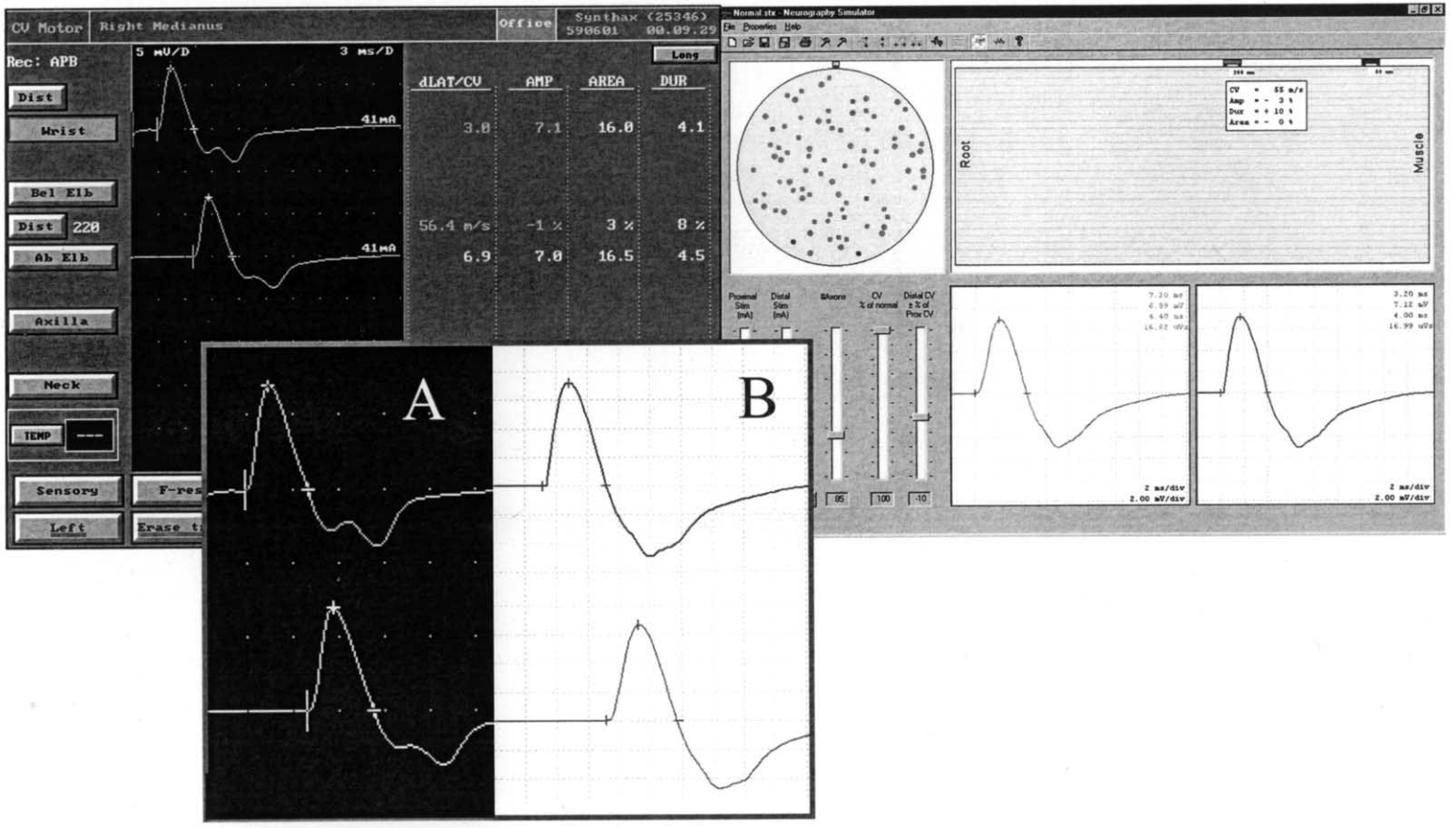

Fig. 3. Background window: CMAP from thenar muscle, left panel live recording, right display from the simulator. Foreground window: (A) live recording after maximal electrical stimulation of the median nerve and (B) constructed by summating 85 individual MUPs obtained during voluntary contraction in the same subject. There is a good agreement in shape of the negative phase. A slight difference is seen in the positive phase, possibly due to contribution from underlying muscles in the live recording.

3.2.2.1. Distal conduction velocity relative to proximal. A percentile value is given as the relationship of CV between distal and proximal segments. In the normal situation, the velocity is higher in proximal segments (Gilliatt and Thomas, 1960). In pathology, slowing is apparent either in proximal or distal segments of the nerve. It should be noted that the physiological more-pronounced terminal slowing is not included in the model.

3.2.2.2. Relationship to motor unit potential (MUP) amplitude. In the model, no relationship has been fixed between the obtained MUP amplitude and the conduction velocity. Such a relationship exists for individual motor units, but is probably completely lost when the MUP is recorded with surface electrodes. The amplitude is so dependent on the distance between the motor unit and recording electrode that the MUP amplitude often does not indicate the size of the motor unit.

3.2.3. F-responses

All axons were presumed to have an equal chance of giving rise to an F-response. This chance can be set to values between 0 and 100%, with a default of 0.9%.

A value for the delay as a result of the central turn around time at the motor neuron, can be inserted (in μs), with no relationship to axon diameter or any other nerve measure, since this is not yet known.

3.2.4. A-waves

A local hyperexcitabiliy site which produces an A-wave can be introduced for individual axons at variable distances from the muscle. An optional delay at this hyperexcitable site can be introduced depending on whether the stimulation is distal or proximal to this site. For proximal stimulation, a jump of the travelling axonal nerve signal is assumed (unpublished observation) and the 'delay' is negative.

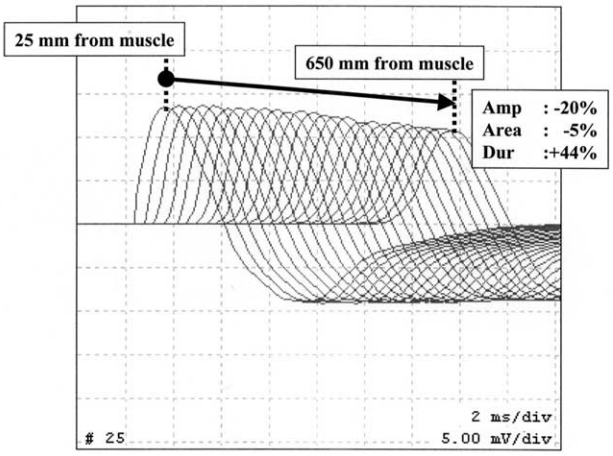

Fig. 4. CMAP with increasing stimulation distance from the muscle.

3.2.5. Focal changes

In order to simulate not only general slowing but also focal changes, the velocity can be changed for an optional length of segment, with different degrees of velocity reduction for a given population of axon diameters. If the velocity is reduced by 100%, a conduction block is simulated. By producing a conduction block at one site (over a segment of 1 mm) and a slowing in the segment just distally or proximally to this, a combined situation of partial block and demyelination can be simulated.

3.2.6. Factors not included in the model

Like most models, this model is incomplete in relation to exact anatomy and physiology. We assume that the missing details should not disallow the principle results obtained from the studies. Such characteristics not included are end-plate location; muscle fibre orientation; number of muscle fibres; territory of the motor unit; events at the stimulation point; effect of recording; and reference elec-

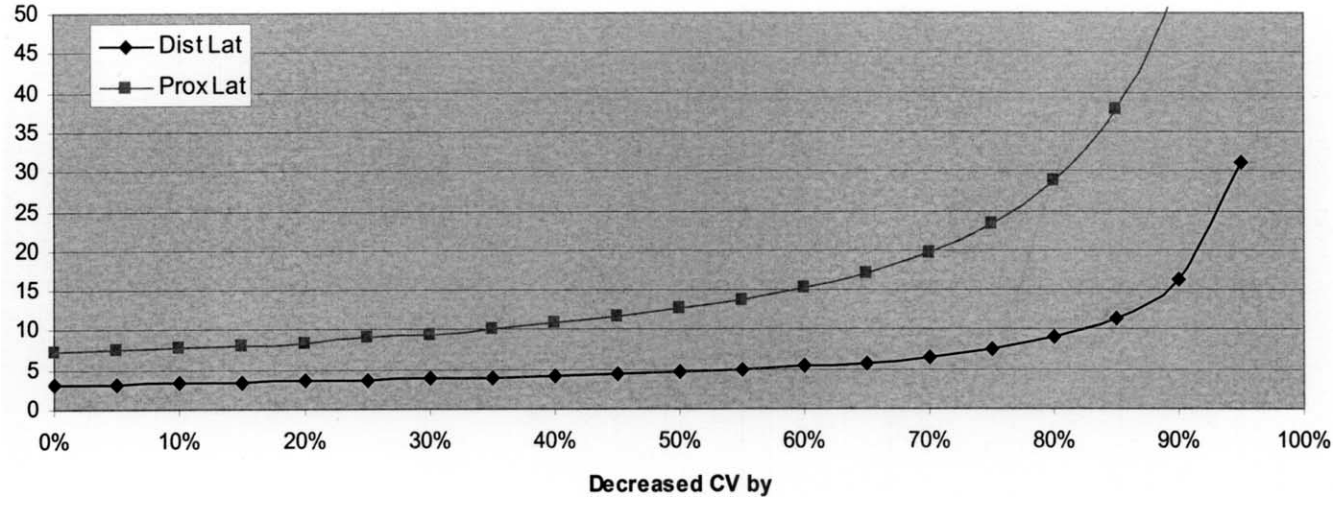

Fig. 5. Change in latency at distal and proximal stimulation sites of 80 and 300 mm with decreasing CV.

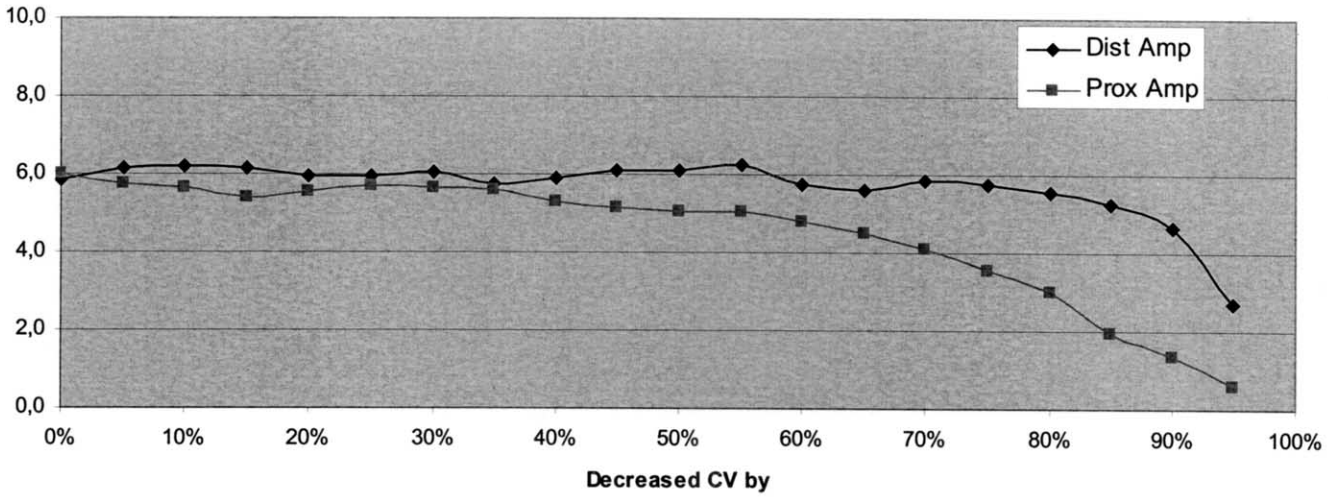

Fig. 6. Change in amplitude at distal and proximal stimulation sites (80 and 300 mm) with decreasing CV.

trode sites. For the normal median nerve, these factors are included in the model but they cannot be changed.

Stimulation is simple compared with a real situation. The stimulus is assumed to occur right beneath the stimulating cathode. No cathodal escape or anodal effect is simulated. Only single pulses can be given.

4. Results

4.1. Construction of the model

The model was constructed by summating a large number of surface recorded motor unit potentials, extracted by spike triggered averaging. In one subject, surface electrodes were positioned for optimal M-response recorded over the thenar muscle with stimulation of the median nerve. This muscle was chosen because the shape of the CMAP is usually easy to optimize and is mainly generated from one muscle. Hypothenar recordings are often more complex.

With this recording position, a single fibre EMG (SFEMG) electrode was inserted in the muscle, under the active surface electrode at different depths. During voluntary activation, individual motor unit potentials were obtained after averaging. The averaging of SFEMG triggered sweeps continued until a flat base line was seen.

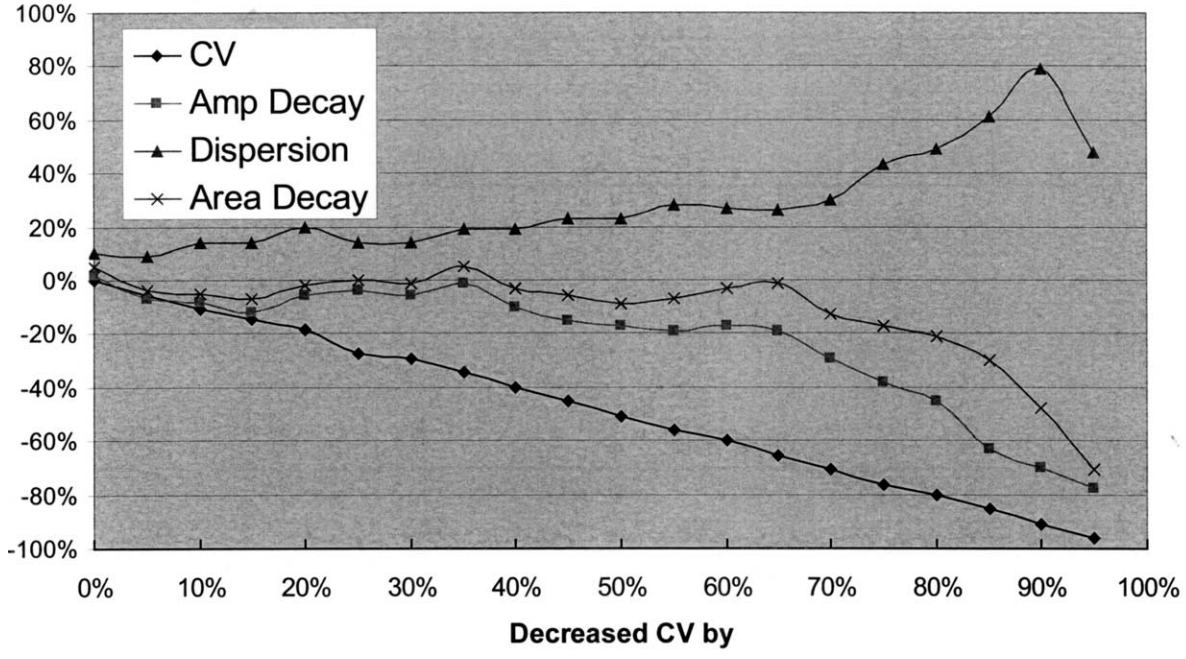

Fig. 7. Change in amplitude and area decay and temporal dispersion with reduction in CV. With very low velocities, the CMAP is polyphasic and therefore the duration value is difficult to assess properly, as seen in the curve.

The degree of contraction was in the lower range of normal, estimated at less than 30% of maximal voluntary strength.

For superficial triggering positions, the MUPs were usually of higher amplitude than for deeper triggering positions. For the deepest positions, no MUP was obtained at all with the surface electrode, with a recognition sensitivity of 5–10 μV.

Sixty different positions of the triggering SFEMG electrode were used, so that each gave different shapes of the surface signal. Up to 60 different motor units were triggered and recorded on the surface. (More positions of the triggering electrode were tested, but in some cases no response was obtained). Of the 60 MUPs with an amplitude above 5 μV, 8 were discarded due to improper quality.

A number of individual MUPs were randomly chosen by the computer from this signal library of 52 MUPs and summated (offset aligned) until the constructed CMAP was similar to that obtained at supramaximal stimulation strength. The shape and amplitude of the constructed CMAP showed good agreement to the maximal stimulation when 85 randomly chosen motor units potentials from the library of 52 were included (Fig. 3). There is a slight difference in the positive phases of the constructed and the real recorded, which may be due to contribution from underlying muscles in the live recording.

The default axon diameter 9.5 ± 1.3 μm was determined from the CV value and the shape of the CMAP obtained in the live recording from the subject. This corresponded to a conduction velocity in axons of 54 ± 14 m/s.

4.2. Proximal/distal difference in CMAP in the normal nerve

The CMAP amplitude and area decreased linearly with increasing distance between distal and proximal stimulation sites while the duration increased (Fig. 4). The effects on amplitude were greater than those on area. At a distance of 650 mm from muscle, the amplitude decreased by 20% compared to a distance of 25 mm from muscle. This still did not fulfil the criteria for CB since the duration was increased by 44%. Reflecting this, the area decreased by only 5% over the same distance.

4.3. Proximal/distal differences with general slowing of conduction velocity

Stimulation was made at 80 and 300 mm from the muscle. The velocity was reduced in all axons in steps of 5%. The CMAP measures were analyzed for different mean conduction velocities. As expected the latencies changed in an exponential way, with more pronounced changes for proximal sites of stimulation (Fig. 5). Likewise, the amplitude changed in an exponential fashion, with greater reductions for the proximal stimulation sites (Fig. 6). The amplitude and area decay, and increase in temporal dispersion, changed linearly but less than CV, until the velocity was reduced by about 80% (i.e. to 20% of the initial CV) (Fig. 7). With a CV reduction exceeding 80% the shape of the CMAP was very complex and it was not meaningful to assess amplitude or area. For a CV reduction of 50%, the decay was about 20%. At this situation the temporal dispersion was 20% and the criteria for CB were not fulfilled (Fig. 7). At 80% slowing the amplitude decay barely reached 50%, and the area decay about 30%. Thus, still the second criteria of >50% amplitude decay, independent of temporal dispersion was not fulfilled.

4.4. Effect of general or selective axonal loss

The situation of a general axonal loss was simulated for the entire range of loss from 0 to 100% (Fig. 8) The ampli-

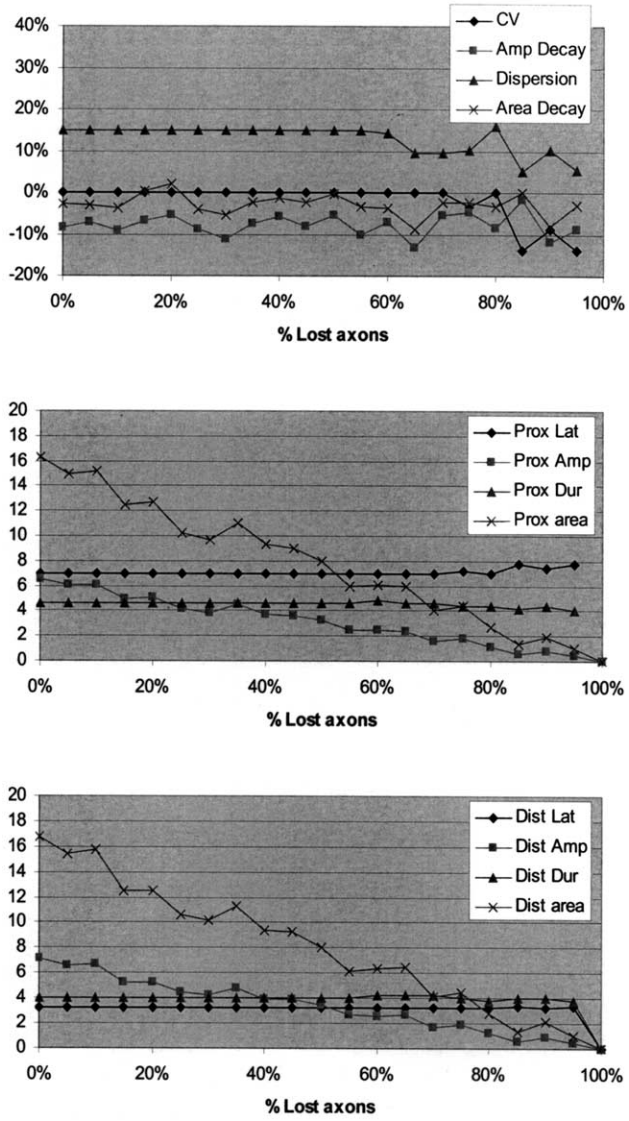

Fig. 8. Effect on neurography parameters of loss of axons of random diameters (shown in 3 panels for sake of clarity). The amplitude decreases but other parameters are relatively unchanged until extreme situations. Note that criteria for conduction block are not fulfilled. *y*-axis scale: upper panel: CV in % of normal. Middle and lower panel: amplitude in mV, latencies in ms.

tude and area fell in proportion to axonal loss. The latency values remained unchanged until more than 90% of the axons were lost, at which time they increased.

The CV was decreased when more than 80% of axons were lost. There was no significant amplitude or area decay or temporal dispersion.

With selective loss of either small or large fibres, the measurements changed quite differently. In the first case, no change was seen in amplitude until fibres larger than 8.5 μm started to disappear (Fig. 9). CV was unchanged until the amplitude was less than 1 mV, at which time the CV was difficult to measure (a slight increase is seen in Fig. 9). The normal and slight amplitude decay of −7% reduced with loss of small fibres and was nearly zero when only the largest axons were left. Dispersion also decreased with loss of the small fibres.

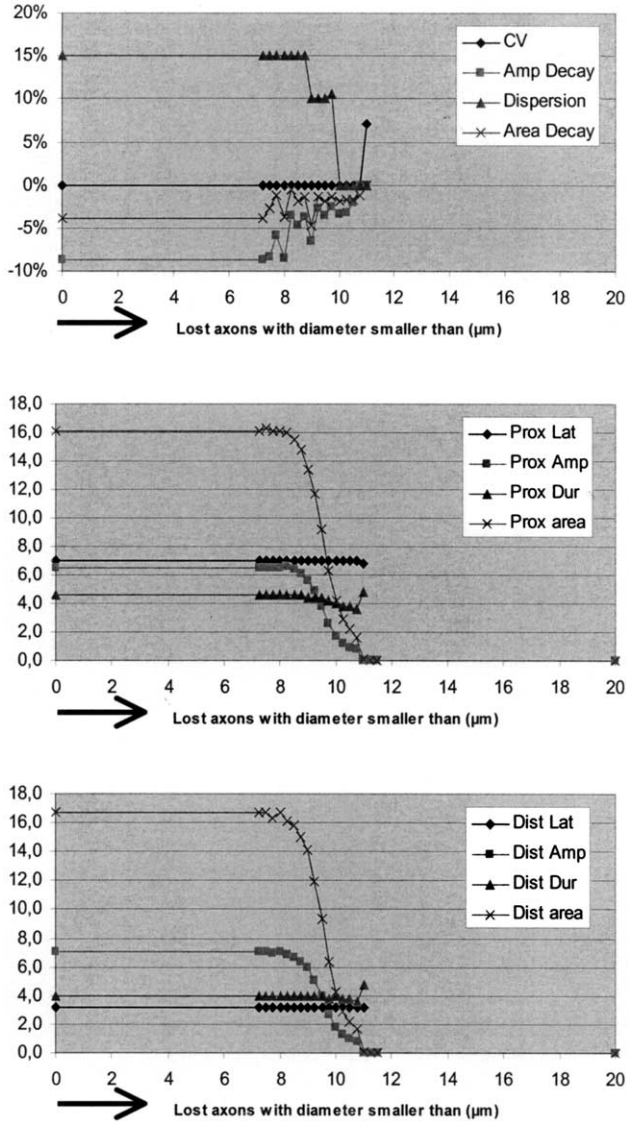

Fig. 9. Loss of axons with smallest to successively larger diameters (shown in 3 panels for sake of clarity). The velocity is mainly unchanged and the amplitude starts to decrease when diameters of 8.5 μ are involved. The criteria of conduction block are not fulfilled. *y*-axis, see Fig. 8.

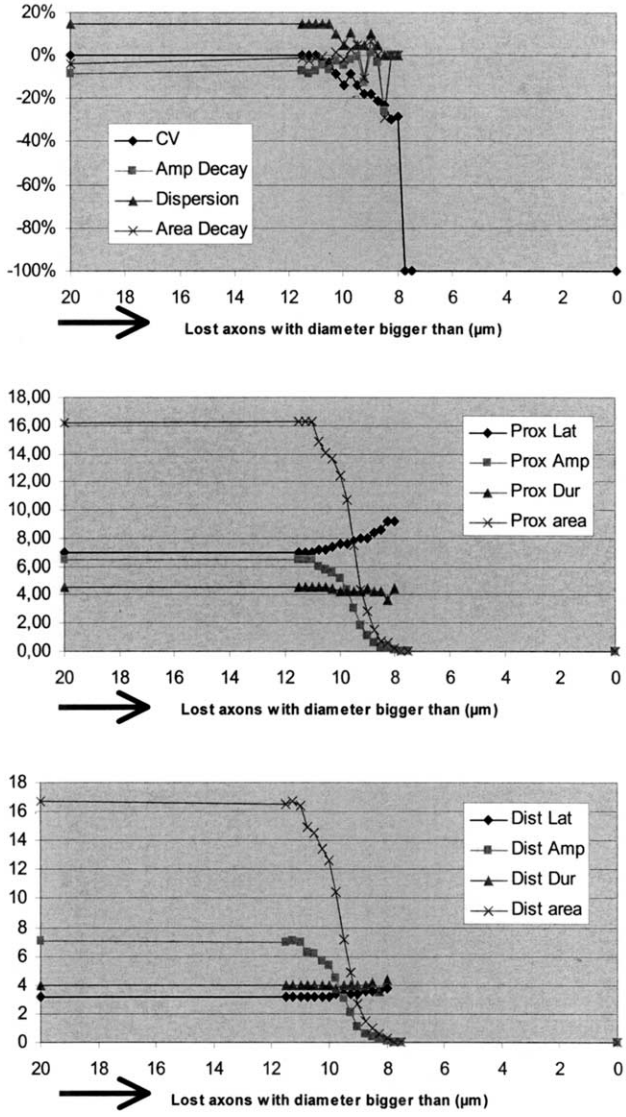

Fig. 10. Loss of axons with largest to successively smaller diameters (shown in 3 panels for sake of clarity). Conduction velocity is sensitive to loss of large fibres. The criteria of conduction block are not fulfilled. *y*-axis, see Fig. 8.

With loss of predominantly large fibres, the amplitude decreased nearly immediately with loss of the largest fibres, about 12.5 μm. Distal and particularly proximal latencies increased with any large fibre loss, and CV decreased correspondingly (Fig. 10). The dispersion did not change much with loss of large fibres.

4.5. Effect of pure focal conduction block

A focal conduction block was introduced between the distal and proximal stimulation sites, randomly affecting axons of different diameters. Three repetitions of the test were performed, with different number of axons (85, 113

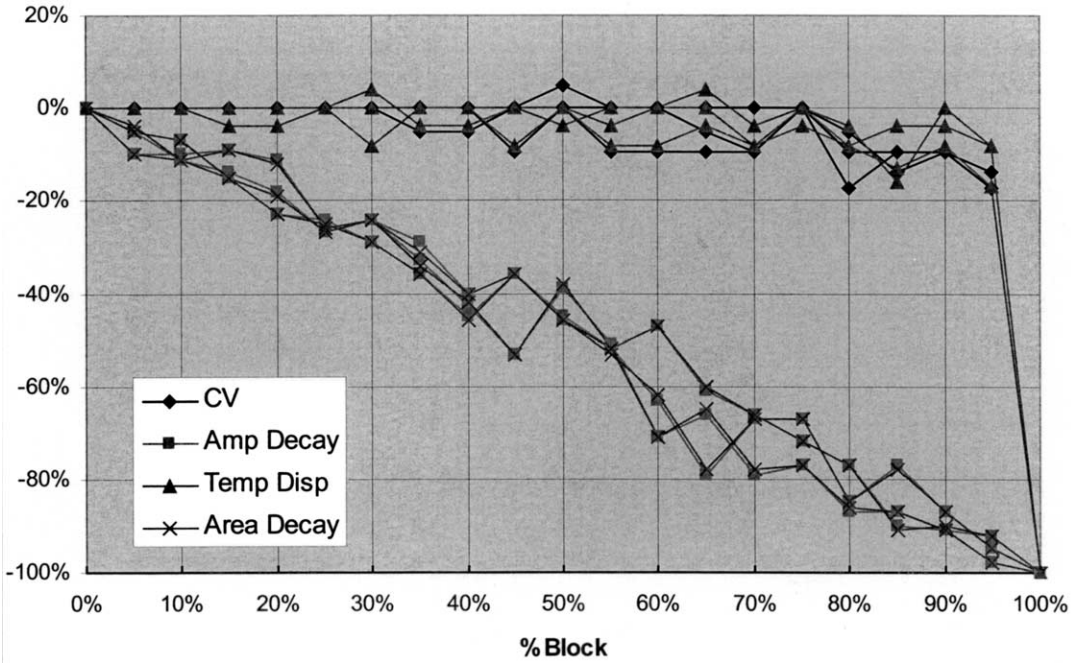

Fig. 11. Ampl decay, area decay and temp dispersion with increasing degree of conduction block. The criteria are fulfilled when about 20% of the axons are blocked. *y*-axis, CV in % of normal.

and 132) in the nerve. None of the three showed any change in latency (not presented in the figure), CV or temporal dispersion, but almost linear reductions in amplitude and area with increasing degrees of conduction block (Fig. 11). Thus, for an amplitude decay of 20%, the temporal dispersion was less than 5% and the criteria for conduction block were fulfilled.

4.6. Change in shape with selective conduction block of certain axonal diameters

When a focal conduction block was introduced between the proximal and distal stimulation site only for selected axonal diameters the results were quite different. In both experiments, the values at distal stimulation were unchanged. Latency with proximal stimulation remained unchanged with a conduction block of the smallest, slowest axons, and the larger axons. The amplitude and area started to decrease when axons larger than 8.5 μm were blocked. At this point no shortening of duration was seen, indicating that amplitude and area were equal sensitive to detect abnormalities. Criteria of conduction block were reached when fibres larger than 9.5 μm were involved. CV did not change as long as a CMAP was obtained (Fig. 12).

In another set of tests, block was introduced in the largest, and faster, axons and then smaller axons were progressively involved. Now the results were very different. The latency started to increase immediately, and significantly changed with loss of all axons larger than 11.25 μm. At this point the duration decreased slightly. When all axons larger than 10.5 μm were blocked, the amplitude started to decrease. When smaller axons were involved, the amplitude dropped further and fell to nearly zero when axons larger than 8.5 μm were blocked (Fig. 13). The CV decreased linearly with this type of axonal loss, and a clear amplitude and area decay was seen, exceeding 50% when axons larger than 9.5 μm were lost.

4.7. Centimetering across a focal lesion

In order to simulate a local conduction abnormality, two 'pure' conditions were simulated. In one, complete conduction block was introduced in 50% of the axons of random diameter. In the other, 50% slowing in conduction velocity was introduced in all axons regardless of diameter. The area of involvement was chosen as 20 mm. As seen in Fig. 14, only the conduction block produced a drop in amplitude. In the situation of local slowing, there was an increase in conduction time between consecutive stimulation points, and no drop in amplitude, other than the normal, from a longer stimulation-recording distance.

4.8. F-waves

In order to demonstrate the effect of motor neuron excitability on persistence of F-waves, two situations were compared: one with a 0.9% chance of initiating F-waves; and another with a 3.6% chance (i.e. 4 times more). As seen there was an increased number of sweeps with F-waves and also a summation of F-waves in the latter case (Fig. 15).

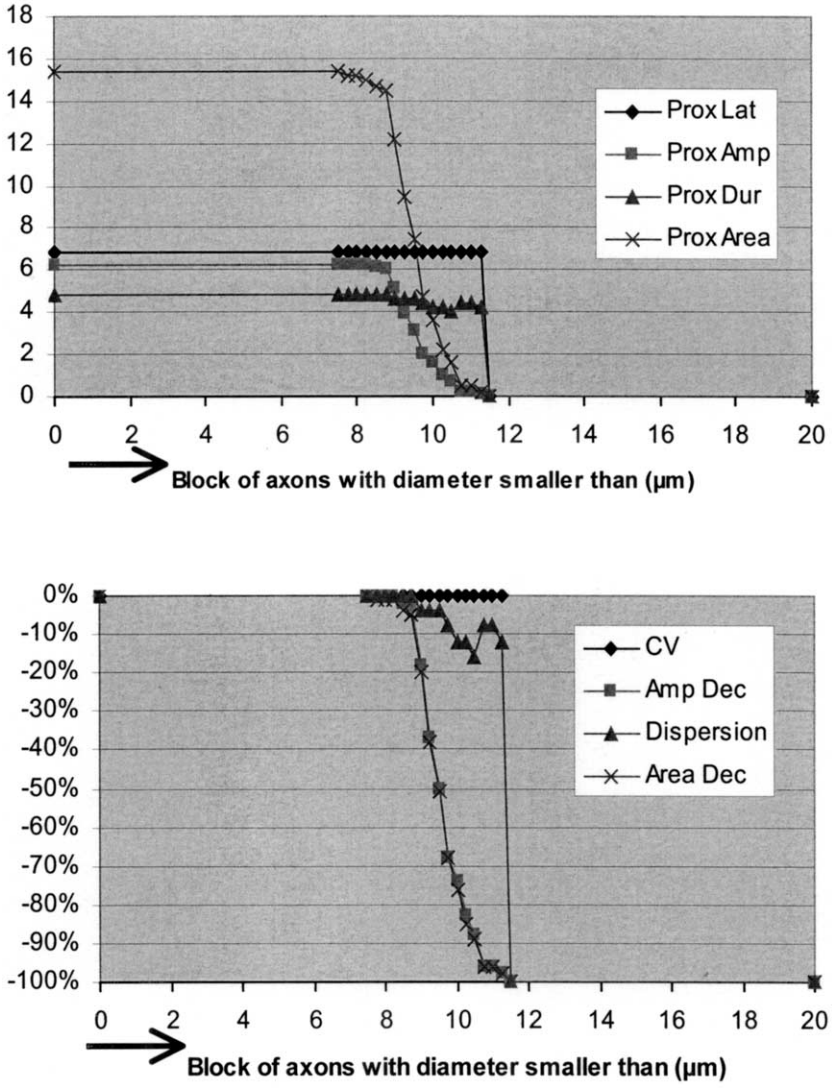

Fig. 12. Ampl decay, area decay and temp dispersion with conduction block of small and then successively larger axons. When axons larger than about 9.5 µm were involved, conduction block criteria were fulfilled.

4.9. A-waves

Local hyperexcitability for individual axons can be simulated in the model. In Fig. 16, an A-wave is generated 400 mm from the muscle in one axon. This was a constant small wave at all stimulations and had a constant latency. With proximal shift of the electrode distal to the generation site, the latency to the A-wave decreased (Fig. 16). With stimulation proximal to the generation site, an unpublished observation is a decrease in latency across the hyperexcitable site (0.5 ms default). This does not change with stimulation position proximal to the generator site.

4.10. Amplitude variation at submaximal stimulation strength

When the stimulation strength was set at different levels of submaximal strength, an amplitude variation was seen. This is due to fluctuation of axonal excitability so that a few individual axons in a certain cross section of the nerve are only activated at random stimuli depending on this variation in the excitation level. This is used as the basis for one the methods to estimate number of motor units, the so-called statistical MUNE (Daube, 1988). Our model may not be used for exact studies of this method since the largest motor units may not be represented in the generation of the model, nor is the fascicular arrangement of axons in the nerve included in the model.

However, it is quite clear that with a constant but submaximal stimulation intensity an amplitude variation was clearly seen when the excitability variation for a given axon was set to ± 5 mA but less evident with a variability of ±1 mA (Fig. 17). When only a few axons were preserved in the entire nerve, even much fewer participated in the

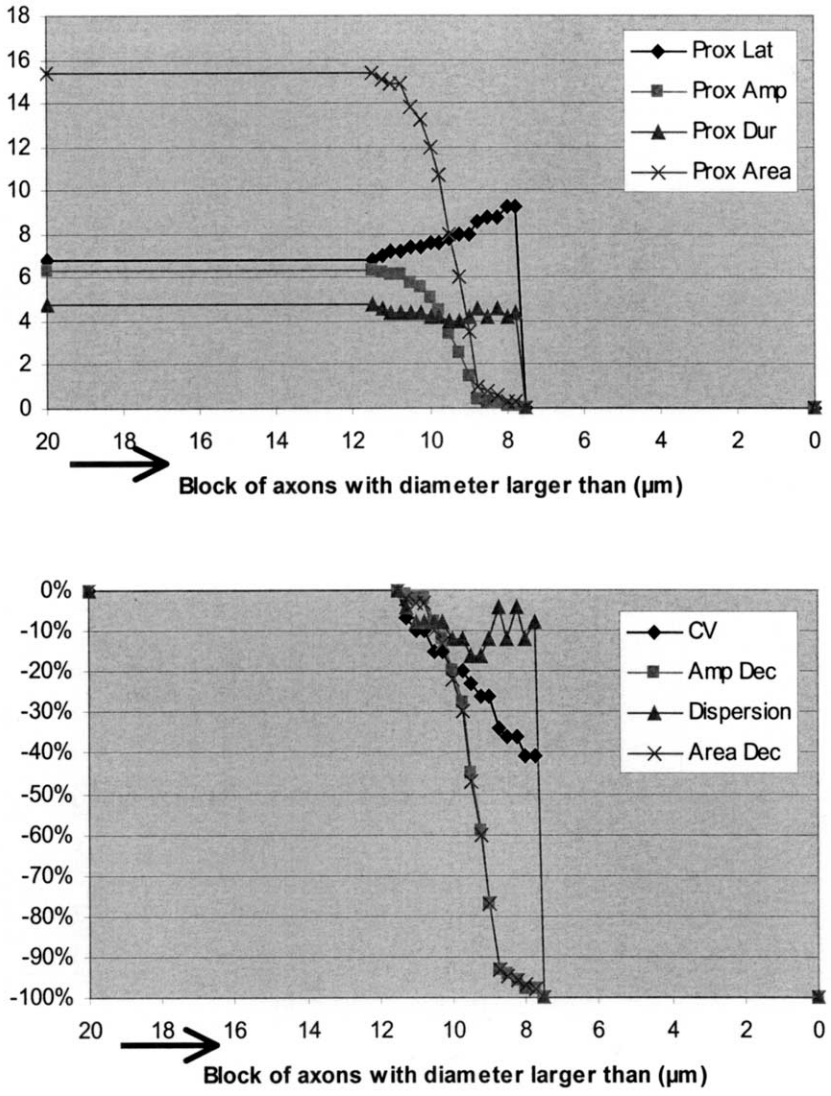

Fig. 13. Ampl decay, area decay and temp dispersion with conduction block of large and then successively smaller axons. When fibres around 9.5 μm were involved, conduction block criteria were fulfilled.

CMAP, and for statistical reasons, the variability may seem to be smaller.

5. Discussion

A computer simulation model for the study of motor nerve conduction has been developed. This allows the quantitative study of the relationship between some anatomic and physiologic nerve characteristics and the results obtained in conventional electrophysiological testing of motor nerves.

The model itself was constructed on the basis of information in literature regarding axon diameters, number of alpha motor axons and conduction velocity. The contribution from each motor unit to the CMAP was obtained experimentally by surface recording of the spike-triggered activity from individual motor units. This technique does not allow all motor units to be studied, only the low threshold motor unit potentials that are participating in the CMAP. It is known that motor units, with larger axons, are larger. However, they do not necessarily give higher amplitudes in the surface recording since the amplitude is to a great extent dependent on the position of the motor unit in the muscle. The deepest motor units did not give any surface signal at all. Therefore, the recorded motor unit signals can be considered to give a reasonably good representation of different sizes of motor units. The sum of a number of randomly chosen samples of recorded motor unit potentials was compared to the CMAP obtained at maximal stimulation strength. Using a simulation with 85 motor units, the constructed CMAP was surprisingly similar to the live recording in the same subject. This is taken as an indication that the model is a reasonable reflection of real conditions. Only a few studies were performed to test the general behaviour of the model.

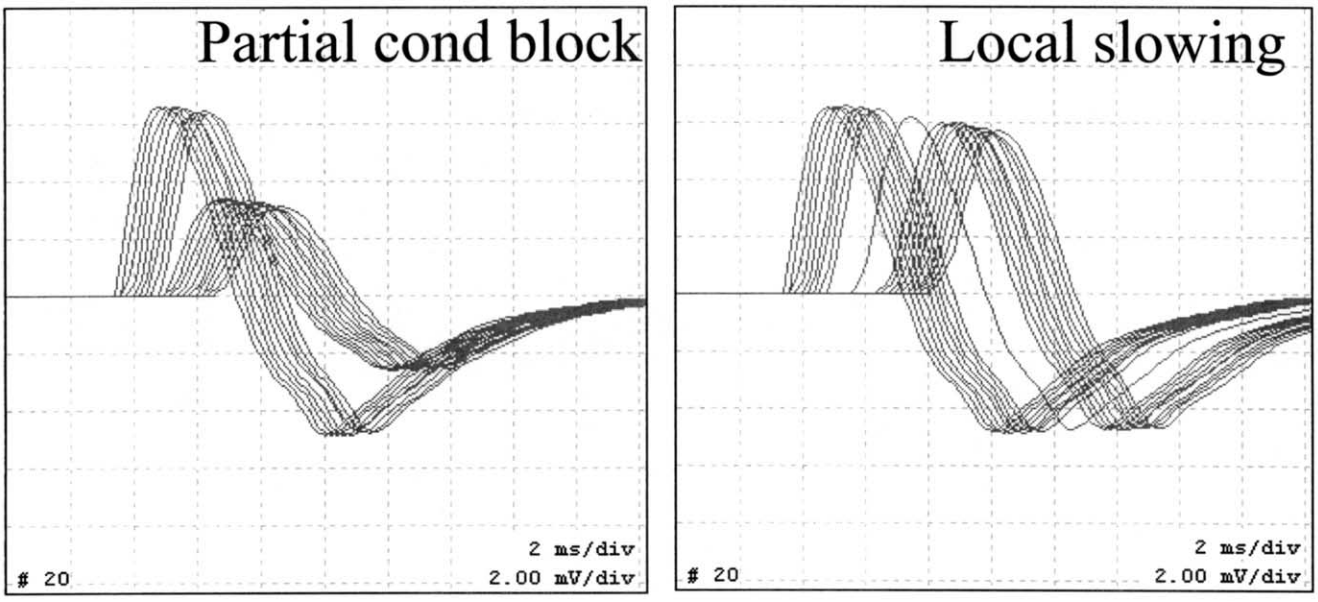

Fig. 14. Conduction studies over short segment (centemetering) in situations of local conduction block (left panel) and in a situation of local slowing (right panel). Note the reduction in amplitude and latency respectively.

The first set of studies concerned phenomena that are seen in the normal condition. With different degree of submaximal stimulation the number of stimulated axons was well correlated to the recorded CMAP amplitude. This model is based on live recordings from the APB muscle. If the model had been constructed from a muscle with shorter individual motor unit potentials, e.g. a facial muscle, the relationship between the number of axons and CMAP amplitude will probably have been slightly different since the effect of cancellation should have been different. Short motor unit potentials summate less efficiently than long duration motor unit potentials.

With increasing distance between stimulating and recording electrodes the amplitude decreased. This is seen in the normal condition and is the explanation for the normal decay in amplitude and area and temporal dispersion that occurs at distal versus proximal stimulation.

With submaximal stimulation a variability in the CMAP was observed. This is seen in live recordings as well and is due to random excitation of some axons at each stimulus,

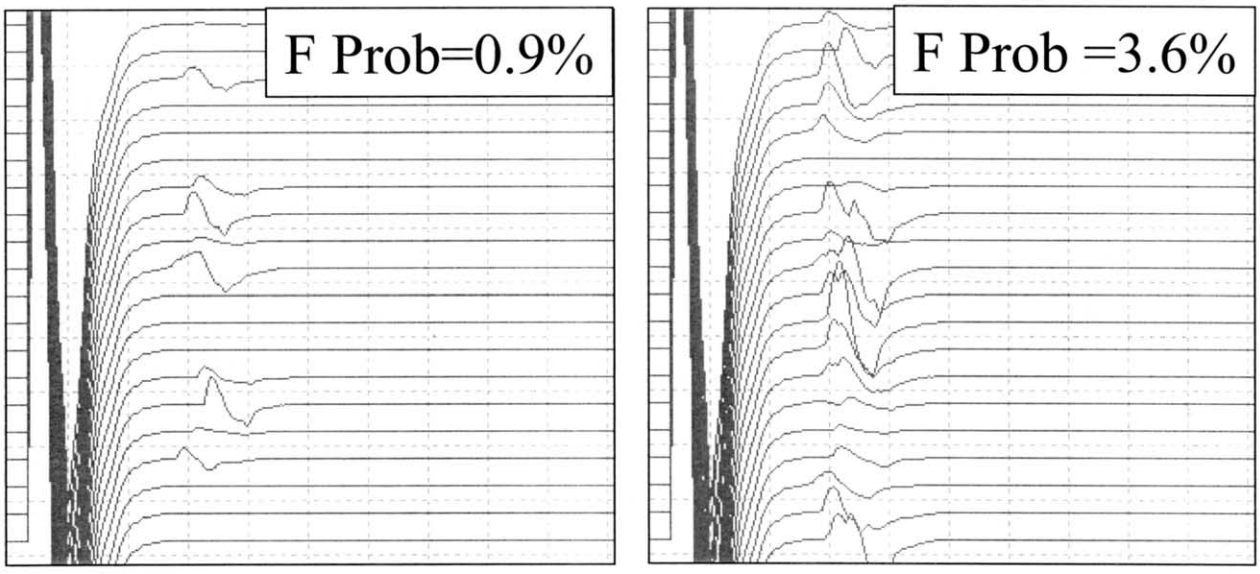

Fig. 15. F-waves at 0.9 and 3.6% chance to elicit an F-wave. In the first case F-waves are seen in 9 traces. In the later, F-waves are seen in 19 traces, and in many instances there is summation of F-waves on each trace.

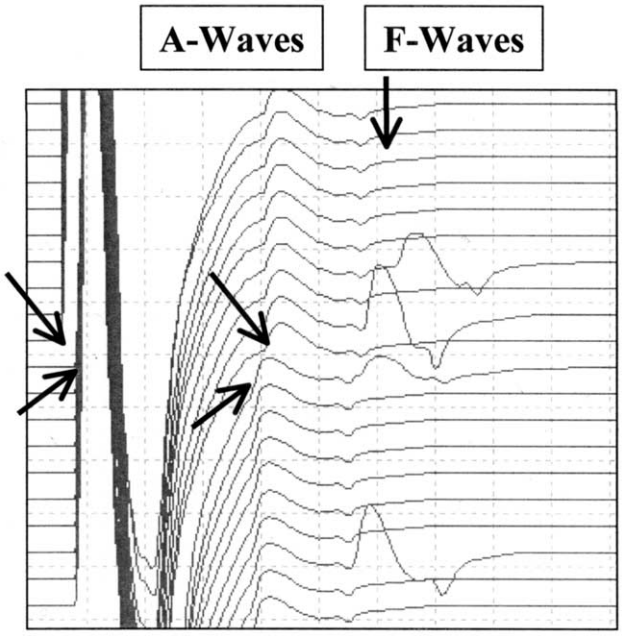

Fig. 16. A-waves and a few F-waves. At the middle of the figure, the stimulation electrode is moved 60 mm more proximally. The CMAP latency increases and the A-wave latency decreases (arrows).

most likely reflecting variable membrane excitability. The default value of this variability was set to ± 5mV. This figure is not found in the literature, but will give a reasonable CMAP amplitude variation. It may therefore be considered as new information from the model, not assessed in the intact nerve. Base on these parameters, it may be possible to study one of the methods for estimating the number of motor units (Daube, 1988). It can be seen that if the random fluctuation in excitability for a given axon is small, the so-called statistical method of motor unit counting will be difficult to apply.

The next set of tests focused on pathological situations. One study concerned the effect of changing CV on CMAP. The distal–proximal amplitude decay increased with slowing of CV and the CMAP became dispersed. These changes were similar to neuropathies with demyeliniation. It reached our upper limit for normal decay value (−20%) at a velocity reduction of 50%. However the temporal dispersion increased in parallel and thus the criteria of conduction block were not fully met. Therefore the definition of conduction block must include temporal dispersion and should also be related to the mean CV in the nerve.

In conditions with random loss of axons, the CV started to decrease once the amplitude was decreased to about 20% of normal. This is important when judging the degree of demyelination in an axonal neuropathy.

When axons of selected fibre diameters were lost, the CV was unchanged with loss of small fibres and amplitude decreased only when larger axons were involved. It should

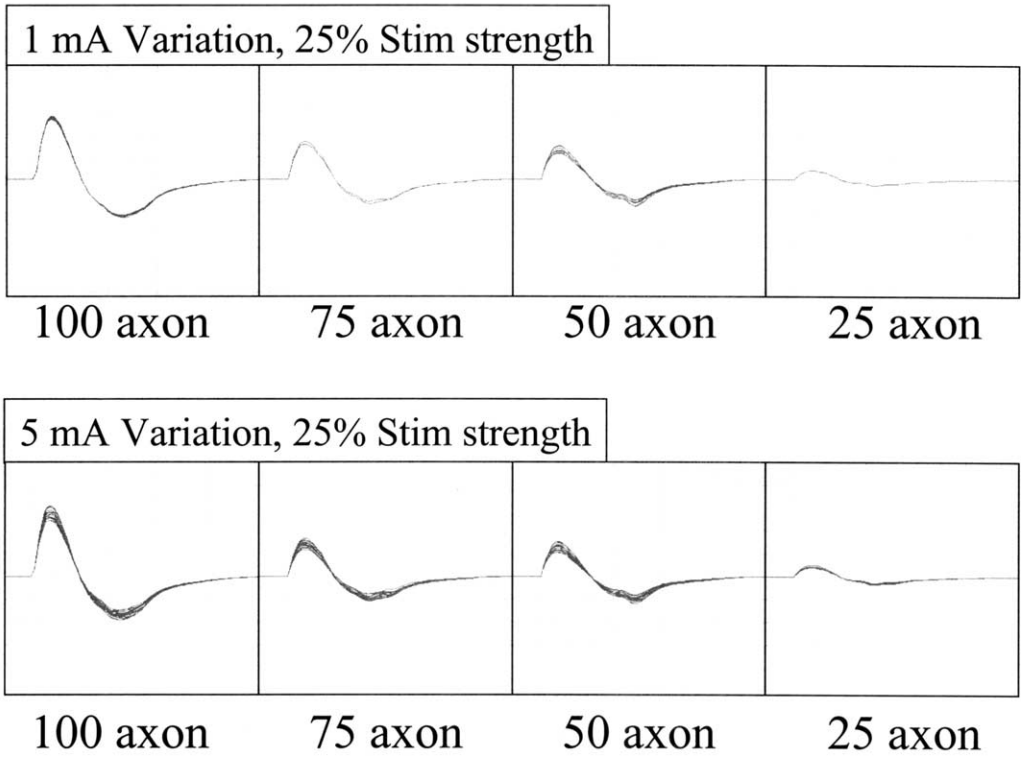

Fig. 17. Amplitude variation of the CMAP at subliminal stimulation strength. The nerve is given various number of axons from 100 to 25. In the upper panels the variation in excitability is small, 1 mA and in the lower it is greater, 5 mA. It is easier to seen the variability in the lower panels. The variation is about the same for different number of axons, but the CAMP amplitude is different.

be noticed that dispersion and amplitude decay diminished with loss of small fibres, probably due to a more homogenous conduction among remaining fibres. With the loss of large fibres, the expected loss in amplitude and decrease in CV was apparent. The dispersion did not change much with loss of large fibres.

The studies of focal lesions showed the expected findings of an amplitude drop, depending on type of lesion. No change was seen in pure focal slowing (demyelination). In simulations of conduction block, the measured amplitude decay was directly related to number of blocked axons. Thus when the CB criteria for arm nerves were reached, about 20% of axons were blocked, In the experiments with blocks of selected smaller axon diameter populations, it was noticed that the amplitude could decrease to nearly zero while the distal latency was unchanged. This is in keeping with the contribution of the largest and fastest fibres to the initial parts of the waveform, and therefore the terminal latency. In contrast, the latency increased and the CV decreased immediately when the largest axons were removed.

The F-waves can also be studied. In the model, it seems that a reasonable persistence, compared to live recordings, was found with a 0.9% chance for individual axons to fire. If this was increased by four times to 3.6%, the F-waves were so frequent that they summated, as seen in spasticity.

The model is likely to be very useful for teaching. It can probably also be used in quantitative assessment of the relationship between axonal properties and electrophysiological neurography measures. In the interpretation of results in future studies the basis of the model has to be well known to the user, in order to avoid false conclusions.

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