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Standards of instrumentation of EMG

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See Editorial, pages 235–236

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HIGHLIGHTS

- Standard instrumentation ensures high quality recordings and enables comparison of results.
- This consensus document on "Standards of Instrumentation of EMG" is written by an expert panel.
- This report covers technical aspects as well as topics for optimal and standardized examinations.

ABSTRACT

Standardization of Electromyography (EMG) instrumentation is of particular importance to ensure high quality recordings. This consensus report on "Standards of Instrumentation of EMG" is an update and extension of the earlier IFCN Guidelines published in 1999. First, a panel of experts in different fields from different geographical distributions was invited to submit a section on their particular interest and expertise. Then, the merged document was circulated for comments and edits until a consensus emerged.

The first sections in this document cover technical aspects such as instrumentation, EMG hardware and software including amplifiers and filters, digital signal analysis and instrumentation settings. Other sections cover the topics such as temporary storage, trigger and delay line, averaging, electrode types, stimulation techniques for optimal and standardised EMG examinations, and the artefacts electromyographers may face and safety rules they should follow. Finally, storage of data and databases, report generators and external communication are summarized.

Contents

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1. Introduction

Instrumentation and technical issues play an important role in an electromyographeŕs daily routine. At one level, everyone is familiar with artefacts and noise which may distort electrophysiological signals and can resemble results from nerves or muscles. High quality recordings are essential to the examination. In addition, it is suggested that increasingly, standardisation of instrumentation and recording will enable comparison of Electromyography (EMG) and nerve conduction studies (NCS) results within and between laboratories. Such standards and guidelines will allow a uniform practice and improve the selection of patients for research studies. Evidence-based documentation is, at present, sparse in electrodiagnostic medicine (Fuglsang-Frederiksen and Pugdahl, 2011). Standardisation is becoming more important in the health care system, with rapidly improving new technology enabling greater standardisation of instrumentation. Most EMG equipment is now digital and computer-based.

Reports on electromyographic instrumentation have been published previously (Guld et al., 1970; Guld et al., 1974; Guld et al., 1983; Bischoff et al., 1999). The present consensus report is an update and extension of the latest report in *Recommendations for the Practice of Clinical Neurophysiology: Guidelines of the International Federation of Clinical Neurophysiology* (EEG Suppl. 52) (Bischoff et al., 1999). In the present report the technical aspects, i.e. amplifiers, filters and instrumentation have been covered in detail, much as in the report from 1999. However, these sections have been updated corresponding to the advanced knowledge in technology in the recent decades. Similarly, the sections on databases and storage of data, report generation and external communication have required considerable updating because of developments in computer science. In the former report, signal averaging and noise reduction were mentioned briefly, only for recordings of SNAPs. In the present document we added evoked potentials, EMG and EEG signals, as well as some practical aspects. In the previous document, the safety section was only mentioned briefly and was limited to electrical safety. In the present report we now also discuss the safety issues of implanted pacemakers, cardiac defibrillators and stimulators and classical and novel anticoagulants in the light of the recent literature.

This report addresses instrumentation for common diagnostic tests – e.g., EMG, nerve conduction, evoked potentials. It was not intended to be a comprehensive review of techniques for which the instrumentation is used, but of necessity aspects of some techniques are considered, focusing on procedures of established clinical value. We therefore mention some of the tests in more detail and in the relevant sections some new developments in neurophysiology have also been covered.

There have been considerable developments not only in the technological improvement of EMG equipment, but also in imaging methods and genetics. EMG remains the primary and most commonly used method in routine clinical practice, even in developed countries, but imaging and genetics can provide complementary data. Among the imaging methods, ultrasonography has gained an established place in EMG laboratories supplementing electrophysiological studies.

For the generation of this consensus document, a panel of experts, in different fields and from different geographical regions, was invited to submit a section on their particular interest and expertise. Then, the merged document was circulated for comments and edits until this consensus was achieved. This report does not present clinical practice guidelines, and a search strategy in e.g. PubMed was not appropriate for this topic.

2. Instrumentation

Contemporary EMG machines have a dedicated hardware unit with amplifiers, stimulators, control panel and a separate com-

puter. This configuration allows the computer to be upgraded or replaced, while keeping the EMG hardware unit. In the EMG hardware, the amplifiers and stimulators are the most important parts. Some hardware includes an ultrasound facility. Often ignored, but an important aspect of any machine is its ergonomics and control panel functions, including the foot switch and hand controls.

When setting up a machine, it should be tuned optimally, preferably by a team including representatives from the users (physicians, technicians, local engineers) and manufacturers. When considering which machine to purchase, these details must be considered, since they influence medical quality, operability and, in the long term, cost efficiency.

Computer hardware

(A) Number of screens: Multiple screens allow EMG signals and data to be shown simultaneously with other data, such as the referral or radiology.
(B) CPU speed and RAM memory size: The minimum limits are specified by the EMG equipment manufacturer. The requirements depend on the complexity of software.
(C) Hard drive size: The minimum limits are specified by the EMG equipment manufacturer. If data is to be stored locally, the minimum size needs to be sufficient for the estimated number of stored patients. Greater memory is usually needed at some time, so anticipation of this is recommended.
(D) Loudspeaker for replay of EMG signals without EMG hardware unit. A good sound quality is essential.
(E) Printer: Local and/or network connected.

Software

(A) Analysis software
  (a) Available tests, workflow and various other features should optimize workflow and be compatible with local practice and reference limits.
  (b) Help function such as strategies and signal quality control.
  (c) Reference limits
    ■ Prepare for ongoing collection of reference material
    ■ Result presentation; Tables, signals, text, color
    ■ Compatibility with used algorithms
  (d) Voice control may be used for some functions
(B) Remote viewer: View ongoing (live) recordings remotely from another computer.
(C) Database support: Ensure the database engine used by the EMG equipment is supported and compatible with the server to be used.
(D) Operating system

The type and version options are specified by the EMG equipment manufacturer.

(E) Reporting
  (a) Multiple designable templates that comply with requirements from all referring sources.
  (b) Digital delivery of text, signals, tables

2.1. EMG hardware and software

The primary function of the electrodiagnostic system is to faithfully record and analyse various biological signals. It is important to have an optimal 'signal to noise ratio', i.e. amplify the neurophysiological signal voltage while attenuating background noise. This is done using analogue hardware and digital signal processing techniques (Fig. 1).

The signal **and** noise are recorded by surface or needle electrodes. It is carried to the amplifier input via electrode leads or cable. These components behave like an antenna and may add more noise. A differential amplifier magnifies the signal while attenuating the unwanted noise, aided by analogue filters. The amplified signal is measured using an analogue-to-digital convertor (ADC) and the voltage values stored as an array of numbers. This digitised signal allows further computerized analysis.

Some algorithms reduce the noise, e.g., digital filters, averaging, smoothing, etc., and others make measurements such as latency, amplitude and area in NCS. More sophisticated algorithms can detect MUPs in needle EMG. Signal characteristics are also assessed from the signal sound, generated either with analogue hardware or using the digital technology.

An EMG machine also offers stimulation devices to excite nerves and muscles. These may generate electrical, visual or auditory stimuli. External devices providing other forms of stimulation, e.g. magnetic field, contact heat, reflex hammer, etc. can be interfaced to provide timing signals through so-called 'triggers'. To achieve this, some instruments pass the digitized signals through a 'digital-to-analogue convertor (DAC)', to convert digital signals (with much less noise) into analogue form. This can be used for research where the investigator wants to re-sample the signals and develop algorithms for their own analysis.

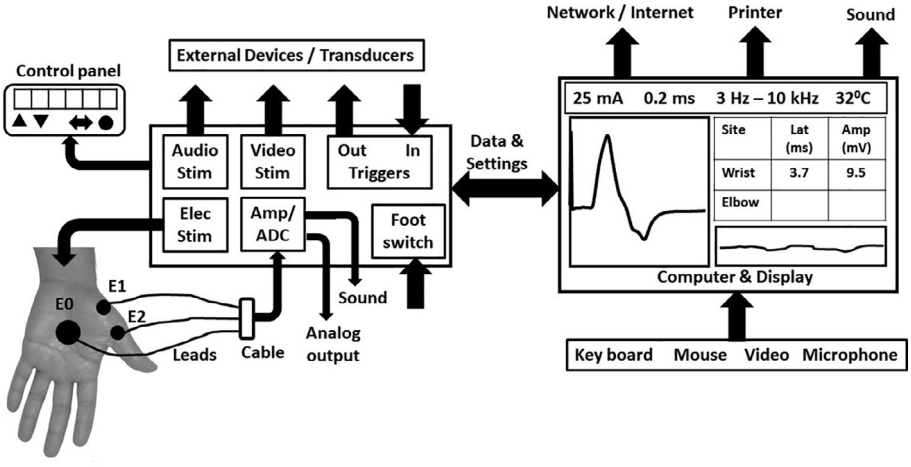

Fig. 1. The organization of various components and accessories to an electrodiagnostic system are shown schematically.

The EMG machine displays signals, measurements, and the settings of the amplifier and stimulator. The latter can be changed using a dedicated control panel or using software commands via a mouse or computer keyboard. Data collection can be initiated using the foot switch.

The software is responsible for signal processing and for generating reports. Databases can be created, and remote review used for second opinions or to help with interpretation. Constant changes in operating systems and in regulations governing patient information protection can make this a challenging task.

The electrodiagnostic systems can also record non-neurophysiological events. Temperature, for instance, should be measured and recorded during NCS. A 'patient response' unit may be used to record the number of times the test subject acknowledges different types of stimuli in cognitive function assessments. Video cameras may be integrated into the system to observe the patient's behaviour during a study, e.g., focusing on the checkerboard pattern in a visual evoked potential investigation. Recently we have seen the addition of ultrasound imaging probes to the device. The handling of these inputs is very different from that of the neurophysiological potentials, and is outside the scope of the current discussion.

2.1.1. Amplifiers

The amplifier is perhaps the most critical component for the quality of the electrodiagnostic system. Selective amplification of a neurophysiological potential while attenuating background noise can be accomplished using a 'differential' amplifier (DA) (Webster, 1998). DA requires inputs or connections from three electrodes (Fig. 2).

In past the electrodes were called 'G1′, 'G2′ and 'ground'. The terms G1 and G2 refer to the grids of vacuum tubes used in old amplifiers which are no longer available. Later these inputs were called 'active', 'reference' and 'ground'. The term 'ground' is confusing. The 'ground' in electrodiagnostic recording refers to a point on the amplifier circuit that is used as a point of reference for voltage measurement. Outside electrodiagnostics, it is also used to describe one of the connections in the power supply and wall outlets. The 'reference' electrode is presumed to be electrically silent but does record large volume-conducted potentials, such as the electrocardiogram (ECG). Given the confusion of terms and their origins, the terms 'E1′, 'E2′ and 'E0′ are recommended for the three connections to the amplifier (Robinson et al., 2016). On most systems these inputs are colour-coded as black (E1), red (E2) and green (E0).

The amplifier does not amplify the voltage at E1 or E2 inputs. It magnifies their difference, and hence it is called a differential amplifier. Fig. 2A shows the E1 electrode (a monopolar needle) recording a 50-μV fibrillation potential. The E2 is a surface electrode placed on the skin surface and for simplicity it is assumed that it records no electrical activity, i.e. 0 μV. Their difference is amplified and the fibrillation potential is seen as a 50,000 μV signal. This amplification by 1,000 is the 'differential' gain of the amplifier. The ambient noise is also recorded by both electrodes and their cables. Here the 'common' noise is 1,000 μV, but the difference between signals at E1 and E2 is zero, and the noise will not be seen at the amplifier output. Similarly, the very large ECG potential can be eliminated by differential amplification. This enables the selective amplification of the small neurophysiologic signal in the presence of high-amplitude noise. The example reflects an 'ideal' DA. In practice the 'common signal' at E1 and E2 inputs is also amplified, but much less. In Fig. 2B, the noise voltage at the output is 500 μV. The ratio of output to input noise voltage, produces a 'common mode gain' of 0.5 for the amplifier.

In this example, the signal-to-noise ratio at the amplifier input is 0.05 and would make it difficult to recognize the fibrillation potential. However, at the output of the amplifier the signal-to-noise ratio is 100, and this would allow it to be recognized quite easily. A DA should have a high differential gain and low common mode gain. These properties are defined in a single characteristic called the common mode rejection ratio (CMRR). It is reported in units of decibels and calculated as

$$\text{CMRR (dB)} = 20 \times \text{Log (Differential Gain/Common mode gain)}$$

In our schematic amplifier, the CMRR is 66 dB. Modern electrodiagnostic systems have amplifiers with CMRR exceeding 100 dB. It is important to note that the CMRR decreases at higher frequencies. Most vendors specify the value at 50 or 60 Hz (i.e., power line frequency).

Another characteristic of the amplifier is the input voltage range. As example, if the range is −50 to + 50 μV, then signals with amplitudes between these ranges can be handled without distortion. If the signal amplitude is outside the range, it will saturate the amplifier and the true signal amplitude cannot be measured. This is recognized from the 'clipped' peaks of the signals on the display. So, the amplifier range should be set higher than the amplitude of signals recorded in the test. In sensory NCS, the stimulus artefact can be much bigger than the nerve response. If the

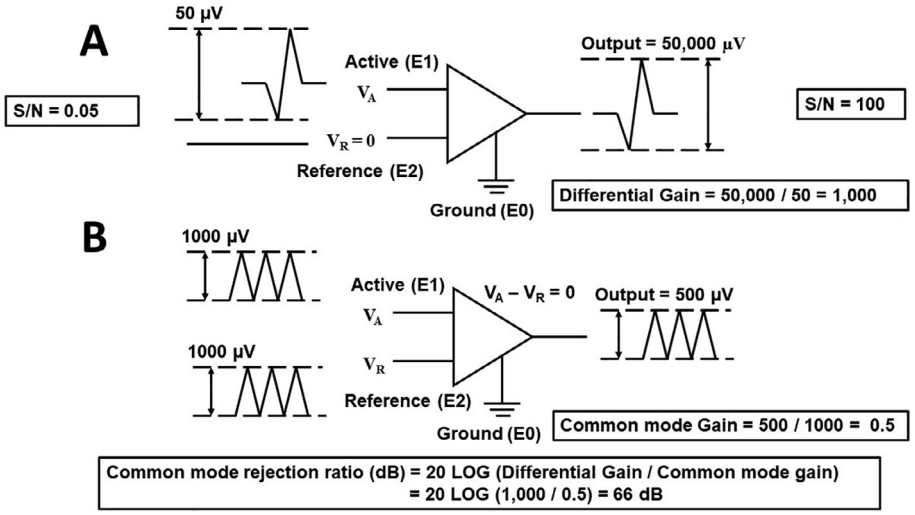

Fig. 2. The operation of the differential amplifier is illustrated. (A) Differential signal inputs are amplified. (B) The common signals (here noise in B) are attenuated. (S: Signal amplitude, N: Noise amplitude).

amplifier saturates, it can generate a long duration artefact that interferes with the sensory potential to be recorded. The range is controlled in the software to avoid such distortion.

The electronic components of the amplifier also produce some noise This is addressed by the E1, E2 and E0 electrodes being connected together and the amplifier output measured. The peak-peak amplitude or root mean square (RMS) value of the signal are reported. RMS is usually less than 1 μV, but also depends on the amplifier range and the filter settings. High amplifier range (i.e. low gain setting) and short band width will give lower noise.

The amplifier is also characterized by its 'input impedance'. As the amplifier needs a tiny amount of current to measure a voltage, the input impedance needs to be several orders of magnitude larger than the input impedance of the generator of the voltage, i.e. muscle, nerve, body fluids. Essentially, the voltage measured (Vm) is given by: Vm = Vsource*(Ropamp)/(Rsource + Ropamp). With Rsource the 'internal impedance' is meant. If Ropamp = Rsource, then Vm = 0.5*Vsource. Without going into details of circuit analysis, the amplifier impedance should be high. Low impedance makes the system more sensitive to environmental noise. It may also underestimate signal amplitude. Fortunately, modern systems report impedances in excess of 100 to 1000 mega-Ω. Just like CMRR, the impedance decreases at higher frequencies.

Modern systems offer 'switching amplifiers'. The unit provides a 'head box' with many input connections. The user can select the inputs in software to select any pair of inputs to make a recording. This facility is used mainly for evoked potential studies where a small set of electrodes is used to create multiple channels of recordings. These channels usually have a much lower CMRR. Such channels may not be suitable for recording signals with high frequencies (e.g., needle EMG) or when the electrodes differ in their impedances (surface versus needle). To facilitate appropriate settings of the amplifier, the signals characteristics of different test procedures are summarized in Table 1.

The best strategy for high quality recordings is to reduce the ambient noise and to ensure that the noise is not different on E1 and E2 electrodes.

2.1.2. Filters

Ideally, our measurement system should reproduce the signal of interest as exactly as possible while rejecting undesired signals. In clinical practice, however, we typically obtain a mixture of signals and 'noise', where the latter refers to any signal that does not contain relevant information for our diagnostic procedure. The undesired signal components can result from ambient power line noise (50 Hz or 60 Hz) or movement artefacts, but can also include EMG signals in a frequency range that is outside the region of interest for a particular procedure. For example, in recording single-fibre action potentials, the signal of interest is in the frequency range 0.5–5 kHz, where lower-frequency components (such as distant EMG potentials) can be safely suppressed. While filtering refers to any process where irrelevant signals are suppressed, in most clinical situations filtering is limited to attenuation of particular frequency components in the signal. The name of a filter is then defined by the frequency values that the filter attenuates (low or high frequency filters) or passes (high-pass filter, band-pass filter). The amount of attenuation depends on the "steepness" of the filter (expressed as the attenuation in dB/octave) and the cut-off frequency. The cut-off frequency is defined as the frequency where the original signal's amplitude is attenuated by 3 dB. In today's equipment, all filters (except for the anti-aliasing filter) are digital, which also allow filtering of frequency components with minimal phase distortion of the signals. We will discuss the most common frequency filters.

Low-frequency filters (LFF; high pass filters)

Low-frequency (or, synonymously, high-pass) filters attenuate low frequency components in the signal. An increase in the low-frequency cut-off causes initial amplitude loss of slowly changing signals, waveform distortion, but more importantly it also decreases the latency to the peak of the waveform and can introduce artefacts (i.e. a tail of the motor unit action potential). When recording motor unit potentials (MUP), the duration as well as the amplitude decreases when the cut-off is increased up to 500 Hz. Using a 500 Hz cut-off the contribution from distant muscle fibres is attenuated because of the soft tissue itself acts as a high-frequency filter. Ideally the low limiting frequency should be one decade (factor 10) lower than the lowest frequency of the signal, to make sure that a phase shift, if present at all, does not affect latencies. Movement artefacts contain slow frequencies. In some cases, the only way to remove this artefact is to increase the lower limiting frequency. This is commonly done for surface EMG recording of movements (e.g., tremor recordings; gait) and may be necessary for motor evoked potential recordings to transcranial magnetic stimulation (TMS). It is usually required if EMG traces are rectified before averaging, e.g., for averaged F waves.

High-frequency filters (HFF; low pass filters)

High-frequency filters attenuate high frequencies. A decrease in the high-frequency cut-off reduces the amplitude and rise time. If using a high-frequency cut-off that is too low, the system will not be able to record adequately the rise of the potential (containing the highest frequencies of the signal), and this may (i) lower the amplitude, (ii) reduce the number of phases and (iii) prolong the duration of the main peak component of the signal. An inappropriate HFF can also affect the measurement of onset latency of a potential. It will be prolonged because the abrupt decline from the baseline is missed and more time elapses before the beginning of the potential can be appreciated.

Band-pass filters

Most filters used are band-pass filters, a combination of a high and low frequency filter. The effects of changing the frequency range of a bandpass filter on recording a MUP is illustrated in Fig. 3.

Notch filter

A notch filter is a special type of band stop filter. In electrophysiology it is normally designed to reduce power line interference (50 Hz or 60 Hz). Ideally, it should not be used because most neurophysiological signals contain significant components at this frequency, and their use may hide interesting components. In

Table 1
Typical signal amplitudes, filter settings and sampling frequency, f_s (Nilsson et al., 1993) in different electrodiagnostic test procedures. Filter settings are defined by the frequencies of the signal of interest.

Recording	Signal amplitude (peak-peak[2])	Typical filters	Sampling frequency, f_s (kHz)
Compound muscle action potential	0–50 mV	1 Hz–5 kHz	20
Sensory nerve action potential	0–100 uV	10 Hz–5 kHz	20
Needle EMG	0–30 mV	2 Hz–10 kHz	50
Single fibre EMG	0–50 mV	500 Hz–10 kHz	50
Surface EMG	0–10 mV	1 Hz–1 kHz	5
Somatosensory evoked potentials	0–50 μV	30–3000 Hz	20
Visual evoked potential	0–0.5 mV	1–100 Hz	1
Auditory evoked potentials	0–50 μV	100 Hz–3 kHz	10
Cognitive evoked potentials	0–50 μV	0.1–200 Hz	1
Sympathetic skin response	0–2 mV	0.1–100 Hz	1
Electrocardiogram[1]	0–5 mV	10–100 Hz	2
Electroencephalogram	0–300 μV	1–200 Hz	500 Hz

[1] For heart rate variability studies.
[2] Peak to peak signal amplitude also includes the background signal level.

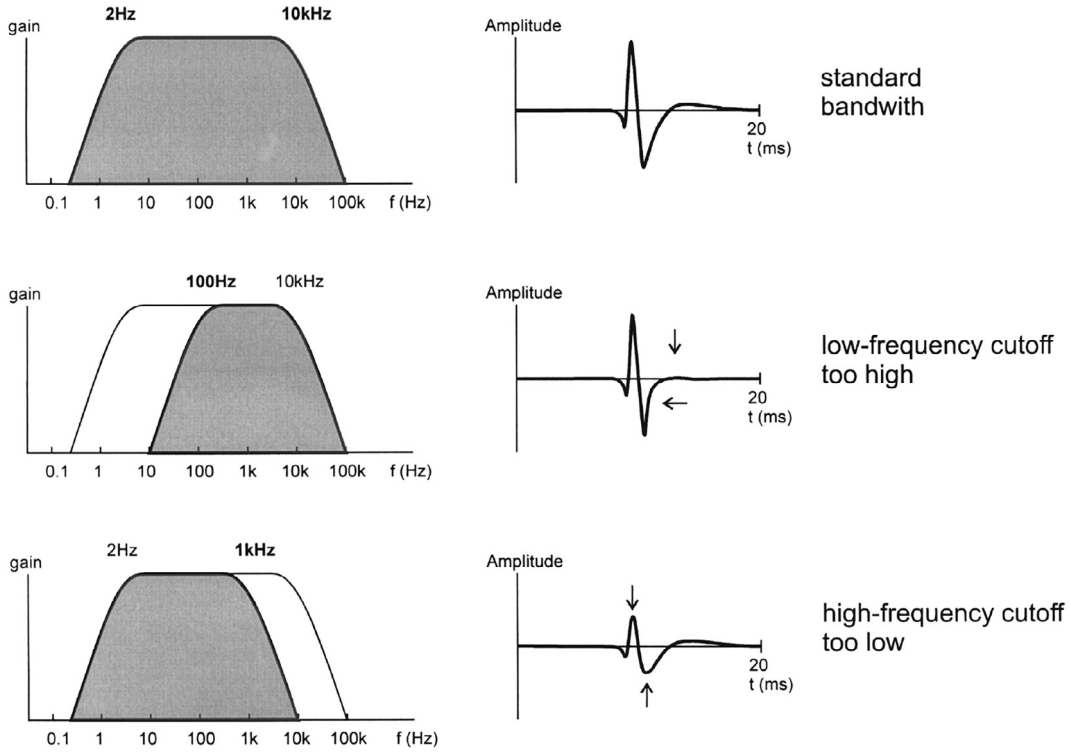

Fig. 3. Effect of different bandwidths of band-pass filters on shape, amplitude and duration of a motor unit action potential. From Bischoff et al., Standards of instrumentation of EMG, 1999.

addition, the phase changes abruptly back and forth around the notch frequency, and this may distort the waveform.

3. Digital instrumentation

EMG equipment uses digital computers for data sampling, storage and signal processing. After the analogue signal has been amplified, the analogue-to-digital (AD) converter discretizes the signal in both time and amplitude, and assigns a digital value to the amplitude at defined time points. This assignment of the amplitude to a digital value is performed by using a finite number of digital amplitude values. In this conversion process, two important criteria must be satisfied. First, the sampling frequency should be sufficiently high to reliably represent the original analogue signal. Second, the digitization of the amplitude should be sufficiently fine to accurately represent the amplitude of the original signal in the digital domain. These two constraints are illustrated in Fig. 4, digitizing an analogue signal, consisting of a sine wave with frequency 1 Hz and amplitude 1 mV using different sampling rates and AD converters. The phenomenon illustrated in Fig. 4, panel B is known as "aliasing": if the sampling frequency, fs, is lower than the highest frequency present in the signal of interest, fmax, the frequency obtained has an erroneous value, in this example 0.1 Hz. Using appropriate algorithms, it is possible to reconstruct the waveform in detail if the sampling rate is more than twice the highest-frequency component of the waveform (Nyquist theorem). In practice, the sampling frequency used is typically 2–5 times the highest frequency component in the signal of interest. In order to guarantee that the maximum frequency in the signal is known, an analogue "anti-aliasing" filter is used before the signal is digitized. Table 1 presents typical values. The required number of bits for the AD converter is defined by the desired amplitude resolution and the maximum amplitude of the signal. Current AD converters are 24 bits or more, which is more than sufficient for most applications (van Putten, 2009).

4. Digital signal analysis

To complement visual analysis of the EMG, various quantitative tools can be used. It is noted, however, that an experienced neurophysiologist can interpret most findings for clinical diagnostic purposes with careful visual inspection and auditory assessment. For research purposes, however, quantitative EMG (qEMG) is extensively used. In some laboratories, qEMG is used routinely for clinical purposes.

4.1. Frequency analysis

When the subject is exerting a constant force, the surface EMG can be used for spectral analysis, creating the power spectrum density. During continued muscle activity, mean and median frequencies typically decrease. Using needle EMG and constant force, frequency analysis of MUPs has shown that the frequency distribution is shifted towards higher frequencies in myopathies and towards lower values in patients with neurogenic disorders (Fuglsang-Frederiksen, 2000).

4.2. Turns-amplitude analysis

In this technique, the amplitude of the interference pattern is plotted versus the number of turns for different levels of contraction. A "turn" is defined as a reversal of voltage of > 100 μV, and if the interference pattern has many turns it will look and sound spiky. By comparing the distribution with normal values, myopathic and neurogenic patterns can be differentiated (Fuglsang-Frederiksen et al., 2016).

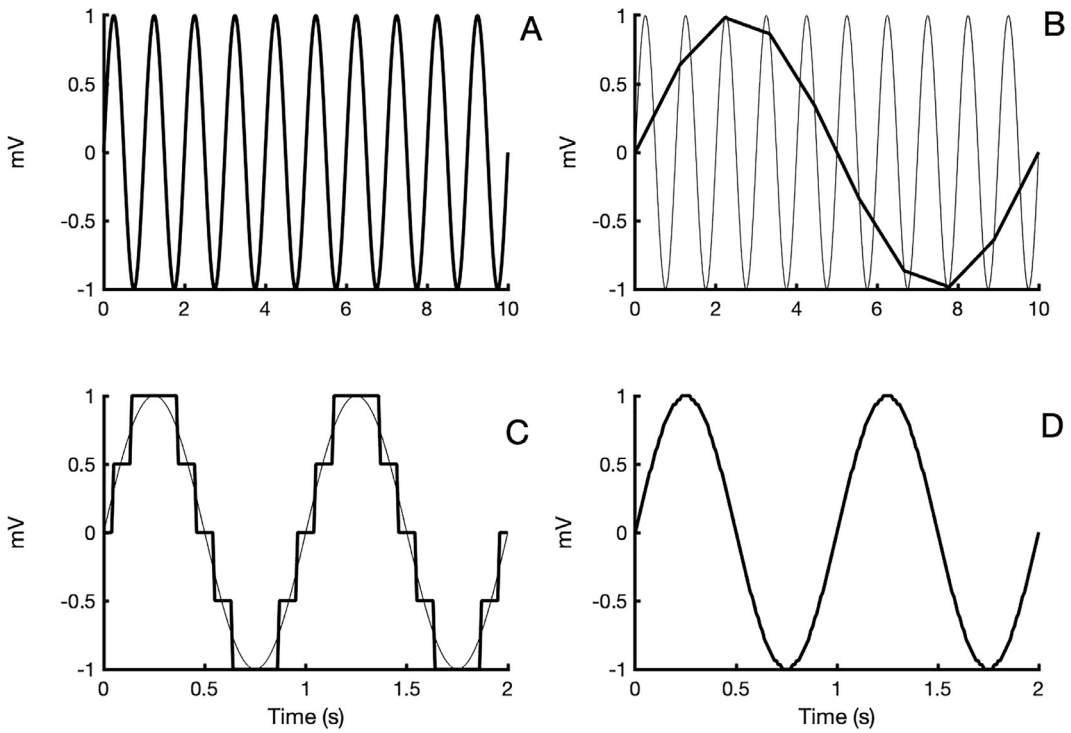

Fig. 4. Panel A: analog sinus signal with frequency 1 Hz and amplitude 1 mV. Panel B. Sampling with 0.9 Hz results in aliasing, where the resultant analog signal is a sinus of 0.1 Hz. Panel C: sampling at a frequency of 100 Hz, but with a 3 bits AD converter, resulting in 5 digital amplitude values (2^3-1), as one bit is needed for the sign (positive or negative) of the signal. This significantly distorts the representation of the signal. Panel D shows the digital signal sampled at 100 Hz with an 8-bit AD-converter, where the analog signal is now reliably represented in the digital domain. Note the altered time bases, which are not given under A and B.

5. Instrumentation settings

The EMG machine setting is one of the important parts for acquiring data. It should be adjusted to the same setting as those when control data were collected by the laboratory.

Gain and sweep speed enable display of waveforms on the screen, and should be adjusted during practice to ensure the waveforms display perfectly in the window, avoiding overlap, and of sufficient size to be viewed and measured clearly (Table 2). The gain, and to a lesser degree sweep speed, can affect the latency measurement of action potentials, including distal motor latency, duration of compound muscle action potential or MUP, etc. As gain is increased (high sensitivity), it will become apparent that where the potential really begins (i.e., the onset latency) is less than at low gain, and the duration will increase. So, when measuring the latency, the gain and sweep speed should be adjusted to the same special setting as used when recording normal control values (Figs. 5 and 6).

Table 2
Recommended gain and sweep speed settings for the commonly used electrodiagnostic recordings.

Test		Gain (μV/division)	Sweep speed (ms/division)
Motor nerve conduction studies		2000	2–5
Sensory nerve conduction studies		10	1
F wave/H reflex studies		200	5–10
Repetitive nerve stimulation		2000	2 or 200
EMG	At rest	100	5–10
	Minimal contraction	200–1000	5–10
	Maximal contraction	1000	100
	Single-fibre EMG	200–1000	0.5–1
Sympathetic skin response		500–1000	500–1000

In digital EMG machines automatic cursor placement algorithms are available. While these are very useful and provide standardization for measurements and usually high accuracy, it is mandatory to inspect visually the accuracy of cursor placement.

6. Temporary storage, trigger and delay line

All modern commercially available EMG machines have the functions of temporary storage, and trigger and delay lines. The latter allows the isolation of a single action potential from other action potentials and so enables analysis and confirmation of the consistency of the shape. By delaying each action potential after it has triggered the sweep, it appears in the same position on the screen every time there is a discharge of that unit. This requires an electronic delay circuit and the temporary storing of the recorded MUP. The sweep is triggered by the potential in real time, but the display is delayed by the preset interval (Kimura et al., 1988; Czekajewski et al., 1969; Nissen-Petersen et al., 1969). With this arrangement, the potential studied can occur repetitively and in its entirety in the same spot on the screen for precise measurement of action potential parameters in a short time. Use of a delay line is essential for the analysis of spontaneous activities, of MUPs in the concentric needle EMG and of jitter in single fibre EMG.

The trigger can be placed at the different levels on the action potential to discriminate between different units. When the signal amplitude is less than the trigger level, the signal is not displayed, and when the amplitude exceeds the trigger level, the system acquires and displays one sweep. However, any potentials larger than the trigger level will trigger the sweep. Some EMG machines can also acquire the potentials with an amplitude between two trigger levels (window trigger), thus allowing the clinician to select a potential that is not the largest. During continuous recordings, a series of action potentials with the same features will be displayed

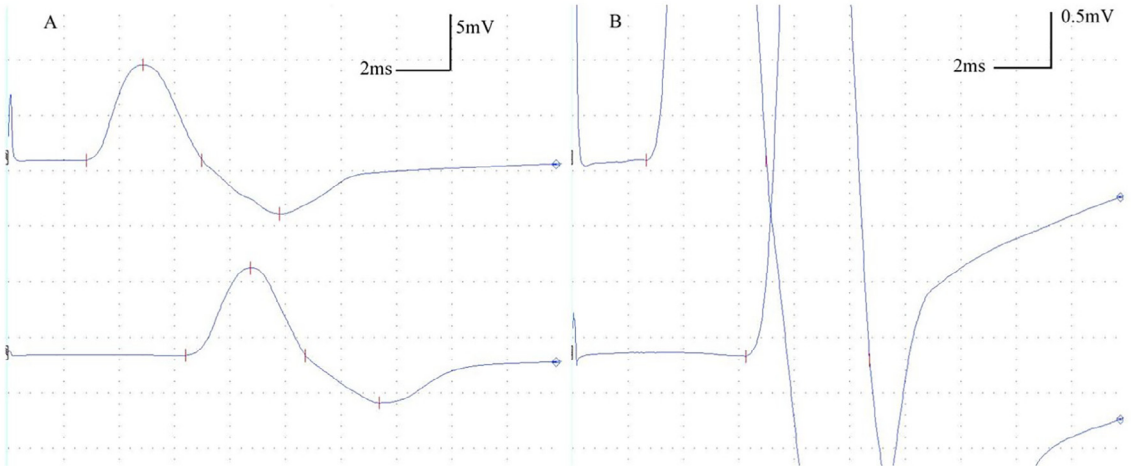

Fig. 5. The distal motor latency (DML) increased with increased gain. A. the DML was 2.8 ms when measured at 5 mV/D, B. the DML was 2.6 ms when measured at 0.5 mV/D. The measurements were done manually.

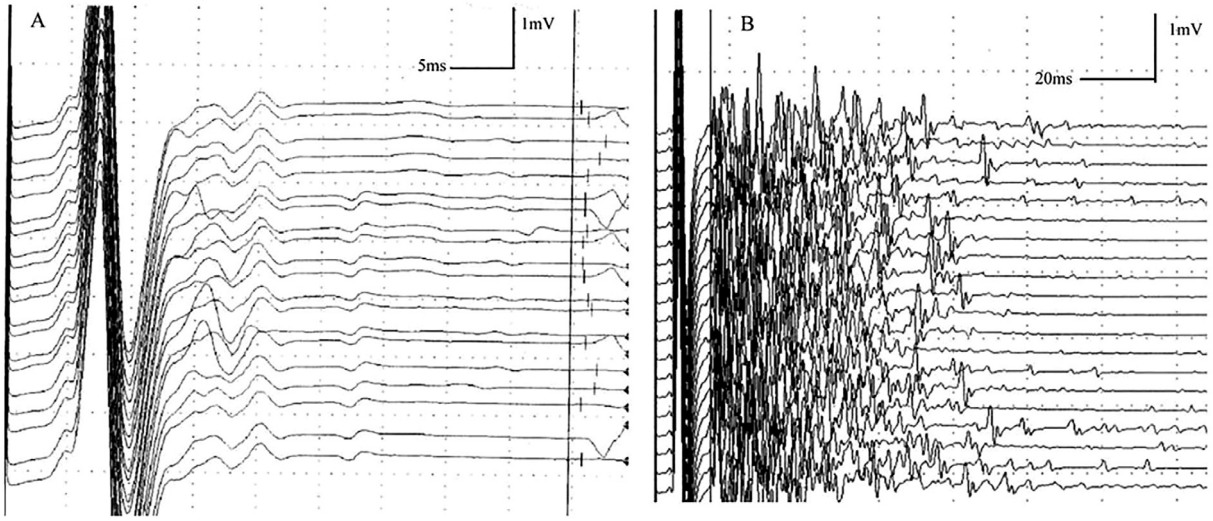

Fig. 6. The sweep speed should be changed according to different conditions. A. F wave studies recorded at routine sweep speed (5 ms/D) in a patient with Morvan syndrome. B. when the sweep speed was adjusted to 20 ms/D, the after-discharges were detected.

on the screen for analysis and be temporarily stored. The amplitude trigger allows the clinician to see the EMG signal after the trigger occurs, the delay line allows the clinician to see the activity that precedes the trigger, and temporary storage allows the signal display on the screen for a short time for analysis. These functions are important for observing the repeatability of the potential during MUP analysis of needle EMG, and for recording stable single fibre action potentials for jitter analysis in single fibre EMG.

Another function of the trigger is to initiate the recording of an action potential. In motor NCS or sympathic skin response, the trigger occurs when the nerve is stimulated. When the computer displays the signals immediately after triggering, the whole waveform can be seen on the screen. In sensory NCS or evoked potential studies, the trigger is important for the averaging technique; only potentials that are time-locked to the trigger will be recorded (Pease et al., 2007).

7. Signal averaging and noise reduction

The widespread adoption of signal averaging in the 1970s has greatly enhanced the precision of NCS, particularly those on sensory nerves, where the signal-to-noise ratio is lower than during motor conduction studies. Prior to the advent of averaging, a common method for defining small potentials was to superimpose multiple sweeps (as in Fig. 7B and the lowest traces in Fig. 8), but this does not allow latencies to be measured precisely. In clinical practice, signal averaging is indicated whenever there is a low signal-to-noise ratio, i.e., when the background "noise" obscures the potential to be recorded or the latencies of that potential.

7.1. Sensory nerve action potentials and somatosensory evoked potentials.

In these recordings, the signal may be so small that the noise inherent in the recording obscures the potential (Fig. 7A). Sensory nerve action potentials (SNAPs) may be recorded with surface electrodes (or near-nerve needle electrodes (Buchthal and Rosenfalck, 1966)) but with both techniques the SNAP is often difficult to define in single sweeps; somatosensory evoked potentials (SSEPs) are always so. Signal averaging is recommended routinely, even when the potential can be visualised readily, because it is critical that onset latency be defined accurately. For example, in orthodromic recordings the sensory potentials of the median and ulnar nerves using surface electrodes may be some tens of μVs at the

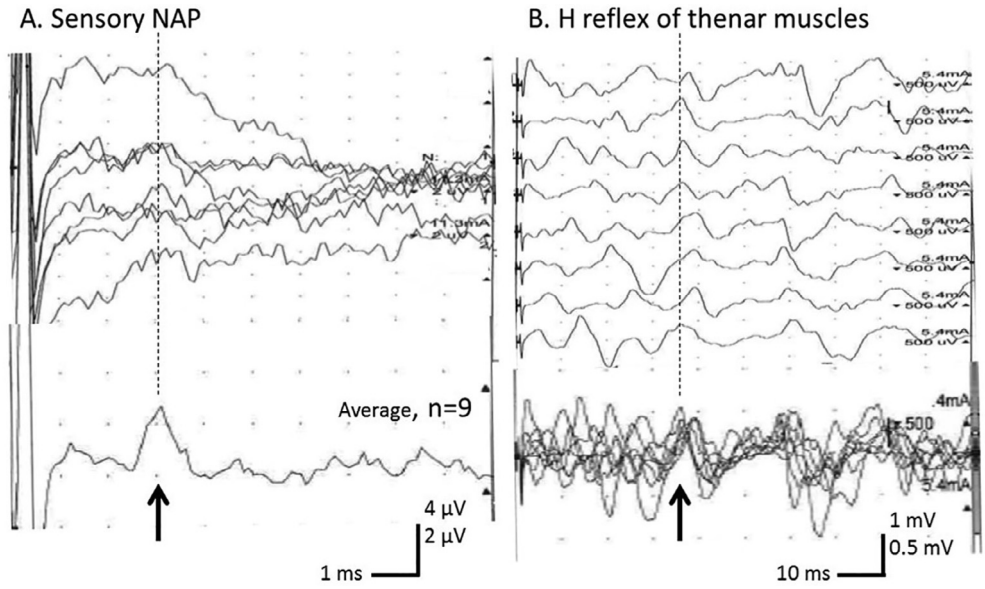

Fig. 7. Averaging to define sensory nerve action potentials and muscle action potentials. A, a small sensory nerve action potential in response to weak stimulation of the index finger (at 11.3 mA) recorded using surface electrodes over the median nerve at the wrist. Eight successive single responses, with an indefinite response peaking at ~3 ms (vertical dotted line). A clearer potential with an onset latency of 2.5 ms is apparent when 9 sweeps were averaged (vertical arrow). B, raster display of EMG activity during voluntary abduction of the thumb, with an uncertain potential, no bigger than the background EMG activity, at the vertical dotted line. Lowest trace:superimposition of the rastered traces at higher amplification, showing a consistent waveform, the H reflex, at the vertical arrow. Note the absence of a direct motor response (M wave) at this stimulus intensity (5.4 mA). To define the reflex latency would require signal averaging (not illustrated).

wrist, but will only be a few μV at proximal sites, such as elbow and axilla, because the sensory volley becomes increasingly dispersed the greater the distance. Dispersion with distance is greater for SNAPs than for CMAPs because of the duration of the unitary potentials that summate to give the compound response (1–2 ms for axonal potentials; 10–15 ms for EMG potentials), such that there is greater phase cancellation for the SNAP. When recorded from Erb's point, the sensory potentials will be much smaller than when recorded in the upper limb, and the traces are more likely to be contaminated by EMG activity. In pathology, the SNAP may be difficult to identify in a single sweep, such that the signal-to-noise ratio is poor even in distal recordings.

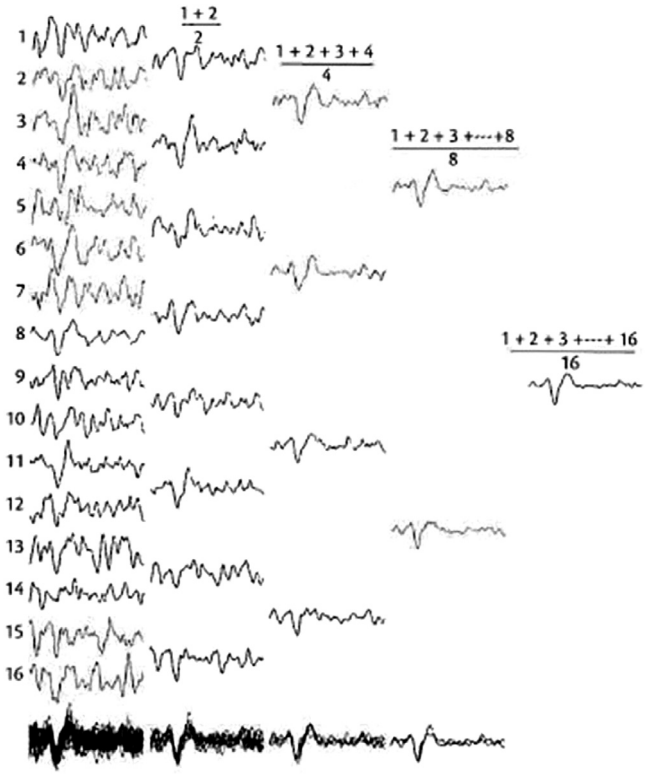

Fig. 8. Improvement in the signal-to-noise ratio. Sixteen raw evoked potential responses are cascaded on the left, and averaged two by two in the second column, then successively to the right averages of 4, 8 and all 16 traces. The raw and averaged traces are superimposed in the bottom row. The potential is not clear in the raw sweeps but becomes clearer as more sweeps are averaged. From Stegeman and Van Putten (2017), with permission.

The "reference" electrode used for SSEPs should be chosen so that activity detected by the reference does not distort the activity recorded by the "active" electrode. For upper-limb nerves, many laboratories use a cephalic reference at F_{pz} but this injects frontal activity into the recording and should be discouraged. Less problematic cephalic reference sites are either the contralateral side or the contralateral earlobe. A remote non-cephalic reference allows far-field potentials generated by peripheral and deep midline generators to be identified, but this is at the expense of greater noise. The contralateral reference will effectively remove these far-field potentials, so that the activity from the relevant sensory cortex can be visualised. With lower limb nerves, there is little frontal activity at F_{pz} and a reference at this site is satisfactory.

7.2. EMG potentials

Not all noise is "machine noise"; it may be biological, and it may even be necessary for the desired activity to appear (as in Fig. 7B). Evoked EMG potentials commonly require averaging for accurate definition when recorded during a voluntary contraction of the target muscle, e.g., when recording the motor evoked potential during a background voluntary contraction of the target muscle (e.g., (Rossini et al., 2015)), or when recording the H reflex from a muscle from which it cannot normally be recorded at rest (such as tibialis anterior, the thenar muscles, extensor carpi radialis; see (Burke, 2016). In Fig. 7B, the background "noise" is the voluntary EMG activity against which the H wave must be identified. Superimposing multiple sweeps may then allow the definition of the target

potential (Fig. 7B), which can then be defined better by averaging multiple sweeps (not illustrated).

Defining single MUPs in needle EMG studies is best done by triggering from the MUP, delaying the display so that the main component of the potential is at or just before the centre of the trace (so that consistent late components can be identified), and superimposing individual sweeps. Of necessity, only weak contractions can be studied, only low-threshold units can be defined, and then only the largest of the active motor unit potentials (unless window triggers are used). It is undesirable to average single motor unit waveforms because components can be averaged out if they are unstable and have a variable latency after the trigger component of the motor unit. This usage will not be considered further.

7.3. EEG activity

In most clinical indications, the activity of interest is produced by a trigger stimulus (e.g., an electrical stimulus), and therefore occurs after the trigger, much as when recording SSEPs. However, digitizing and storing the signal in a buffer allows access to activity that precedes the trigger, in addition to that which follows it. With electrical stimuli delivered by the computer, averaging pre-trigger activity allows one to define a clear baseline uncontaminated by the stimulus artefact and early components of the response. When the stimulus is external, the timing of the trigger is not known with certainty, and there needs to be continuous sampling of the activity to be averaged. This is the situation with cortical event-related potentials, such as the Bereitschaftspotential, with which the trigger signal is the EMG activity produced by a voluntary movement. Averaging the activity that precedes the EMG trigger allows insight into the cortical processes underlying the voluntary movement (Shibasaki and Hallett, 2006). Similarly, "jerk-locked back-averaging" may allow the definition of spike activity in the EEG prior to myoclonic jerks (Shibasaki and Hallett, 2005).

7.4. Practical issues when averaging signals

In the averaging process, the recorded trace is averaged against the stimulus that evoked the activity. In diagnostic studies, this is usually electrical. Activity evoked by the stimulus will be tightly synchronized to it, and gradually emerge from the background noise, as the noise averages towards zero because it is not locked to the stimulus (Fig. 7, 8). However, if the major source of noise is mains interference at 50 Hz or 60 Hz, problems can occur if the stimulus is delivered at a sub-harmonic of these frequencies because averaging would then enhance the mains interference rather than reduce it. This problem is avoided by delivering stimuli at a rate slightly off subharmonics of the mains frequency – perhaps 4.1 or 5.1 Hz for the upper limb SSEPs during intraoperative studies. It then takes about 1 min to produce the required number of sweeps to be certain that a change in the SSEP is genuine. At these rates, there is only a small effect on the early SSEP components. The use of notch filters to minimize the mains interference is acceptable only if there is little or no energy at 50–60 Hz in the response being averaged.

For NCS, there is no fixed number of trials to be averaged for any one indication: the number varies with the signal-to-noise ratio. It is recommended that averaging is not be stopped automatically when some arbitrary number is reached, because there may be too few sweeps in the average to define small potentials. Instead multiple averages should be made using as many traces as required to define the potential. These averages can be superimposed to confirm small potentials and then summated into a single grand average (Fig. 8), avoiding any individual average that is contaminated by artefact. Many practitioners turn off the sweep limit in the program (or increase it to, e.g., 9999).

For intraoperative monitoring, particularly of SSEPs, "continuous averaging" can be employed without the need to stop averaging after a defined number of sweeps and start again from zero. As new traces are added, older traces are discarded from the moving average (Sgro et al., 1989). In a further refinement, the weighting of the traces in the displayed average can be adjusted so that the most recent traces have a greater influence on the displayed waveform than older traces, a process that provides an exponentially weighted moving average. With this weighting, once the preset count has been reached, the exponential average is continuously updated and looks like a running average, except that the more recent data have a greater influence on the displayed average. This allows more rapid identification of deterioration in the SSEP.

The artefact reject facility may be useful when recording SNAPs and SSEPs. Using artefact rejection, when the input exceeds a specified voltage the trace is considered to be too contaminated by artefact, and it is not included in the average. This can occur due to inadvertent movement, EMG contamination or a decaying stimulus artefact. In the latter case, the rejection can be set to occur after the artefact has decayed sufficiently.

To define a small target potential against the background noise, separate averages are preferable to a single average of all responses because a genuine response should be reproducible in different averages. Doubling the number of traces in an average does not double the signal-to-noise ratio: it improves it by only the square root of 2, i.e., by 1.4. Visual inspection of superimposed shorter averages may define a waveform better than a single long average, and the separate averages can then be combined into a single grand average, perhaps omitting those contaminated by artefact (Fig. 8).

It is crucial that both the current trace and the updated average be displayed simultaneously. This allows the examiner to identify artefacts affecting only single trials, and either to reject those trials from the average or to reject the average and start again.

Averaging will only define accurately activity that is tightly synchronized to the stimulus, unless the recorded traces are full-wave rectified. This is the reason why unstable MUPs may be difficult to define accurately in qEMG. With reflex activity, only the short-latency reflex (H reflex) can be defined clearly in unrectified traces, and the long-latency reflex activity is less-well defined, both in latency and size because it is polysynaptic, and there is then greater latency variability. Similarly, F waves cannot be defined by averaging raw traces because each F wave has a slightly different morphology and latency (Fig. 9A and B) so that phase cancellation affects the average – unless the traces are full-wave rectified before averaging (Fig. 9C). If this is done, it is imperative that the rectified trace has returned to baseline before the target activity appears, and a 100-Hz high-pass filter may then be desirable.

8. Electrodes

Standard electrophysiological recordings require the use of a minimum of two electrodes since all such recordings are differential—meaning that the signal measured at the first is compared to that obtained at the second. In so-called "unipolar" or "referential" recordings, one electrode is in close proximity to the active fibres or fibres of interest (the active electrode (E1)) and the second is placed at a distance in a region expected to receive minimal contribution from the active fibres (the reference electrode (E2)). In so-called "bipolar" recordings, the two electrodes are placed in relative close proximity to the active fibres. Whereas unipolar/referential recordings assume that the recording area is electrically silent, in some situations, most notably when recording certain surface motor responses (e.g., ulnar or tibial motor responses), this reference electrode also senses substantial volume-conducted electrical

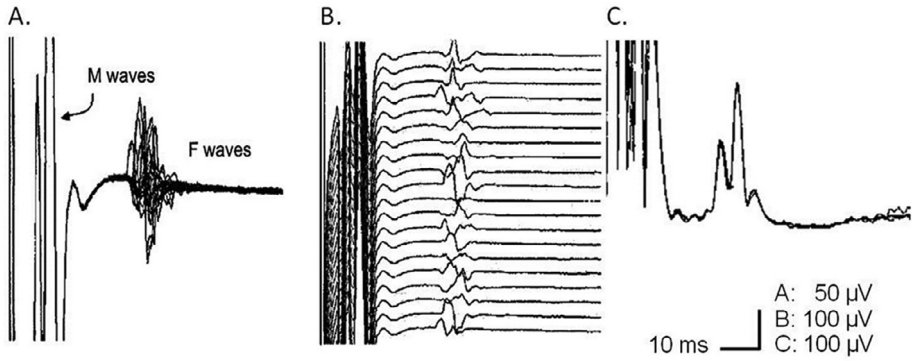

Fig. 9. Averaging F waves of the thenar muscles. A, superimposed sweeps (n = 20). B, raster display of the 20 sweeps, at lower gain, showing variability of the morphology and latency of the F waves in consecutive traces. This renders averaging the raw EMG traces invalid. C, average of full-wave rectified traces recorded using a high-pass filter of 100 Hz. A and B are reproduced from Fig. 1.10 in Pierrot-Deseilligny and Burke (2005), and C from Fig. 3 in Espiritu et al. (2003), with permission.

activity. A third "common reference" electrode is also generally employed (see Section 2.1.1 "Amplifiers" for further explanation).

More recently, electrical impedance methods have also been introduced into the field of neuromuscular medicine (Sanchez and Rutkove, 2017). Electrical impedance methods typically require a minimum of four electrodes to reduce electrode contact impedance, two for applying an external electrical current through the tissue and two other electrodes for measuring the resulting voltage. Since the electrical current applied is high frequency (e.g., 50 kHz), it does not excite tissues, there are no bioelectrical signals being generated, and so the electrodes are not referred as "active" or "reference" electrodes—rather both current and voltage electrodes assess the region of tissue beneath and between them. The details of this method are beyond the scope of the present recommendations and have been discussed in detail in a separate IFCN guidelines "Standards for Quantification of EMG and Neurography" (Stålberg et al., 2019).

8.1. Electrode materials and other considerations

Materials commonly used in electrodes include: platinum, stainless steel and silver-silver chloride. Most surface electrodes require a conductive medium to ensure good electrical contact with the skin; this may consist of electrode jelly/paste, saline, or an adhesive gel. Whenever possible identical materials should be used for the electrodes to help reduce electrode contact impedance mismatch which could deteriorate the signal-to-noise ratio. The contact impedance between tissue and the electrode can be modelled as a circuit with a capacitance and resistance in parallel, resulting from the electrode surface, the electrolytes, and the tissue. The contact impedance increases as the electrode area decreases and decreases with increasing frequency. The single-electrode impedance can vary from one to several hundred kΩ.

The contact of a metal with an electrolyte (electrode paste/jelly or the tissue itself) creates an electrical potential difference between 100 and 600 mV called the electrode polarization potential. Movement of an electrode within the tissue may change electrolyte concentration locally and thereby create changes in galvanic cell voltage for a short period of time, and is the likely cause of movement artefacts. At rest, this potential does not contribute to the observed values.

8.2. Needles

In standard electromyography (EMG), a concentric needle (i.e., comprising an outer cannula [reference electrode] and inner core [active electrode]) is usually preferred although monopolar needles (i.e., the cone tip of the needle serves as single electrode) can be used as well. As the recording surface of both of these needles is large relative to the diameter of individual muscle fibres, they record from the cumulative activity of many muscle fibres of a motor unit. The MUP itself represents a summation of the electrical activity of a number of muscle fibres belonging to the same motor unit.

The concentric needle consists of two electrodes, the first electrode is a wire electrode, typically platinum that is insulated and housed within a steel cannula acting as the second electrode. The surface area of the wire electrode depends on the wire diameter and the bevel angle of the needle and is usually between 0.01 and 0.09 mm^2, typically 0.07 mm^2. The differential recording is then achieved by measuring the voltage between the wire electrode (active electrode (E1)) and the entire cannula shaft (reference electrode (E2)). The main spike component of the MUP is generated by approximately 2–12 fibres within a radius of about 0.5–1 mm around the tip of the needle. More distant fibres contribute to the initial and late parts of the potential. Due to the short distance between the electrodes, a great common mode voltage recorded by the active and reference electrodes is present leading to the elimination of much distant activity and providing a relatively sharp and self-contained MUP.

Monopolar needles for EMG recordings are usually constructed from a stainless-steel core that is coated with Teflon except for an exposed cone tip of 1–5 mm that acts as the active electrode. The recording area is approximately 0.03–0.34 mm^2. The potential difference is measured between the exposed tip of the needle and a second reference electrode. This reference electrode may be a needle placed subcutaneously or a surface electrode at some distance from the active electrode. The reference electrode should be placed over an electrically silent area, such as a tendon or a bone. Impedance mismatch between the active monopolar needle and a surface electrode can lead to a reduced common-mode signal and greater artefacts, including power line interference (50 or 60 Hz). Monopolar needles record larger amplitudes and greater duration than concentric needles, but the number of phases is comparable.

Monopolar needles can also be used as recording electrodes for sensory nerve action potentials in the near-nerve technique (Kural et al., 2017) and as stimulation electrodes (e.g., stimulated single-fibre EMG) (Kouyoumdjian and Stålberg, 2008). In the former situation, the reference electrode is also usually a monopolar needle placed subcutaneously at a distance from the nerve. Hollow core monopolar needles are also used for botulinum toxin injection, assisting with correct muscle localization prior to injection.

Single fibre EMG electrodes have an active region consisting of a platinum wire approximately 25 μm in diameter exposed on a side port of a steel cannula, with the cannula itself serving as the reference lead (similar to a concentric needle). Within the pick-up range

(a semicircle with a radius of 300 μm, pick-up area 0.0005 mm^2) in healthy muscles there are usually no more than 2–3 fibres, allowing for pairs of fibres to be easily obtained. Concentric needles can also be used to collect "single-fibre-like" data; this is achieved by increasing the cutoff frequency of the high pass filter so as to help distinguish individual spikes within the MUP.

There are a variety of other less commonly used needles designed for specific applications. For example, in microneurography insulated tungsten electrodes, exposed for 5–10 μm at the needle tip, are used. Bipolar and multipolar needle electrodes' configurations are also used for MUP analysis during strong effort, volume conduction studies, assessing the muscle fibre conduction velocity, or evaluating the territory of a motor unit. One additional unusual needle is that used for macro-EMG. This can be thought of as a combination single fibre-monopolar electrode. The side port electrode is used only to trigger recording and the actual potential is recorded between the exposed tip and remote reference electrode (subcutaneous or surface). A final class of needles include those that can be used for electrical impedance myography, either alone or in combination with standard monopolar EMG electrode (Kwon et al., 2018). An impedance-EMG needle may have 4-impedance electrodes around an insulated shaft of the needle with a 5th electrode, the exposed tip, serving as the monopolar (active) EMG electrode.

Due to the risk of transmission of infectious diseases (e.g. hepatitis, human immunodeficiency virus, prion disease), disposable needles are used in all circumstances. Given this and the expense of single-fibre EMG electrodes, many laboratories choose to measure "jitter" using concentric needle electrodes designed for facial EMG (e.g., diameter 0.3 mm, recording area 0.02 mm^2) and a more restricted bandpass (1 kHz to 10 kHz) (Kouyoumdjian and Stålberg, 2008; Kokubun et al., 2012).

8.3. Surface electrodes

Surface electrodes are used as stimulating or recording electrodes for NCS, for recording surface EMG data, for serving as reference electrodes for monopolar needle EMG, and as a common reference or "ground" electrode. In the past, surface electrodes generally consisted of small round or square reusable metal disks or metallic wire loops (the last for use in measuring sensory potentials from the digits), all employed in conjunction with a conductive electrode gel. However, to reduce the risk of infection and for reasons of convenience, this approach has been increasingly replaced with the use of self-adhesive, disposable electrodes. These are generally silver-silver chloride electrodes, with an adhesive conductive gel overlying the electrode surface; they can often be used several times on a single patient before they need to be replaced, generally because the adhesive loses its efficacy. Reusable, saline-saturated Velcro fabric band electrodes are also used to record sensory potentials from the digits. For surface recordings of electrical impedance myography, both reusable metal and disposable carbon-based electrodes have been used. Electrical impedance myography has been discussed in detail in a separate IFCN guidelines "Standards for Quantification of EMG and Neurography" (Stålberg et al., 2019).

A variety of surface stimulating electrodes are used for nerve conduction studies. Most commonly these include metal "prong" electrodes used with a small amount of adhesive gel or saline-soaked felt electrode pads or pledgets. In either case, the electrodes are embedded within a handheld stimulator that can be easily repositioned to help identify the best region for stimulation. Small metal disk or adhesive electrodes, described above for recording, can also be used for stimulation, especially if repeated recordings from a single nerve are desired over an extended period of time. This is the case, for example, when performing studies of nerve excitability (including measurements of strength-duration time constant, threshold electrotonus and recovery cycle). The details of excitability techniques are beyond the scope of the present recommendations and have been discussed in detail in a separate IFCN guidelines "Measurement of axonal excitability".

Although surface electrodes are widely used for NCS, conventional surface EMG methods consisting one bipolar signal from two electrodes cannot provide detailed information about motor unit morphology, including their distribution across the muscle endplate. Therefore, special multi-channel high density surface EMG (HD-sEMG) techniques have been developed. HD-sEMG requires sophisticated instrumentation and signal analysis of measures from multiple closely spaced electrodes, overlying a restricted area of the muscle. This enables measurement of both temporal and spatial EMG activity, thus providing different aspects of motor unit characteristics, such as muscle fibre conduction velocity measurements, motor unit number estimation and the evaluation of single motor unit characteristics. HD-sEMG has been shown to be beneficial for the assessment of different clinical conditions including motor neuron disorders (Wood et al., 2001; Drost et al., 2004) and disorders (Huppertz et al., 1997) and pathological changes have been shown at the motor unit level in neurogenic and myopathic muscles. However, HD-sEMG has not yet been incorporated into clinical practice as a diagnostic tool. Recent research has also mostly focused on physiological studies (Sleutjes et al., 2018; Lapatki et al., 2019), sports medicine (Martinez-Valdes et al., 2017) and rehabilitation (Gallina et al., 2016) rather than the primary diagnosis of neuromuscular disorders. Detection of the HD-sEMG signals requires high quality amplifiers with suitable specifications. Several kinds of amplification chains have been described for different strategies. As HD-sEMG remains a research method, further details of these techniques are beyond the scope of the present report.

9. Stimulation

For nerve conduction studies, repetitive nerve stimulation test, stimulated single fibre EMG, and nerve excitability testing, an electrical stimulus is delivered to the nerve. Standard stimulation techniques use surface electrodes, whereas needle electrodes are used for nerve root stimulation or deep nerve stimulation (e.g., the sciatic nerve). Usually two surface electrodes are placed over the nerve with an inter-electrode distance of 2–4 cm with the cathode (where the nerve is stimulated and membrane depolarisation occurs) placed closest to the recording electrode. Inversion of the polarity of the stimulation electrode will affect the point of stimulation, and thereby the onset latency and nerve conduction velocity.

With deep nerves, a short interelectrode distance should be avoided because a greater stimulus is required the deeper the nerve and, it is then more painful. This may be an issue when stimulating the radial nerve in the spiral groove or the femoral nerve.

The duration of the stimulus is usually between 0.1 ms and 1.0 ms. The activation time of axons varies with the duration of the stimulus, even when it is supramaximal, and the measured latency includes this time. In routine nerve conduction studies, short duration stimulus pulses are therefore preferred, and this also (1) minimises patient discomfort, (2) restricts the site of stimulation which may spread with longer duration pulses, as well as high intensity pulses, and (3) reduces the stimulus artefact. In H-reflex studies, a longer stimulus duration (1.0 ms) is used to favour the activation of the large sensory fibres (Ia afferents) responsible for the reflex. The stimulus can be applied as single pulses, paired pulses, or as trains with repetition frequencies between 1–2/s and 50/s for repetitive nerve stimulation test. High-frequency stimulation (20–30 Hz for 1–2 s) has been used for detection of incremen-

tal responses in Lambert-Eaton myasthenic syndrome. More recently a single shock before and after a brief maximum voluntary contraction is preferred to demonstrate increment because this reduces discomfort and is equally effective.

Two types of stimulators are used. The constant voltage stimulator delivers a constant voltage (0 V to 400 V). The disadvantage of this type is that the resultant current is not constant because of the fluctuations of the electrode-tissue impedance. Constant current stimulators deliver a constant and stable current (0 mA–100 mA). Stimulus current is independent of electrode/skin impedance as long as the stimulator is not overloaded. Constant current stimulation is therefore preferred by most physicians.

Supramaximal stimulation is required in standard nerve conduction studies and repetitive nerve stimulation test to activate all axons at the same time for measurement of motor and sensory response amplitudes, and nerve conduction velocity. Particularly when stimulating at proximal sites (e.g., Erb's point) or in nerves with very high threshold due to pathology (demyelination, nerve hypertrophy), it may be difficult to reach a supramaximal level. The most proximal parts of peripheral nerves can be activated by TMS or high-voltage electrical stimulation over the spine, providing additional information to that from peripheral NCS (Matsumoto et al., 2010). Conduction across proximal segments of peripheral nerves, plexuses and nerve roots is commonly tested using H-reflexes and F-waves. An alternative technique using magnetic stimulation or high-voltage electric stimulation involves direct stimulation of the nerve roots, and this may be preferable. Conversely too-high stimulus currents will result in both distal displacement of the stimulation site, leading to a shorter onset latency, and stimulation of nearby nerves. Avoiding a stimulus that is too high is important to ensure the most information with the least discomfort or pain. However, this must be tempered by the fact that erroneous reports of conduction block occur when the stimulus was not really supramaximal, particularly when stimulating at proximal sites. If a supramaximal stimulus causes discomfort that is regrettable but preferable to an erroneous conclusion.

10. Artefacts

The goal of the recording system is the exact reproduction of the physiological signals generated in muscle cells and peripheral nerves, but artefacts are unavoidable (Webster, 1984). They can have a technical or a biological origin (Amrutha and Arul, 2017). The most frequent cause of artefact is the electromagnetic radiation from power sources of 50 or 60 Hz, since its frequency is within the physiological range of the EMG signal. However, the neurophysiologist should know other possible causes.

Technical origin

a. Cable motion artefact, with possible additional triboelectric (electrostatic) effect (low frequency range, 1–10 Hz) (Klijn and Kloprogge, 1974).
b. Transducer noise from displacements in the gel-skin interface, including changes associated with skin stretch (Webster, 1984).
c. High electrode skin-electrode impedance (Basmajian and De Luca, 1985).
d. Intrinsic noise from the EMG machine (e.g. from amplifiers semiconductors).
e. Biomedical devices (e.g. pacemaker)

Biological origin

a. ECG
b. Neighbouring muscles (crosstalk)

It is important to consider a number of procedures to reduce the impact of artefact on the quality of the recording.

Isolate electrical circuit of the EMG machine from the ones for other electrical devices, unplug and disconnect unnecessary electrical devices and lights located in the room (Bischoff et al., 1999), avoid use of fluorescent lights and dimmer switches (they give high frequency noise spikes).
For conduction studies and surface EMG, skin surface should be cleaned using sand paper, abrasive gel or 70% alcohol to reduce skin impedance by removing electrically non-conducting elements forming a high-impedance transcutaneous potential generator, which is increased by stretch-deformation (Edelberg, 1973; Türker, 1993). Skin abrasion with or without a drop of peeling paste is generally effective (Tam and Webster, 1977) and although puncturing the skin with a needle has been proposed as a well-tolerated option (Burbank and Webster, 1978), this is often not necessary.
Select the appropriate electrode size and their distance according the muscle volume to reduce the chance of cross-talk. It should be considered that smaller surface electrodes have higher impedance, requiring more careful skin preparation. Double differential recording can be used to eliminate cross-talk in demanding protocols, in the latter technique signals arriving simultaneously at both electrodes are deleted, since propagating signals are time-delayed (De Luca and Merletti, 1988).
Filtering the signal to remove frequencies outside the known physiological source is important (like mechanical and electrical noise). However, elimination is not complete for the frequencies above and below the setting limits. Filtering is not useful for cross-talk, since desired and cross talk signals have similar frequency ranges (Türker, 1993).
Proper patient grounding is essential to reduce electromagnetic noise. The patient ground electrode is attached to the amplifier as a reference to differential inputs to improve rejection ratio mode. A large surface ground electrode or felt band ground electrode is recommended, positioned close to the recording electrode (between stimulator and recording electrode in conduction studies), not overlying electrically active surfaces like as muscle, and with a low electrical resistance (<3–5 kOhms) (Türker, 1993; McGill et al., 1982). Sometimes it is advisable to ground the examiner too, in order to reduce power line artefact. Make sure the power outlet used for the electrodiagnostic system (equipment grounding) has good connection to 'earth' (i.e. to a pole buried in the earth outside the building). This is also required for safe operation of the instrument.
Cables should be short, fixed, shielded, and separated from others (in particular recording and stimulator cables).
Stimulus artefacts depend on its intensity, duration and distance between recording and stimulation sites. They can distort the waveform and interfere with the accurate measurement of latency with short nerve segments. As always, it is recommended that the lowest supramaximal intensity is used.
Ideally, EMG should be performed in a quiet, temperature-controlled room, separated from any source of electrical noise. Screening of the rooms is not necessary anymore due to better amplifiers.

It should be considered that when the amplitude and/or decay of the stimulus artefact is an issue, attention needs to be paid to the grounding, skin perspiration, the orientation of the stimulating and recording electrodes, the quality of the skin-electrode interface and the high-pass filter, for instance, are the recording electrodes dry? If attention to these factors does not fix the problem, the

amplification may need to be reduced so that the trace remains within the linear range of the amplifier and A/D converter. Removing artefacts may be even more difficult during electrophysiological examinations in intensive care units. To minimise artefacts, all unnecessary plugs should be removed.

11. Safety in NCS and EMG

11.1. Electrical safety and leakage currents

There are certain agreed international standards on safety of electrodiagnostic equipment. For example, the maximum current which leaks to ground is dependent on the type of the medical devices but usually it should not exceed 10 mA at 50 Hz according to IEC 60601–1 (International Electrotechnical Commission 2005) recommendations (IEC, 2005). This leakage current should be measured by a biomedical engineer or technician and a proper grounding provided. Some authorities mandate that equipment be checked annually and a certification plaque be fixed to the EMG machine. All ground sockets in the laboratory should be connected to a single installation ground lead point. Ideally, all other electrical devises including heating lamps must also be connected to this point. No other ground terminals should be used (e.g. water pipes).

Although, the electrical currents used in NCS are too small to damage the skin or underlying tissues, the heart is a sensitive organ to any strong current across it. A small amount of current may leak from the internal electronics when the electrical medical devices are connected to the patient. This small current leakage is often without any danger but there are certain conditions that this current may be dangerously enhanced, for example, by stray currents in power cords, which correlates to the length of the cords, for example with extension cords (AAEM, 1999). In normal conditions, the 3rd prong on an electrical plug serves as a ground. This enables dissolving the leakage currents on a power cord safely, but in case of a malfunctioning ground, the leakage current may induce arrhythmia while passing across the patient́s body. This may happen if the ground electrode is placed on the contralateral side to the stimulating electrode although this is more a theoretical risk rather than an established risk (London, 2017). To avoid this; (1) the ground electrode should never be placed contralaterally to the stimulation site and (2) extension cords should not be used. Special attention should be paid in intensive care units where the patients are connected to several electrical medical devices.

11.2. Implanted pacemakers, cardiac defibrillators and stimulators

Pacemakers are used to treat bradycardic episodes while intracardiac defibrillators treat tachycardic events such as ventricular fibrillation. Both function as sensing and stimulating devices, and most electromyographers are concerned that these devices may be charged improperly during NCS. Existing studies showed that pacemakers or intracardiac defibrillators cannot sense NCS stimulations including supraclavicular stimulations even by using stimulus intensities and durations that probably exceed those routinely used (LaBan et al., 1988; Schoeck et al., 2007; Cronin et al., 2013). The only risk may arise in patients with old pacemakers with monopolar sensing configurations in case high intensity proximal repetitive stimulation is used. This may alter the pacing for 2–3 seconds which will in fact not cause more than lightheadedness in these patients (London, 2017). Some pacemaker or automatic implantable cardioverter-defibrillator companies require the placement of a "magnet" on the devices to monitor heart rhythm during NCS. However, an earlier study showed that magnet-placed patients reported more symptoms so this is not recommended during NCS (Ohira et al., 2013). While modern pacemakers with bipolar configuration and automatic implantable cardioverter-defibrillators implanted below the skin are shown to be safe, NCS are still contraindicated in patients with temporary transvenous cardiac pacemakers because they may have a direct electrical conduit from the surface of the skin to the heart (London, 2017). Peripheral intravenous lines in extremities are safe but for the safety of central venous catheters, further research is necessary. Some authors have suggested in these patients that proximal NCS or NCS in the ipsilateral extremity should not be performed because the catheters in the internal jugular or subclavian veins extend to the heart (Al-Shekhlee et al., 2003) while others did not show any influence of NCS on electrocardiographic monitoring (London, 2017). No interaction was found between NCS and deep brain stimulator devices (London, 2017). It is suggested that caution should be excised in this area.

11.3. Recommendations on electrodiagnostic studies and anticoagulation

In a recent review, no precautions were recommended during needle EMG examinations in patients on warfarin therapy if INR < 3.0 or on antiplatelet medication (London, 2017). If the INR > 3, the studies may be performed at the discretion of the examiner. In both conditions, close surveillance during and immediately after the examination is essential. There is no literature on the risks of heparin or other oral anticoagulant therapy, but precautions are likely to be unnecessary at therapeutic doses. However, a recent survey showed that some electromyographers are as cautious as with warfarin about the novel (direct) oral anticoagulants, particularly for EMG of the paraspinal and facial muscles and single fibre EMG (Lee and Kushlaf, 2018). Prospective risk–benefit studies are necessary to establish safety guidelines.

12. Storage of data and databases

Following the developments in computer technology over the last decades, storage of data is far easier. This has led to more data being recorded and so available for review, and comparison within and between departments. EMG machines store data in different ways; raw signals stored during recording and then reanalyzed when numerical information is needed, or a combination of signals and numerical data that results from algorithms. However, the large increase in data storage is expensive, requires external hard disks or servers, and raises issues about confidentiality. Data are typically copied to the data storage facility of the hospital to allow reliable long-term storage and retrieval.

EMG reports and data should have common EMG terminologies and dataset structures (Johnsen et al., 1994). Telecommunication between laboratories based on these standards would enable exchange of EMG data between laboratories, for consulting, and research on multicentre databases e.g., the international multicenter ESTEEM project (Pugdahl et al., 2017). ESTEEM is a quality development project which has been going on since 1992, and the extensive data collection built up a multicentre EMG database with more than 1000 cases being used for medical audit studies and development of standards and guidelines for EMG practice.

Depending on local security legal aspects, coded diagnostic labels and photos or films may be included with NCS/EMG data. Thus far, manufacturers and different hospitals specialties and nations have not agreed common data protocols for storage, though there are current initiatives on this. One way, not yet used widely, is to use intermediate software to retrieve data from any database and transform these to a common agreed standard that allows more widespread accessibility with necessary security. While necessary, this is likely to prove arduous.

With increasing amounts of data from neurography, quantitative EMG and other methods, there is an obvious need for databases for automatic calculation of deviation from normal, reporting, archive functions, scientific or pure clinical statistical summaries. Many EMG labs now have tens of thousands of patients in databases which are assisting the refinement of electrodiagnosis. As yet, just as there is no international standard for storage, retrieval and exchange of data, there is no standard for data formats, databases and report generators in EMG/NCS. However, the above-mentioned ESTEEM project aims to establish these, and recently an IFCN committee has been constituted to consider a standard format, so that data can be shared among investigators and analyzed on any machine. With a standard format it is possible to build large databases for educational purposes, research on rare disorders, quality development within and between laboratories and for expert consultation. With data mining on large databases from different laboratories, it may be possible to develop artificial intelligence or support systems to assists the examiner in the examination strategy and diagnoses of neuromuscular disorders, now more obtainable than 25 years ago (Vingtoft et al., 1993).

13. Report generators

There are no agreed standards for report generation. General principles have been formulated, but content and layout vary considerable from one EMG lab to the other (Johnson, 1988; Stålberg et al., 1991). A report generally, contains:

- Patient ID data
- Previous and recent medical history; usually a summary of referring request
- The results of a short neurological examination
- Preliminary strategy
- NCS/EMG results, with narrative information, numerical data in tables with sometimes, graphs showing reference limits
- An interpretation of the NCS and EMG
- Other electrodiagnostic parameters
- A general conclusion with the electrodiagnostic findings placed in a context of the patient's presenting complaint. It is paramount that neurophysiological findings relevant and those not relevant to the patient's problem are distinguished. For instance sometimes a mild carpal tunnel syndrome may be irrelevant to someone with a more severe and symptomatic radiculopathy.
- Some laboratories also enclose various signals, other do not but display them on regular rounds (Stålberg et al., 1991). Data in the report can either be imported directly from the EMG machine after editing or produced later from the database.

14. External communication

Remote internet connections for external communication are widely used such as servers within hospitals for storage and administrative functions and for consultations and remote interpretations. Here HL7 standard is recommended. Regional and national interactions are becoming more common and are facilitated by standardization. The transfer of text, signals and video has become more frequent in clinical neurophysiology (Stålberg and Stålberg, 1998; Jabre et al., 2000; Stålberg, 2002) though no standards have evolved. The platforms for such data communication include:

Local Area Networks (LAN): between local equipment, office stations, local server, and between the laboratory network and hospital administrative networks.

Wide Area Networks (WAN): between satellite and central laboratories or to outside laboratories for bilateral consultations. For any communication, local hospital regulations on security and data integrity must be followed. A safe and encrypted VPN connection is recommended for external communication. For an even higher degree of safety, MPLS-VPN may be considered. Live testing of video conference programs is recommended to ensure correct functionality, since some programs are blocked by hospitals for security reasons. For service and educational purposes, it may be useful to have a Remote Support program installed in the EMG machine, is installed which allows a remote trusted user to adjust settings or give advice in critical situations

15. Concluding remarks

EMG machines are now highly sophisticated, and serve not only the performance of tests but also report generation and data storage. To obtain optimal return on the investment in a new machine, the clinical neurophysiologist must understand its workings, be fully aware the effects of different electrodes and different stimulus and recording parameters, and be able to personalize the computer programs. As data accumulates, the EMG machine will become increasingly able to "suggest" the next appropriate steps in an examination and the final diagnosis.

Declaration of Competing Interest

Dr. Sanjeev D Nandedkar is an employee of Natus Medical.

Prof. Seward Rutkove has equity in, and serves a consultant and scientific advisor to, Myolex, Inc. a company that designs impedance devices; he is also a member of the company's Board of Directors; he also holds several patents in the field of electrical impedance.

Prof. Michel J.A.M. van Putten is co-founder of Clinical Science Systems, a company that provides EEG systems and analysis software.

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