INVITED REVIEW

ABSTRACT: The interference pattern of the electrical activity of muscle can be quantified by amplitude measurements, different spike counting methods, and power spectrum analyses. Interference pattern analysis (IPA) methods are used to describe the degree of activation of different muscles, muscle fatigue, occupational work, muscles in chronic pain syndromes, disused muscle, and dystonic muscle treated with botulinum toxin. In patients with neuromuscular disorders, the turns/amplitude analysis is useful for diagnosis. High diagnostic yields can be obtained without force measurements, for example, by using the amplitude as an indicator of force (the peak ratio method) or plotting the amplitude against the turns (cloud analysis). The diagnostic possibilities of the power spectrum analysis and the motor unit firing rate obtained by decomposition techniques are still unclear.
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THE UTILITY OF INTERFERENCE PATTERN ANALYSIS

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Interference pattern analysis (IPA) of the electromyogram (EMG) is a useful tool in the description of muscle activity, muscle fatigue, occupational work, chronic muscle pain, disused muscle, and dystonic muscles treated with botulinum toxin and in the diagnosis of patients with neuromuscular disorders. In the following sections, the IPA in these conditions of human muscle will be described and the utility of the IPA indicated.

With an increase in force from zero up to maximum voluntary contraction (MVC), the EMG shows an increase in number of spikes and amplitude. At weak effort, one can identify individual motor potentials, whereas at higher efforts, there is interference with summation and cancellation of action potential components. In order to quantify the interference pattern (IP), automatic methods are needed. The IPA describes the electrical activity of the muscle from a weak effort up to maximum effort. Motor unit potential analysis[20] may reflect only pathophysiological and physiological changes in motor units recruited at weak effort, whereas IPA may reflect changes in motor units recruited in the whole force range.

Different methods of IPA can be used to evaluate the EMG (Tables 1 and 2).[66] Amplitude measurements and spike counting are methods within the time domain, whereas power spectrum is analyzed within the frequency domain. For more detailed descriptions of the methods, readers are referred to the indicated literature.

For most nondiagnostic purposes, IPA recorded with surface or wire electrodes is more representative of the muscle than that recorded with needle electrodes. In EMG studies of patients with neuromuscular disorders, a concentric or monopolar needle electrode is usually used. In recordings obtained by electrodes with a bigger pick-up area, such as a surface or wire electrode, pathological changes may be obscured.[79,97] With further development, surface EMG may in the future be useful for diagnostic purposes.[108,177]

MUSCLE ACTIVITY AND FORCE

Integrated Electrical Activity and Average Amplitude. The average amplitude or the integrated electrical activity of the IP increases with increasing submaximal force.[99,138] There have been some discrepancies with respect to the shape of this relationship. The relationship is linear or close to linear up to 30% of MVC. At higher force, most studies found

Abbreviations: EMG, electromyography; IP, interference pattern; IPA, interference pattern analysis; MPF, mean power frequency; MVC, maximum voluntary contraction; RMS, root mean square

Key words: electromyography; fatigue; interference pattern analysis; muscle force; neuromuscular disorders

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Table 1. References on IPA methods.*

IPA method	Reference
Amplitude measurement	
Average peak-to-peak amplitude	Hass, 1926[99]
	Møller, 1966[152]
Amplitude after full-wave rectification and low-pass filtering	Inman et al., 1952[110]
	Møller, 1966[152]
	Stephens and Taylor, 1972[194]
RMS amplitude	Stetson and Boumann, 1933[195]
	Johnson, 1978[115]
Integrated electrical activity	Snyder et al., 1949[192]
	Lippold, 1952[138]
	Woods and Bigland-Ritchie, 1978[210]
Frequency analysis	
Power spectrum	Richardson, 1951[175]
	Walton, 1952[205]
	Kaiser and Petersén, 1963[120]
	Christensen and Fuglsang-Frederiksen, 1986[27]
	De Luca, 1997[42]
Spike counting	
No. of spikes per time unit	Hass, 1926[99]
	Close et al., 1960[35]
No. of zero crossings per time unit	Fusfeld, 1971[84]
	Hägg, 1981[93]
No. of turns per time unit	Willison, 1964[207]
	Fuglsang-Frederiksen and Månson, 1975[73]
	Jørgensen and Fuglsang-Frederiksen, 1991[116]
Motor unit firing rate	
Decomposition	Mambrito and De Luca, 1984[141]
	McGill and Dorfman, 1985[147]

For more details on early references see Fuglsang-Frederiksen.[66]

the amplitude to increase more than the force.[66] Some of the differences are probably due to differences in methods, the different muscles studied, and different degrees of fatigue. The mean amplitude per turns of the turns/amplitude analysis increases linearly with force up to MVC.[29] The increase in amplitude with increasing force is due to recruitment of motor units with large amplitudes[103] and to summation of action potentials.[66]

Number Of Spikes Per Time Unit. As early as 1926, Haas[99] found that the number of spikes per time unit of the needle EMG increased with increasing force at low forces. The number of zero crossings of 100 µV or more per time unit increased with increasing submaximal force up to 40% to 60% of MVC and thereafter leveled off.[29,35] Willison[207] found that the number of turns per time unit increased with force up to 2 kg in the brachial triceps muscle, corresponding to 12% to 30% of MVC. Later studies showed that the number of turns per time unit increased up to about 50% of MVC and above that leveled off (Fig. 1).[29,73] The number of spikes of the IPA is influenced by the number of motor units recruited and their firing rate up to about 50% MVC, but this relation is obscured above 50% MVC, probably due to interference of action potentials with cancellation of small spikes.[66]

Power Spectrum Analysis. The first studies analyzing the power spectrum of needle EMG found the distribution of frequencies to be independent of muscle force.[53,205] A later study examined the relation between the power spectrum of the IP and the force in more detail.[27] They found a decrease in high/low ratio, i.e., a decrease in high frequencies/

Table 2. Definitions of IPA terms.

Term	Definition
Integrated activity	Integration of the area of the rectified electrical activity per time unit.
RMS	Root mean square: the square of amplitude is averaged by filtering, followed by the calculation of the root.
Zero crossings	Number of voltage crossings of the baseline per time units, often with a trigger level of, for example, 100 µV, to avoid noise.
Turns amplitude*	Turns: number of potential reversals of more than 100 µV per time unit (independent of baseline).
	Mean amplitude: average of amplitude between two turns.
	Ratio: number of turns per time unit divided by mean amplitude.
	Number of small time intervals: number of time intervals between two turns, which is less than, e.g., 1.5 ms.
	Number of small segments: as above.
	Activity: summation of time intervals between two turns encountered during, for example, 1s.
Power spectrum†	Mean: the average frequency.
	Median: that frequency which splits the area of the power spectrum histogram into two parts of the same size.
	Total power: sum of squared amplitude.
	Power of a certain frequency: the power in a certain frequency band, for example, 1400 Hz.
Firing rate of individual motor units	The firing rate or firing frequency is usually obtained by some kind of decomposition.

**Values are usually calculated corresponding to 1 s.*
†Often fast Fourier transformation is used. The signal is decomposed into sinus waves of different frequencies and shown as a histogram of squared amplitude against frequency.

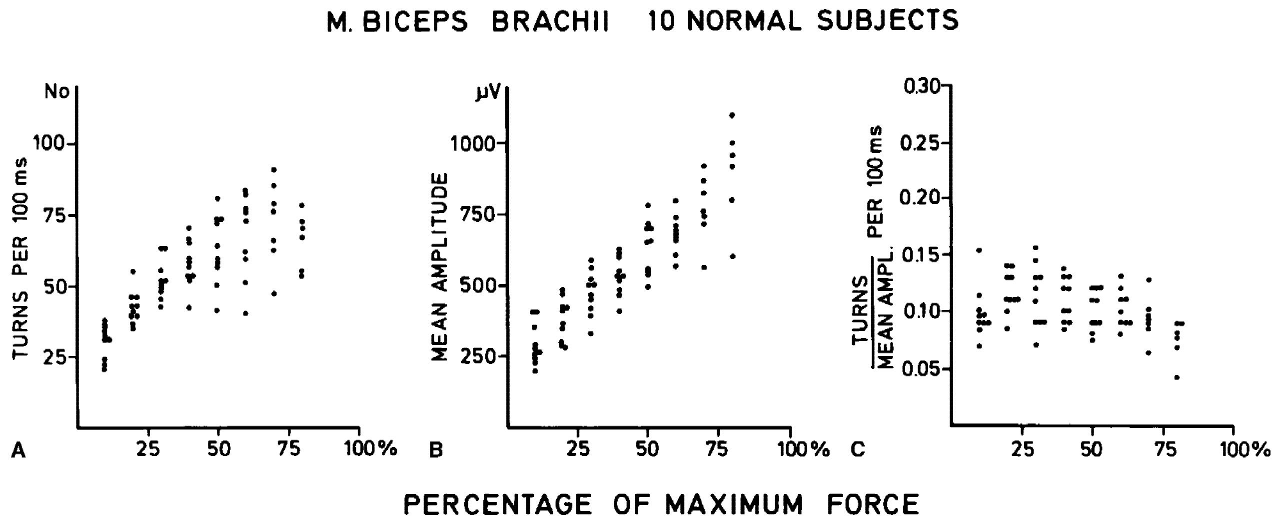

FIGURE 1. (A) Number of turns per 100 ms, **(B)** mean amplitude per turns, and **(C)** ratio related to the gradually increasing force. Each point is the mean of three recordings, and the lines join mean values, biceps brachii muscle, 10 subjects. (From Christensen et al.,[29] with permission from Elsevier Science).

increase in low frequencies of the needle EMG with increasing force from 10% to 80% of MVC. The decrease in frequency with an increase in force is possibly due to an increase in summation and cancellation of action potentials. Surprisingly, the mean power frequency (MPF) of the needle EMG increased with increasing firing rate of motor units between subjects.[77] In contrast to needle recordings, surface recordings showed an increase in MPF from zero to 20% MVC but were unchanged between 20% and 50% MVC.[95] The increase in frequency with force may be due to a decrease in low-pass filter effect of tissue as more motor units near the surface of the muscle are recruited. In kinesiology studies, interaction of different muscles contributing to the same action may be quantified by the methods mentioned above.[42,46,73]

Comments. During the last 70 years, knowledge about the function of the muscle has increased greatly, partly due to studies involving IPA. Nonetheless, our understanding of how the IP is built up is not complete, indicating a need for more studies. The motor unit activity during muscle activation has been studied by various decomposition techniques but is outside the scope of this article. (References are provided elsewhere.[39])

MUSCLE FATIGUE

During a sustained muscle contraction, different IPA techniques can be used to describe and monitor the degree of fatigue. Fatigue can be defined as the inability to generate the maximum force produced by the muscle in its fresh state.[142] With increasing time of sustained isometric contraction, either maximal or submaximal, median and mean power of the power spectrum analysis decreases (Fig. 2), probably due to a decrease in conduction velocity along the fatigued muscle fibers and possibly due to synchronization,[2,3,10,13,16,21,28,30,42,118,122,133,134,137,151,155,156,158,171] although the latter statement is controversial.[42] The decrease in conduction velocity along the fatigued muscle fiber is not fully understood but may be due to low intracellular pH and increased extracellular potassium concentration.[117] The number of spikes per time unit (i.e., number of zero crossings and number of turns)[11,30,43,93,109] and the amplitude of the IP[12,30,48,149,194] decrease during a sustained MVC, due to drop-out of motor units and decrease in their firing rate,[11,12,143] possibly due to an inhibitory peripheral reflex,[183] decrease in conduction velocity along fatigued muscle fibers, and synchronous firing of motor units.[30] During a sustained moderate to high submaximal contraction, the amplitude may increase or decrease due to the opposing influence of several of the mechanisms mentioned above, and the number of spikes decreases.[28,60,66,145,204] During submaximal force, recruitment of more motor units or increase in their firing rate in order to sustain the force may contribute to an increase in amplitude.[3,28,66] The fatigability of muscle during a sustained low submaximal force (e.g., 10% of MVC) is controversial.[28,119] A recovery period of 10 min after 1 h of a sustained contraction of 10% MVC was not enough to restore the muscle in one study.[28]

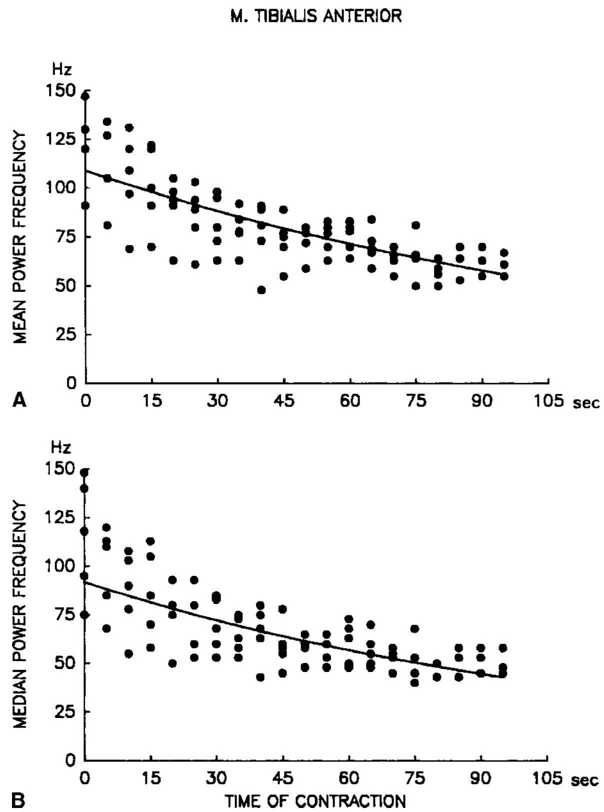

FIGURE 2. (A) Mean power frequency and **(B)** median power frequency for the anterior tibial muscle of five subjects during sustained maximal effort. (Modified from Christensen et al.,[30] with permission from Elsevier Science).

After some time of sustained contraction (1 min of sustained maximal effort and 10 min of a sustained force of 10% of MVC), the amplitude continues to increase, but there is no further decrease in mean and median power frequencies and number of turns per second (Fig. 3).[28,30] This increase in ratio of electrical activity to force may reflect contractile element fatigue (i.e., more motor units are needed to exert the same force).[122,194]

The changes in mean and median frequency of the power spectrum of the EMG during the initial sustained contraction may be used to predict the endurance time of the contraction.[150,203] Turns and amplitude analyzed during submaximal contractions have been used to evaluate postoperative fatigue.[31] In the early postoperative period, a decrease in amplitude and number of the turns per second at a force of 30% MVC, associated with a decrease in MVC, suggested a functional impairment probably of central origin. In the late postoperative period, an early increase in amplitude during a sustained submaximal contraction suggested an early onset of muscle fatigue. In dynamic contractions, it remains unclear whether frequency parameters are suitable as indicators of muscle fatigue.[157,202]

OCCUPATIONAL WORK

The role of muscle fatigue is of importance in occupational long-term work. One study of occupational long-term work with muscle contractions mostly between 7% and 33% did not show any EMG changes in amplitude and power spectrum indicating fatigue.[26] Similarly, intermittent contractions of a low force of, e.g., 20% of maximum for 1 h, gave no sign of fatigue in the EMG.[28] The number of zero crossings per time unit has also been used in occupational studies.[94] A study of light assembly work found that after 6 h, there was an increase in EMG amplitude and a decrease in number of zero crossings per time unit, indicating fatigue.[144] These changes recovered 4 h after work. An increase in EMG amplitude and a shift towards lower frequencies were found in muscles of urological surgeons during operation, indicating some muscular fatigue.[140] Electromyography (EMG) may be used to obtain information about the load on individual muscles during work, using the amplitude probability distribution function.[14,26,95,96]

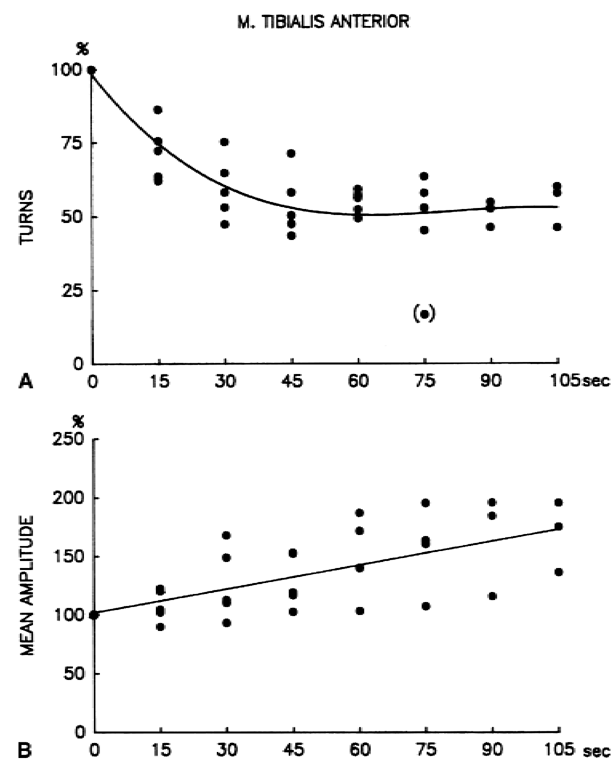

FIGURE 3. Values in fatigued muscle (sustained maximal effort) as a percentage of values in fresh muscle at the same force in the anterior tibial muscle of five subjects as a function of time. **(A)** Number of turns. **(B)** Mean amplitude. (Modified from Christensen et al.,[30] with permission from Elsevier Science).

CHRONIC MUSCLE PAIN

Tension-Type Headache. The international headache classification recommends evaluation of EMG in pericranial muscles in order to classify patients with tension-type headache.[105] However, the value of EMG in the classification of headache patients has been debated. Electromyography of pericranial muscles of subjects with chronic tension-type headache, and probably also in subjects with very frequent episodic tension-type headache, shows increased amplitude at rest compared with controls[100,111,114,185] and during function.[32] In the study by Jensen et al.,[114] the EMG method was validated and found reliable, and correction for influence of sex and age was obtained from a population study.[112,113] The increase in amplitude is probably due to increased tension of the muscle. During MVC, subjects with chronic tension headache show a decrease in mean and median frequency of EMG of pericranial muscles.[114,201] This decrease was more pronounced in patients with frequent headache than in those with less frequent headache.[114] The decrease in frequency may be due to muscle fatigue or to a shift in fiber-type distribution.[88] In a recent review, the belief that subjects with tension-type headache have increased EMG amplitude at rest was questioned.[209] The EMG changes in tension-type headache are seen only in group comparisons but nonetheless indicate a peripheral factor. The fact that the EMG may not differentiate individual subjects from controls indicates that the diagnostic value of EMG in tension-type headache is limited.

Low Back Pain. The rate of lumbar paraspinal muscle fatigue measured by median frequency of the EMG power spectrum during endurance is faster in patients with chronic low back pain than in controls.[180,181] Similar findings were seen in the gluteus maximus muscle.[121] The changes in frequency parameters of the EMG may be used to distinguish individuals who have low back pain from those who do not.[42]

Orofacial Pain. In patients with orofacial pain, the amplitudes of the EMG of masseter and temporalis muscles show an increased level of postural activity compared with controls.[4,5,44,182] The reason for this is not fully understood. The activity could be a response to the pain[197,213] or, more likely, part of the mechanisms involved in pain development.[6,153] Thus, after treatment, a reduction of symptoms and signs was associated with a reduction of postural EMG activity in the temporalis and masseter muscles.[187]

Myofascial Trigger Points. Myofascial trigger points show higher average amplitude (root mean square, RMS) of the needle EMG at rest in muscles of humans[107] and of rabbits[189] compared with control points. This finding was confirmed in a study in which the physician who performed the needle EMG was blinded with respect to trigger point versus control point of the muscle (Couppé, Fuglsang-Frederiksen, Hilden, Midttun, Jørgensen, Oxholm, unpublished findings). Visual analysis of the EMG activity in trigger points at rest suggests this activity to be due to electric activity originating in the end-plate zone.[22,51,206]

DISUSED MUSCLE

The effect of inactivity on the force produced during MVC has been studied with the turns/amplitude analysis.[78] In eight patients, the leg was immobilized for 4 weeks by a plaster cast because of a lesion of the medial collateral ligament of the knee. After removal of the cast, the force increased faster than could be accounted for by an increase in the cross-sectional area of the muscle fiber (Fig. 4). On the day after removal of the cast, when the patient could just bend his knee (day 0), the force of the disused quadriceps muscle was diminished by 40% to 80% compared with the force of the contralateral muscle. Eight days later, the decrease in force was only 15% to 30%. From day 8 to day 30, the force recovered more slowly and reached about 90% of the force of the contralateral quadriceps muscle. In the disused quadriceps muscle examined at a force of 10% (or 30%) of MVC at day 0, turns per second and the mean amplitude per turns were diminished (Fig. 4), consistent with functional loss of active motor units. Eight days later, when most of the force had been regained, turns per second and mean amplitude were again normal. The same was the case 3 weeks later. The slow increase in force after day 8 is probably solely due to an increase in the cross-sectional area of the muscle fibers.[78]

In another study, muscle activation was decreased in patients with disused muscle due to previously immobilized ankle fractures compared with controls.[9] Muscle activation was measured using compound muscle action potentials superimposed on the integrated EMG of the voluntary contraction of plantar flexors of the foot. Reversible motor dysfunction as described above may be due to lack of sensory feedback. The rapid reactivation of motor units is an example of the plasticity of the nervous system in the regulation of voluntary effort.[78] One may hypothesize that the immobilization transiently introduces a change in the cortical network representing the specific movement. Actually, the cortical

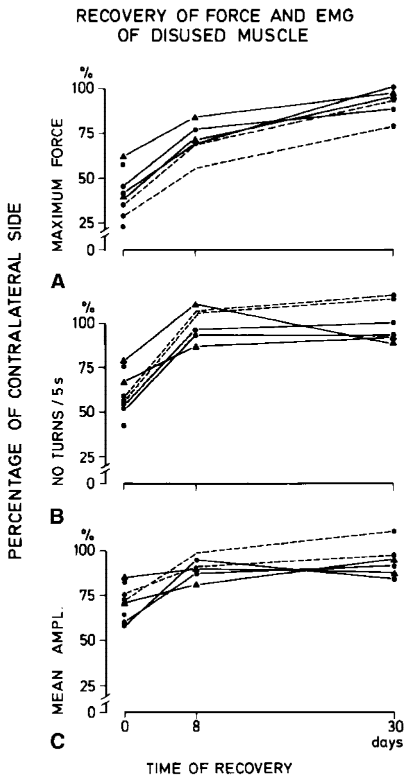

FIGURE 4. (A) Maximum voluntary contraction, **(B)** turns per second, and **(C)** mean amplitude per turns in the disused quadriceps muscle in percentage of the healthy contralateral muscle. The abscissa denotes days after the patient could just bend his knee to 90° or to 45°. (Modified from Fuglsang-Frederiksen and Scheel,[78] with permission from BMJ Publishing group).

representation of the movement of the ankle joint obtained by transcranial magnetic stimulation was diminished in patients with an immobilized ankle joint.[129] Similarly, a change in cortical representation of the thumb was seen after training of the movement.[33] Another possible explanation could be "silent synapses," as suggested by McComas[146] and in agreement with the finding of some motor units without force in the posterior tibial muscle of cat after disuse.[176]

Interference pattern analysis of disused muscles has thus hinted at a high plasticity of the nervous system. New information on the pathophysiology of disused muscle will probably be obtained by newer methods, such as mapping of functional cortical areas by magnetic stimulation.

DYSTONIC MUSCLES

Quantitative EMG seems helpful in the localization and evaluation of dystonic muscles in patients with torticollis.[167] In a comparison of the effect of botulinum toxin treatment of dystonic muscles with and without EMG assistance in patients with torticollis, a significantly greater magnitude of improvement was present in the group with EMG assistance.[38] Analysis of turns and mean amplitude per turns of the EMG of dystonic muscles in patients with torticollis shows a decline in muscle activity after botulinum toxin treatment (Fig. 5).[19,56,82,167] Similar changes are seen in spastic hyperactivity.[55] "Geste antagonistique" did not cause any additional reduction in turns per second and amplitude of the EMG of dystonic muscle during maintenance of midposition of the head of patients with torticollis.[18] An increase in ratio of turns to amplitude 6 weeks or more after botulinum toxin treatment suggest a reversible, random loss of muscle fibers.[65,81,168] This finding accords with the decreased mean duration of individual motor unit potentials that occurs after treatment.[166] In long-term treatment with botulinum toxin (i.e., on average, 1½ year) the noninjected sternocleidomastoid muscle showed a decrease in turns per second and amplitude at MVC, indicating an inability to recruit all motor units or a decrease in their firing rate.[49,169] This may be due to spreading of the botulinum toxin by blood or retrograde axonal transport or to a feedback mechanism in the motor control system.

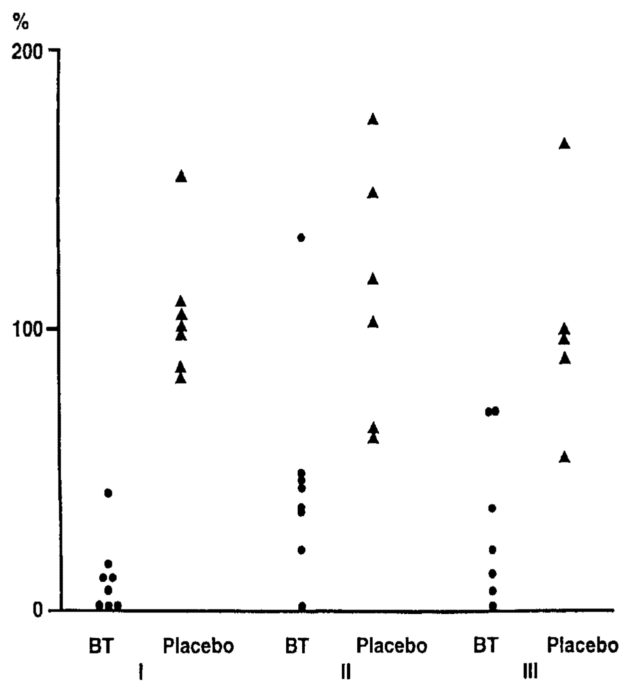

FIGURE 5. Turns per second 6 weeks after treatment in percentage of pretreatment values, i.e., 100% corresponds to the pretreatment value at rest. Individual values: I, contralateral sternocleidomastoid muscle; II, ipsilateral posterior neck muscles; III, contralateral posterior neck muscles. (Modified from Østergaard et al.,[168] with permission from Elsevier Science).

Turns/amplitude analysis is also very useful in botulinum toxin treatment of patients with laryngeal dystonia[41,75,139] and patients with oromandibular dystonia[50] and has been used to characterize the EMG of patients with diaphragmatic myoclonus.[25,36]

An argument that speaks in favor of using IPA during treatment of dystonic muscle is that the amount of botulinum toxin may be minimized both by selection of muscles with proven involvement and to some extent by quantifying the abnormal activity. It seems reasonable that such monitoring of muscle function should be offered when patients are treated with a potential poison.

NEUROMUSCULAR DISORDERS

Number of Zero Crossings. In order to differentiate patients with neuromuscular disorders from controls, Close[34] suggested that the number of zero crossings per time unit should be analyzed. In patients with myopathy, Fusfeld[85] found that 53% had increased number of zero crossings per time unit compared with controls at a force level where interference was seen. Kopec and Hausmanowa-Petrusewicz[124] found the number of zero crossings (or the number of intervals between successive spikes, called "density") at MVC to be an accurate method for differentiating patients with myopathy and patients with neurogenic diseases from normal subjects. The mean phase duration of the IP weighted with respect to amplitude was measured at MVC in children with myopathy.[154] The method is similar to the measurement of the number of zero crossings. The mean value of the mean phase duration from each muscle was increased in 60% of the patients.

Others have found analysis of zero crossings to be of little use in diagnosing patients with neuromuscular disorders.[188] Zero crossings and turns were compared in patients with myopathy and neurogenic disorders and controls, during a gradual increase in force from zero to maximum.[71] The highest sensitivity of number of zero crossings per second was seen between 10% and 40% of maximum force. The degree of abnormal findings of the analysis of turns was the same as that of the analysis of zero crossings. In agreement with this, the number of zero crossings was linearly related to the number of turns in controls, patients with myopathy, and patients with neuropathy (Fig. 6). In other words, although the number of zero crossings often was abnormal in some muscles of the patients, the method was neither superior nor supplementary to the turns/amplitude analysis.

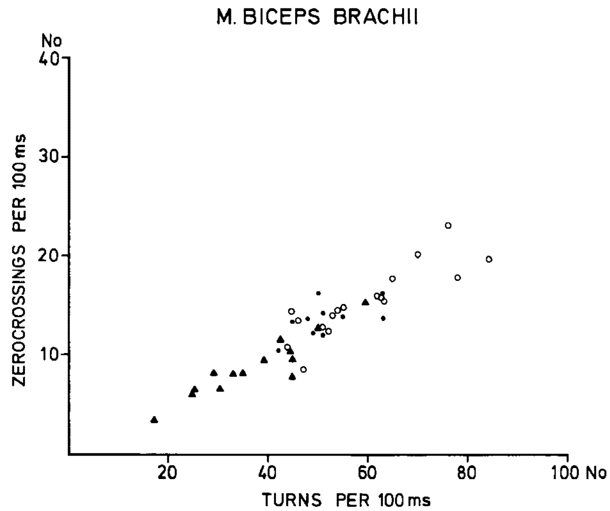

FIGURE 6. Number of zero crossings as a function of turns obtained at a force of 30% of maximum in patients with myopathy (open circles), patients with neurogenic disorders (triangles), and controls (closed circles). (Modified from Fuglsang-Frederiksen et al.,[71] with permission from Elsevier Science).

Integration of Electrical Activity. In patients with myopathy, the integrated electrical activity increases as a function of force in kilograms with a steeper slope of integrated activity against force in kilograms than in normal muscle.[87,128,190] This is also true in patients with poliomyelitis.[128] These findings are probably nonspecific due to weakness of the muscle, as a weak but healthy muscle has a steeper slope of integrated activity against force in kilograms than a strong one.[29] When the force is expressed in percentage of MVC, the slope of integrated electrical activity against percent force is the same regardless of whether subjects have myopathy or neuropathy or are healthy. The integrated electrical activity at a force relative to MVC is decreased both in patients with myopathy and in patients with neurogenic disorders. Thus, the analysis of the integrated electrical activity, although often abnormal in diseased muscle, cannot be used to differentiate between myopathy and neuropathy. The integrated activity is linearly related to the amplitude of the turns analysis in controls and patients and had the same diagnostic sensitivity (Fig. 7).[71]

Plotting of integrated electrical activity against number of zero crossings per time unit during increasing voluntary contraction was found to differentiate a muscle of a patient with Erb's palsy (high integrated electrical activity/low zero crossings) from a control muscle and from a muscle of a patient with muscular dystrophy (low integrated electrical activity/high zero crossings).[34] These findings were later confirmed in patients with neuromuscular dis-

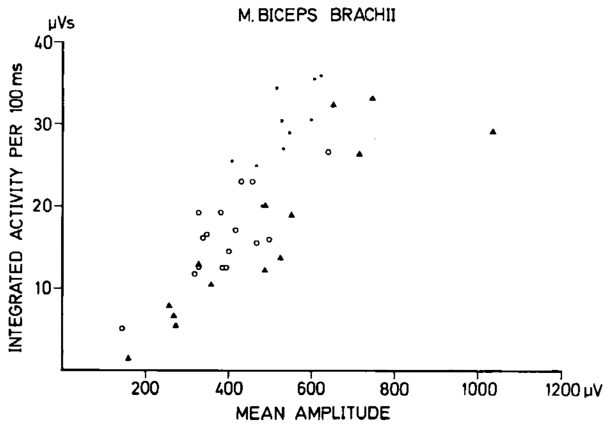

FIGURE 7. Integrated electrical activity as a function of mean amplitude per turns obtained at a force of 40% of maximum in patients with myopathy (open circles), patients with neurogenic disorders (triangles), and controls (closed circles). (Modified from Fuglsang-Frederiksen et al.,[71] with permission from Elsevier Science).

orders.[71,125] In the same patients, the sensitivity of turns/amplitude analysis was higher than that of the plot of integrated activity against number of zero crossings.[71] The analysis of the plot of integrated electrical activity against the number of zero crossings is similar to the modification of turns amplitude analysis with plotting of mean amplitude against turns.[193]

Power Spectrum Analysis. The frequency spectrum of the EMG is displaced towards higher frequencies in patients with myopathy than in normal subjects.[175] The findings of an increase in high frequencies in muscles of patients with myopathy[205] and an increase in low frequencies in muscles of patients with neuropathy[126] suggested that the spectrum analysis could be used as a diagnostic tool. Kopec and Hausmanowa-Petrusewicz[123] compared the frequency spectrum analysis with measurement of duration of motor unit potentials. The authors found the analysis of the frequency spectrum to be less sensitive for recognizing myopathy than the measurement of motor unit potentials. Similarly, Gardner-Medwin[87] concluded that the analysis of individual motor unit potentials was more sensitive for detecting myopathy than was the analysis of the frequency spectrum. Other studies[135,184,212] of the power spectrum of EMG in patients with neuromuscular disorders have not clarified the diagnostic possibilities.

The earlier studies used a simple form of spectrum analysis with analogue octave band filters. It is now possible to use fast Fourier transformation with a higher resolution (Fig. 8). In patients and controls, MPF, the power at 140 Hz, 1400 Hz, 2800 Hz, and 4200 Hz in parts per million of the total power, and the high/low ratio were obtained at force of 10% MVC and 30% MVC.[178] The best diagnostic param-

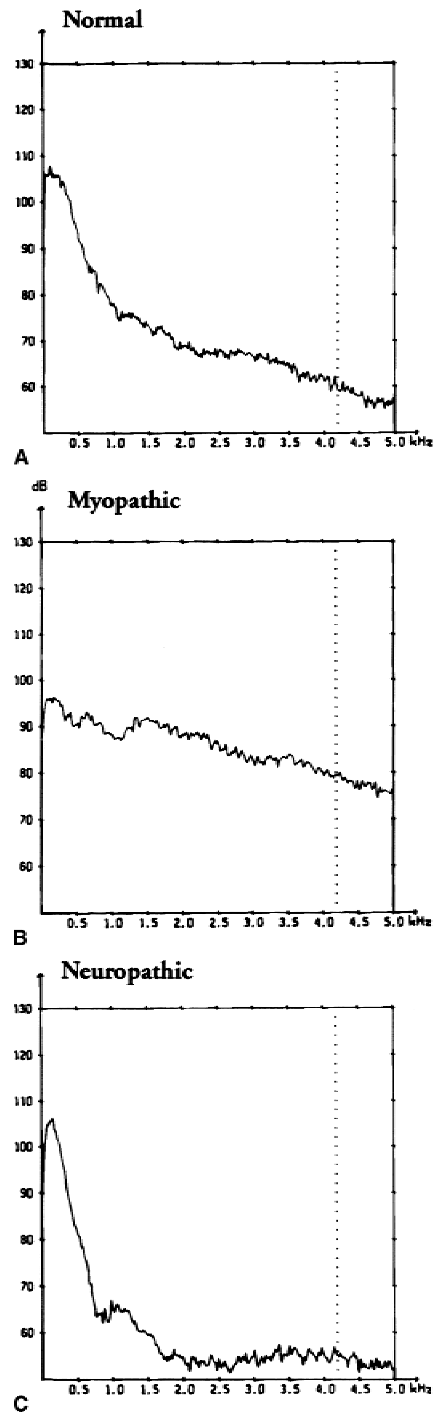

FIGURE 8. Examples of power spectra of EMG from one site in the brachial biceps muscle from **(A)** a control subject, **(B)** a patient with myopathy, and **(C)** a patient with neurogenic lesion. (Ordinate, power in dB; abscissa, kHz.) (From Rønager et al.,[178] with permission from Elsevier Science).

eters of the spectrum analysis were the relative power at the 1400 Hz window and the MPF.[178] In 55% of 20 patients with myopathy, the power spectrum showed a displacement towards higher frequencies. The diagnostic yield of the turns/amplitude analysis and of the measurement of the duration of individual motor unit potentials was about the same as that of the power spectrum.[76] However, the methods supplemented each other. In 11 patients with neurogenic disorders, the power spectrum analysis showed displacement towards lower frequencies. Neurogenic lesion was indicated by power spectrum analysis in 64%, by turns analysis in 73%, and by duration measurement in 91% of the patients. The proportion of high frequencies increased with increasing ratio of turns to mean amplitude in pathological muscles (Fig. 9). The sensitivity of spectrum analysis was higher at 30% of MVC than at 10% of MVC, indicating the necessity of analysis at a given force. Neural network analysis of the frequency analysis of IPA at MVC in patients with neuromuscular disorders gave diagnostic yields of 60% to 80%, similar to that of the turns/amplitude analysis.[1]

The number of zero crossings and the number of turns can be obtained from the normalized spectral moments of higher orders.[136,174] However, one should be aware that when zero crossings and turns are obtained from the frequency domain, there is no threshold for avoiding small potentials due to noise. This is in contrast to zero crossings and turns obtained from the time domain and may well change both the relationships to force and the diagnostic possibilities.

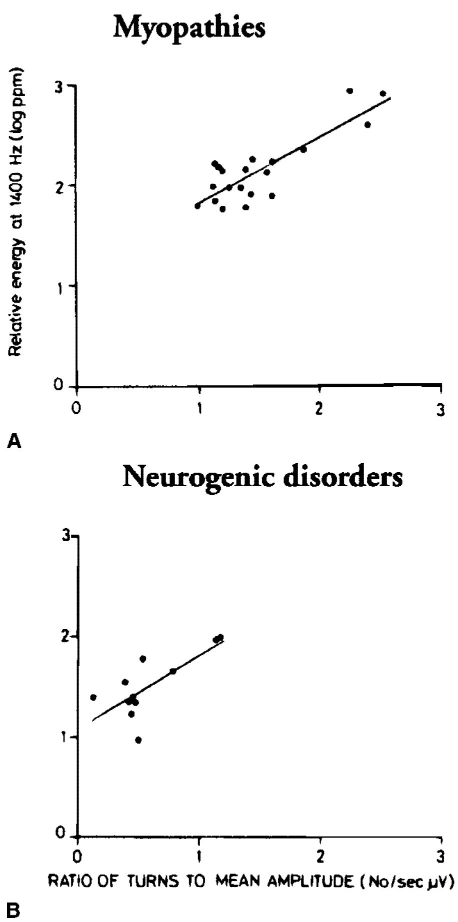

FIGURE 9. Power at 1400 Hz in parts per million of total power (ppm, logarithmic values) as a function of the ratio of turns to mean amplitude in **(A)** 20 patients with myopathy and **(B)** 11 patients with neurogenic disorders. Each point indicates the mean of 10 sites in the brachial biceps muscle of one patient. (Modified from Fuglsang-Frederiksen et al.,[76] with permission from Elsevier Science).

Analysis of Motor Unit Firing Rate. Visual qualitative analysis of the firing rate of motor units has been related to the degree of muscle contraction.[170] In myopathy, early recruitment may be seen, i.e., too many motor unit potentials are present in the IP for the level of muscle contraction. In patients with neurogenic lesions, discrete activity of the IP may been seen at maximum MVC as an expression of loss of motor units. The literature about the diagnostic possibility of quantitative analysis of motor unit firing rate is conflicting. Fuglsang-Frederiksen et al.[83] found the same firing rate at a force of 10% of MVC in patients with myopathy, patients with neurogenic disorders, and controls. However, with the decomposition techniques, it is possible to analyze the firing rate at higher efforts.[39,141,147]

At 30% of MVC or higher force levels, the motor unit firing rate is increased in patients with myopathy.[45,172] More studies are needed to obtain precise information on sensitivity and specificity of the methods.

Turns/Amplitude Analysis at Different Force Levels. A manual turns/amplitude analysis was introduced by Willison[207] in the 1960s. A few years later, an automatic analog turns/amplitude analysis was introduced.[64] Analysis of the IP at a given force of 2 kg showed increased number of turns per second in most patients with myopathy, in some patients associated with decreased mean amplitude per turns.[37,74,79,179,200,207] The diagnostic yield of the turns/amplitude analysis at a force of 2 kg was found to be of the same order as that of conventional EMG.[37,173,214] In patients with neurogenic disorders, analysis of the EMG IP at a force of 2 or 5 kg showed an increase in mean amplitude associated with normal number of turns per second.[52,80,102–104] However, at a given force (e.g., 2 kg), the number of turns per second increases with decreasing strength of the muscle of control subjects,[73] i.e., the weaker the subject, the higher the number of turns per second. Measurement of increased number of turns per second at a force of 2 kg in a weak subject may therefore suggest a false-positive finding of myopathy.[79]

Analysis of turns/amplitude at a force fixed relative to maximum (e.g., 30% of MVC) in muscles from patients with myopathy or neurogenic disorders indicated that this method was better at discriminating between myopathic, neurogenic, and normal muscle than analysis at a force of 2 or 0.3 kg.[15,79,80,98] The number of turns per second was increased and mean amplitude per turns decreased in myopathic muscles, whereas the opposite was the case in neurogenic muscles. Two other parameters of the turns/amplitude analysis supplement the number of turns per second and the mean amplitude: (1) the ratio of turns to mean amplitude, which was increased in patients with myopathy and decreased in patients with neurogenic disorders[40,79,80,91,186,191]; and (2) the number of small time intervals between turns (e.g., less than 1.5 ms per time unit), which was increased in patients with myopathy and decreased in patients with neurogenic disorders.[47,79,80]

Turns/amplitude analysis at a force of 30% of maximum and analysis of individual motor unit potentials sampled at weak effort were compared in the brachial biceps muscle of 38 patients with muscular dystrophy and 30 patient with neurogenic disorders.[79,80] The two methods gave a similar diagnostic yield and supplemented each other. Analysis at higher force levels did not improve the turns/amplitude method,[58,66,69,86,101,106,188] nor did a modified method analyzing RMS divided by turns.[63]

Detection of carriers of Duchenne dystrophy may be supported by turns/amplitude analysis in a few patients.[47,59,200,208] In patients with myasthenia gravis, turns/amplitude analysis has shown conflicting results.[40,70]

Analysis of turns/amplitude at a given force level of the muscle requires cooperation of the patient. The given force is not possible to obtain for all muscles and is time consuming to obtain. Therefore, several modifications of turns/amplitude analysis have been suggested, disregarding estimation of muscle force (see below).[24,68,72,90,161,193] Although a curvilinear relationship between cumulated amplitude per second (corresponding to turns × mean amplitude) and turns per second[199] seems promising with respect to differentiating patients with neuromuscular disorders from controls,[89,90] the results have not been compared with those of a known method.

To diminish noise in the turns/amplitude analysis, a threshold of 100 μV is usually used. Some authors have considered other levels of threshold.[79,98,196,207,211] The influence of age, sex, and temperature on the turns/amplitude parameter is minor or nonexistent.[58,60,73,130,193]

Cloud, Activity, and Number of Small Segments. A plot of mean amplitude as a function of turns can be obtained without measurement of force. The distribution of values from control subjects measured at low and high forces of the muscle, respectively, at 20 sites in each muscle has been called "the cloud."[193] If one subject had two points outside this cloud, it was considered pathological. In patients with myopathy, mean amplitude/turns values were found to be low, whereas patients with neurogenic lesions had high values. In patients with mitochondrial cytopathy, the sensitivity of the cloud analysis is rather low in comparison with that of single-fiber EMG and macro EMG.[92,198] The cloud analysis has been examined and compared with motor unit potential analysis in patients with myopathy, controls, and neuropathy (Fig. 10).[165] The sensitivity of the cloud analysis was about 74%, and the sensitivity of the individual motor unit potential analysis was about 49%, whereas the specificity was the same for the two methods (i.e., 80%). In nine mildly affected patients with poliomyelitis, 87% of the muscles examined had a neurogenic pattern with the cloud method, whereas 97% of the muscles had an increased fiber density.[17] The method may give rise to false-negative findings in patients with myopathy. In half of 17 patients with myopathy, the force level had an influence on the sensitivity of the cloud method. In these patients, values obtained between 10% and 30% of the MVC were abnormal, indicating myopathy, but at force levels above 50% of MVC the values disappeared into the normal range and the pathology was obscured.[69] Nandedkar et al.[162] showed that if mean amplitude/turns values were obtained at near MVC in control subjects, these values were actually above the limits of the original cloud introduced by Stålberg et al.[193] This means that control subjects may have values outside the cloud, falsely indicating neurogenic lesion.

The same group later developed a modification of the cloud analysis.[160,161,163,164] In an attempt to extract parameters similar to those used visually by the clinical neurophysiologist, three parameters were developed: activity, upper-centile amplitude,

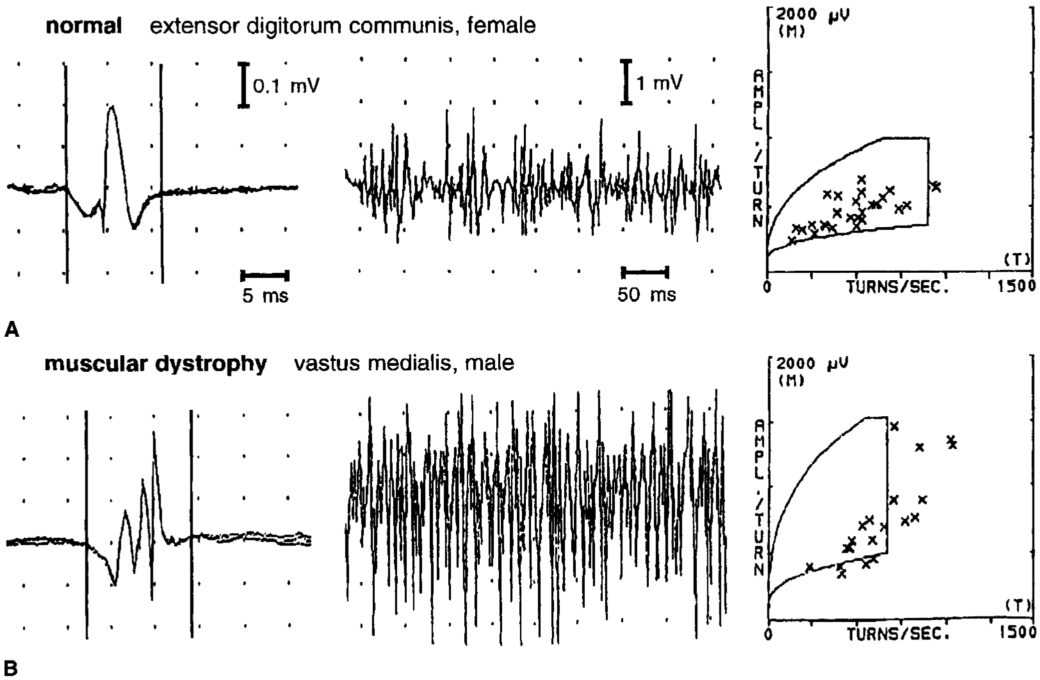

FIGURE 10. Typical results showing a representative motor unit potential, a representative IP, and the mean amplitude vs. turns cloud of IPA. **(A)** Normal subject. **(B)** Patient with normal mean motor unit potential duration and increased polyphasia. Interference pattern analysis shows many points with increased turns per second and normal mean amplitude. (Modified from Nirkko et al.,[165] 1995, with permission from Elsevier Science).

and number of small segments. Activity corresponds to the time within an epoch during which motor unit action potentials are present. This means that activity quantifies the fullness of the IP. Activity is the sum of the duration of segments between turns (i.e., the time intervals between turns) below a duration of 1.5 to 3.0 ms, depending on the amplitude (i.e., long segments corresponding to a flat baseline are excluded). Upper-centile amplitude, or the envelope amplitude,[159] quantifies the amplitude of the largest spikes of the IP. Number of small segments corresponds to number of turns obtained from voltage variation within the motor unit potentials, excluding turns obtained between motor unit potentials. The number of small segments is the sum of the segments below a certain duration, depending on the amplitude, e.g., less than 1.5 ms for segments with amplitude of up to 0.5 mV. A muscle is considered abnormal if more than 10% of the analyzed epochs are outside the upper-centile amplitude/activity cloud or the number of small segment/activity cloud. Control values have been published.[160,161]

In a study of the brachial biceps muscle of eight patients with motor neuron disorders, the upper-centile amplitude was increased compared with controls in all patients. All patients had datum points above the cloud of upper-centile amplitude against activity.[161] The number of small segments was decreased or normal. Fullness of IP, i.e., activity, was incomplete in two patients but full in the others.

In muscles from nine patients with myopathy, the number of small segments was increased in all, though the datum points were usually within the normal cloud of number of small segments against activity. Upper-centile amplitude was normal or reduced. The fullness of IP was incomplete in one patient. In all patients, the interpretation from the plots agreed with qualitative assessments of the IP made by a clinical neurophysiologist. In muscles from 37 patients with inflammatory myopathy, analysis of the IP was more sensitive than motor unit potential analysis: 78% of the patients demonstrated a myopathic IP, whereas 67% had myopathic motor unit potentials using an averaging method (Fig. 11).[7] Similarly, the sensitivity of the IPA was high in patients with sporadic inclusion body myositis.[8] Using a stepwise linear discriminant analysis method, 81% of all studies were accurately classified as being normal, myopathic, or neuropathic.[23] The method is now available as part of commercial EMG equipment.

Peak Ratio. The peak ratio method is a modification of the turns/amplitude analysis disregarding

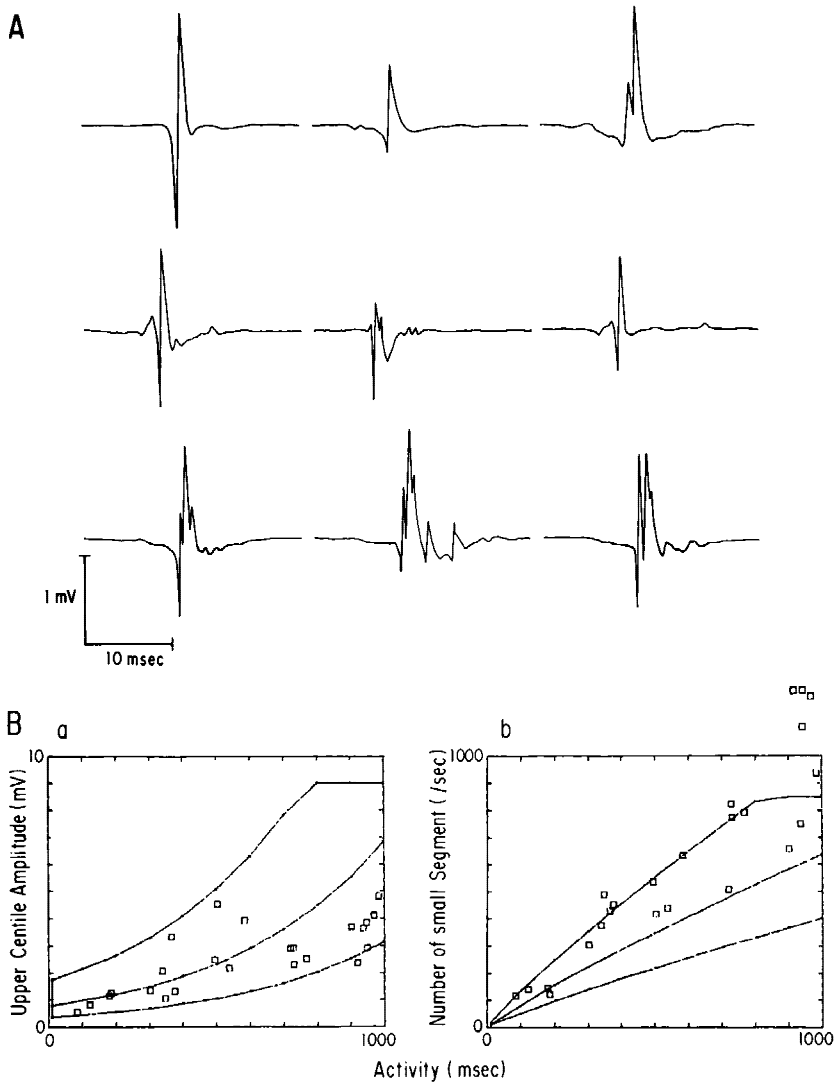

FIGURE 11. From a muscle of a patient with inflammatory myopathy. **(A)** Individual motor unit potentials. **(B)** Interference pattern analysis. (From Barkhaus et al.,[7] with permission from John Wiley & Sons, Inc.).

force measurement, i.e., the maximum value of the ratio of turns per second to mean amplitude obtained by using the mean amplitude per turns as an indicator of force.[72] Electrical activity is analyzed continuously during a gradual increase in force from zero to maximum over 10 s. From the ratio of turns to mean amplitude plotted as a function of force, the highest value of the ratio is obtained (peak ratio, Fig. 12). Mean amplitude can be substituted for force, as mean amplitude increases linearly with force.[29,130,132]

The peak ratio is measured in at least 10 sites in each muscle in order to obtain representative values. As the IP varies in different parts of the muscle, these 10 sites should be carefully distributed in the muscle, using at least three insertions in each muscle.[73] The depth of the electrode should be changed in steps of at least 5 mm. The pause between contractions has to be at least 30 s in order to avoid fatigue. At each site in the muscle, the peak ratio is obtained from the IP during a gradual increase in force from zero with an online display of a plot of ratio of turns to mean amplitude against mean amplitude. The increase in force should be performed within 10–20 s of the muscle contraction, which should be as near an isometric contraction as possible, with the force exerted against the hand of the examiner. It is easier to obtain a gradual increase in big muscles than in small muscles. At low force, there will be a simultaneous increase in ratio and mean amplitude. At moderate force, of about 10% to 30% of maximum, the ratio will reach a maximum, while mean ampli-

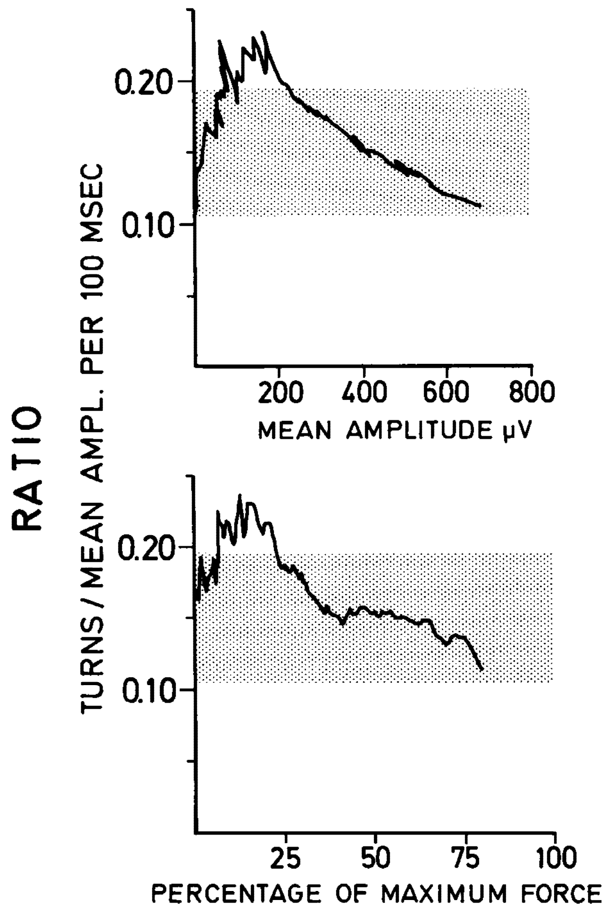

FIGURE 12. Ratio of turns to mean amplitude related to increasing force (below) and to mean amplitude per turns (above) from one record in a patient with myopathy. The hatched areas indicate the mean ± 2SD of the peak ratio in controls. (Modified from Fuglsang-Frederiksen et al.,[72] with permission from Elsevier Science).

tude continues to increase. At higher force, the ratio will decline, associated with an increase in amplitude. At that moment of gradual increase in force, when the ratio starts to decline while the mean amplitude continues to increase, the peak ratio has been obtained and analysis at that site of the muscle may be stopped. During the gradual increase in force, the IP is analyzed every 100 ms. From the averaged curve of ratio, the peak ratio is determined. From the 10 100-ms epochs of EMG selected for the peak ratio, the number of small time intervals less than 1.5 ms per second are calculated. For the latter parameter, a logarithmic transformation is further performed.[130]

Among 25 patients with different kinds of myopathy, 92% had an increased peak ratio and 84% of the patients had increased number of small time intervals less than 1.5 ms in the brachial biceps muscle.[131] The individual motor unit potentials sampled at weak effort were analyzed in the same muscle; 52% had decreased duration of all potentials and 72% had decreased duration of simple potentials. Finsterer et al.[61] also found the peak ratio method to be better than motor unit potentials analysis, although the sensitivity for both methods was lower than in the former study, probably due to inclusion of more borderline cases. In 20 patients with myopathy infected with human immunodeficiency virus, the analysis of peak values of turns per second, mean amplitude, and ratio was more sensitive than the cloud method (95% versus 80%, respectively).[127]

In 21 patients with different neurogenic disorders, the peak ratio was decreased in 86% and the number of small time intervals less than 1.5 ms was decreased in 43%.[131] All patients had either a decreased peak ratio or a decreased number of small time intervals or both. In the same muscle, the mean duration of individual motor unit potentials was increased in 95%. In the tongue of patients with bulbar-onset amyotrophic lateral sclerosis, Finsterer et al.[57] found that the sensitivity of the peak ratio method was higher than that of motor unit potential analysis, whereas in patients with limb onset, the motor unit potential analysis had the higher sensitivity. In a study of the anterior tibial muscle of 21 patients with neurogenic disorders, 81% had a neurogenic peak ratio analysis.[54] Although spontaneous activity was seen in most muscles, it did not influence the peak ratio parameters, whereas the turns/amplitude analysis could be used to quantify the amount of spontaneous activity.[54]

Why is this method sensitive in the diagnosing of neuromuscular disorders? On the one hand, the peak ratio probably reflects that point in the increase of force where the summation has eliminated most silent periods between motor unit potentials, while, at the same time, there is still too little summation and cancellation to obscure abnormality. If this point is sensitive for discriminating patients with neuromuscular disorders from controls, the peak ratio method is clearly a good choice.[67] This point may be reached at different force levels at different sites in the muscle, depending on the density of the motor units. On the other hand, the number of small time intervals between turns supplements the information obtained by turns, mean amplitude, and ratio. The information given by the number of small time intervals reflects the time parameters within the motor unit potentials.[73] The peak ratio is a fast method that can be performed in 5–10 min for each muscle. The method is available with commercial EMG equipment.

Turns/Amplitude Analysis and Pathophysiology. The number of motor units and their firing rate influence the number of turns per second.[73,83,148,163] The degree of summation due to accidental overlap of motor unit action potentials (or due to synchronization) influences both the number of turns and the amplitude.[29,130] The more summation, the more cancellation of small spikes and the higher the amplitude of the IP. The duration of individual motor unit potentials influences the number of turns secondary to the influence on the degree of summation. In muscles from patients with neuromuscular disorders, an increase in duration results in more summation and cancellation of small spikes and may give rise to low numbers of turns per second and vice versa.[66,76,80] The amplitude of the IP is also dependent on the amplitude of the individual motor unit potentials.[103,163] The shape of individual motor unit potentials, i.e., the incidence of polyphasic potentials, has an influence on the IP: the higher the incidence of polyphasic potentials, the higher the number of turns.[66,80]

In the muscles of patients with myopathy, the random and diffuse degeneration of muscle fibers as well as regeneration are reflected in the short-duration, low-amplitude, and polyphasic shape of individual motor unit potentials.[20] As indicated above, these changes in individual motor unit potentials influence the IP, resulting in an increase in number of turns per second, a decrease in mean amplitude per turns, an increase in ratio of turns to mean amplitude, and an increase in number of small time intervals between turns. Initially, it was thought that the increase in number of turns per second at a force of 2 kg seen in muscles from patients with myopathy was at least partly due to an increased firing rate.[207] However, in a study of firing rate of motor units at a force of 10% of maximum, there was no difference between patients with myopathy and controls.[83] The impression of an increased firing rate in patients with myopathy is possibly false, at least at low force levels. Owing to the weakness of the muscle, the patient has to use a relatively higher force associated with a higher firing frequency or early recruitment.[20]

In muscles from patients with neurogenic disorders, peripheral sprouting is reflected in increased duration and high amplitude of individual motor unit potentials. The large motor unit potentials influence the degree of summation in the IP in the direction opposite that seen in myopathy. The large motor unit potentials are associated with a decreased number of turns per second, increased mean amplitude per turns, decreased ratio of turns to mean amplitude, and decreased number of small time intervals.[80] This is reflected in a proportional increase in amplitude divided by turns per second with increasing fiber density.[62] In the neurogenic muscle, the loss of whole motor units results in a further decrease in the number of turns per second.[80]

Comments. For the diagnosis of patients with neuromuscular disorders, the integrated electrical activity and number of zero crossings are obsolete as electrodiagnostic tools. The power spectrum analysis and the turns/amplitude analysis at a given force (e.g., 30% of MVC) and the motor unit potentials analysis have about the same sensitivity but supplement each other. Most studies of the turns/amplitude methods without force measurement, for example, the peak ratio, have shown that these methods have a superior sensitivity compared with that of motor unit potential analysis. However, different techniques for motor unit potentials analysis (e.g., averaged versus nonaveraged potentials) have been used in different studies, which makes it difficult to perform an exact comparison between studies. The IPA methods which have electrodiagnostic potential in the future, such as the power spectrum analysis, the motor unit firing rate analysis, the cloud activity method, and the peak ratio method are available only in some commercial EMG machines, and control values are available for only a few muscles in the upper and lower limbs and the cranial nerve muscles at best.

The use of quantitative EMG is especially necessary in patients with different types of myopathy and in patients with different types of anterior horn cell disorders in whom other electrodiagnostic methods are of little help. The author usually applies both manual motor unit potential analysis (about 15 min per muscle) and the peak ratio method (5–10 min per muscle) to a few muscles in patients with these disorders. In others patients, for example, those with polyneuropathy, quantitative IPA in a muscle may indicate the degree of chronic partial denervation.

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