SOME EXPERIENCES WITH WALTON'S FREQUENCY ANALYSIS OF THE ELECTROMYOGRAM

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In the clinical interpretation of electromyogram (E.M.G.) records, obtained by a needle electrode, the activity at insertion, possible spontaneous activity, and activity at voluntary contraction are taken into consideration. This procedure usually demands a fairly detailed examination in order to make a diagnosis. The interest is mainly focused on the shape of the action potential, its duration, amplitude, and number of "phases"; but the grouping of the impulses is also observed. Since these parameters show a great variability from one action potential to another it is seldom possible to draw any conclusions merely from single potentials in a record. A large number have to be investigated, with the result that a reliable analysis becomes rather time-consuming. Attempts to make these measurements automatic have therefore not been lacking. Richardson (1951) described a method of analysis which gave the proportion of the frequencies above 400 c./sec. to the frequencies below 400 c./sec. A method more satisfying as a frequency analysis was used by Walton (1952), in which a frequency spectrum of the record was furnished by means of an "audiofrequency meter". One of the main problems for the E.M.G. investigation is undoubtedly to decide whether muscular wasting is of myopathic or of neuropathic origin, and in a report of 174 cases Walton claimed that his method definitely facilitated the E.M.G. diagnosis. The aim of our investigation was therefore to test his method.

Frequency Analysis of Electromyograms

It may be of some interest to elucidate from a general point of view what information can be obtained by means of a frequency analysis of electromyograms. In a previous paper the results of a Fourier analysis of neuronal time series has been discussed (Krakau, 1956). It was concluded that a frequency analysis of a record, representing a single element, composed of a series of identical formations, may under certain circumstances be smoothed to an approximation of the spectrum

of a single formation (action potential). This spectrum is widely independent of the distribution of the formations in the series. It is presumed that the formations do not overlap. If the analyser, however, has a high resolving power, a detailed spectrum is given, which also permits of conclusions about the impulse grouping. We presume that there exists, for a certain mode of recording, certain trends in the shape of the action potential which may be considered as characteristic for a given muscle. The reasons for the great variations in shape at different positions of the electrode will not be discussed.

When the activities of several elements of an ensemble intermingle the situation becomes more complicated. A certain amount of overlapping has to be expected, even if the impulses of the different elements are falling mutually at random. Let us assume that the contributing motor units are (1) located at distances of the same order of magnitude from the electrode and (2) are eliciting similar action potentials. If the motor units are working without synchronization, the action potentials from the different units will fall at random and the general form of the spectrum to be expected will remain (except for a proportional factor) that of a single representative element.

If we in this situation change one factor, namely, the phase relations between the active elements, a synchronization may be introduced. If synchronization is defined as an overlapping of potentials to an extent higher than might be expected when the impulses are arranged at random, synchronization will result in an increase in the total energy of the spectrum. If the elements, which are falling into some degree of synchronicity, are firing at a certain common impulse frequency, an accentuation of these special frequencies and a change in the shape of the spectrum will result. Such a non-affine augmentation of the spectrum is seen, for instance, when the Piper rhythm appears. Therefore, from an ideal frequency analysis, conclusions concerning the impulse form, the impulse grouping of a single motor unit, and the

synchronization of a population's activity can be drawn if the precautions are properly chosen. It may then be asked which of these qualities can conveniently be estimated by means of an audio-frequency meter of the type used by Walton.

Analysis with an Audiofrequency Meter

This question is elucidated by some data from the instruction booklet for the "standard" spectrometer. It may at first be pointed out that this analyser, like most others, delivers an energy spectrum and not the Fourier analysis. The frequency terms are given in square values which means that all phase relations are omitted. Further, the frequency values have a non-continuous representation. They are given as discrete points, three per octave: 40, 50, 64 . . . c./sec., thus the uncertainty of a frequency reading $\approx \pm 10\%$ (Standard Telephones and Cables, 1954).

A band pass filter corresponds to each frequency point. When a pure sine wave, with the frequency of any one of these frequencies, is applied to the analyser, the adjacent frequency filters also give a response which is 20% of the central frequency. The resolving power is low, for if the analyser is furnished with a mixture of two pure sine waves, the relation between the two frequencies has to be ≥ 2 , if they are represented as two peaks with a lower frequency value in between. The amplitude values are linearly proportional to the input voltage, provided the input amplifier is not overloaded. The analysis epoch may be taken to 163 or 343 m.sec. This means that several formations will generally contribute to each spectrum. In conclusion, we may state that the spectrum produced by this equipment is a smoothed and broadened approximation of the true spectrum of the input. When the input time function is dominated by a single motor unit, the spectrum delivered will correspond to that from an approximated action potential. The details of impulse grouping are hidden in the smoothed spectrum. In Walton's treatment the frequency analysis is used to represent the form of the action potential, and this is also the case in our material. However, the method could also supply information about synchronization entering during a contraction, though no doubt a machine with a lower limit of frequency, less than 40 c./sec., would have been more convenient for such a study.

Practical Aspects

Finally, from the practical point of view, can we hope *a priori* that the analysis is facilitated by this automatic device?

A series of formations (the action potentials) is

transformed into a new formation. On the action potential, which is obtained as a time function, those points where the curve has a maximum or a minimum are easily measured. The voltage there can be directly estimated and the time lapse between them can also be measured with accuracy. Knowledge of the absolute height of the potential is, however, of limited value, since it is strongly influenced by the position of the electrode in relation to the motor unit. Though the action potential is a rather complex curve, the time lapse between maxima and minima is strongly correlated to the frequency maximum of the spectrum. On the other hand, the duration of the potential is often a measure of very little accuracy since the curve often regains the base line in a slow, asymptotic manner.

The potential defined in its Fourier transform permits of direct measuring of parameters which characterize the shape of the potentials. No doubt the transform of a function like the action potential is for comparing the shape of potentials in general equally well suited for measuring as the time function.

As an illustration, let us analyse an action potential, the form of which is simplified to a single and complete sine wave. If the duration of the wave is, say, a complete period (Δl) of 5 m.sec., there will be a peak in the spectrum around 200 c./sec. The approximative width ($\Delta \rho$) of this peak is given by $\Delta l \times \Delta \rho \approx 1$, and may thus be put at 200 c./sec. (Fig. 1a). Then let the complete wave have a duration of 10 m.sec. (b). The maximum at

FIG. 1.—Sine-shaped potentials (a, b, c) and their spectra (a', b', c' arranged schematically).

100 c./sec. has the width of 100 c./sec. Finally, let us take a more "polyphasic" potential consisting of two complete sine waves with the duration of 10 m.sec. (c). The spectrum has a peak at 200, but its width will be ≈ 100 c./sec.

We may conclude that it is certainly possible to obtain an impression of the shape of the action potential by means of the audiospectrograph. Whether this shape is more rapidly and exactly caught by means of frequency analysis than by study of the direct time function is a purely practical question.

Method

The E.M.G. recordings have been made by means of a "disa" electromyograph, type 13 A 50, with a three-channel A.C. amplifier. The leads have been taken with a bipolar coaxial needle electrode, using Buchthal's apparatus (maker: Disa Ltd.). The output from one of the leads has been connected to a 74100 A spectrometer, made by Standard Telephones and Cables (1954). The spectra have been photographed with a Zeiss "contaflex" camera.

Material

The material embraces a total of 38 cases, of which the muscle activity was as follows:—

Normal	..	..	..	..	5
Inactivity-atrophy	..	..	..	..	8
Neurogenic atrophy	..	..	..	..	15
Myogenic atrophy	..	..	..	..	9
Nuclear cases	..	..	..	..	1

In addition, the activity in the quadriceps and in one of the external eye muscles of rabbits has been investigated.

As the histograms from the frequency analyser have in the majority of cases had only one single maximum, we have considered that with the help of three parameters a fairly reasonable idea of its appearance can be given. We have, therefore, given the frequency for the maximum and usually two frequency values where the amplitude has fallen to half the maximal. These values have the advantage of being, within wide limits, independent of the degree of amplification. When two separated maxima of approximately equal height have been present, both have been included. The same holds for the half-values. Exceptionally, one spectrum may thus be represented by two values for maxima and four values for half-values. No fine structure in the spectrum can indeed appear in this form of analysis and a number of configurations with double maxima and such like are of course hidden by such a recording procedure. In a series of diagrams (Fig. 2) we have tabulated the material in groups, each diagram showing the distribution of the maximum on different frequencies, and also the

Fig. 2.—Distribution of peak- and half-values in different groups. Thick line = peak values, thin line = upper half-value, dotted line = lower half-values.
a = normal, slight contraction
b = " transitory state

TABLE I
CLINICAL DETAILS OF HISTOGRAMS

Diagnosis	Age	Muscle	E.M.G. Findings	Number of Spectra	Peak Frequency Values in c./sec. (mean value)	Frequency Values		Remarks
						Min.— $\frac{1}{2}$	Max.— $\frac{1}{2}$	
Normals (4 cases) (Fig. 2a, b, c)	25-30	Quadr. fem. tib. ant. deltoid, inteross. dors. I	Normal	90 79 67	200 200 200	40, 80 40, 80 40, 80	400 400 400	(a) Slight contraction corresponds to single oscillations, (b) moderate contractions correspond to trans. state, (c) strong contraction corresponds to interference pattern
Normal	23	Facial L.	Normal	10	320	64,250	500,1250 2000	Facial paresis on right side
Rabbit 1	Weight 1 kg.	Dorsal	Mean duration about 6.5m.sec.	9	320-400	200	500	
		Ext. eye muscle	Thin spikes	7	800	250, 640	1250	
Rabbit 2	Weight 1-100 g.	Dorsal	Mean duration about 6.5m.sec.	8	400	40, 100, 160	400, 1000	
Atrophy from inactivity after fracture of femur, 5 cases (Fig. 2d)								
1	65	Quadr. fem. R.	Normal	4	—	—	—	Circumference 15 cm. above patella
2	16	" "	"	6	—	—	—	right, 2 cm. < left side
3	41	" "	"	6	200	40, 160	400	Circumference 10 cm. above patella
4	25	" "	"	4	—	—	—	right, 3 cm. < left side
5	45	" "	"	6	—	—	—	Circumference 15 cm. above patella
Atrophy secondary to rheumatic polyarthritis 3 cases (Fig. 2e)								
1	58	Extensor muscles of left forearm	Normal	18	—	—	—	right 4 cm. < left side
2	58	" "	"	19	200	40, 80	400	right 6 cm. < left side
3	50	" "	"	19	—	—	—	Excessive atrophy of affected muscles 3 cases
Post-poliomyelitis paresis (Fig. 2g, f)	47	Tib. ant. R.	Only s.o. denervation potentials with prolonged mean duration. Increased synchronization	20	100	40, 80	200	
Amyotrophic lateral sclerosis (Fig. 2g, f)	63	Tib. ant. R.	Only s.o. prolonged mean duration	12	80-125	40	125, 200	Very feeble power of dorsiflexion of right foot
Charcot-Marie-Tooth disease, 2 cases (Fig. 2f)								
1	34	Tib. ant. R.	Only s.o. increased amplitude, prolonged mean duration, increased synchronization	10	100, 200	40, 80	125, 250	Very feeble power of dorsiflexion of right foot. spasticity
2	31	" "	S.o.-trans. state, susp. on increased synchronization	18	100, 200	40, 80	320	Atrophy of calf with drop
Hereditary progressive spinal muscular atrophy, 3 cases (Fig. 2f)								
1	24	Quadr. fem. L.	Sometimes very polyphasic potential	7	200, 320	40	400	" "
2	19	Tib. ant. + quadr. fem.	S.o.-trans. state, increased mean amplitude, prolonged mean duration, increased synchronization	8	200	40	250	Excessive atrophy of the tight muscles
3	27	Pectoralis major R.	Some very polyphasic potential, potentials of denervation	9	100, 125, 200	80	400	No obvious atrophy but slight reduced power
Syringomyelia (Fig. 2f)	58	Inteross. dors. I, man. L.	S.o.-trans. state, scattered denervation potential, increased mean amplitude, no special polyphasic potential	13	200, 320	80	500	Excessive atrophy
Cerebellospinal ataxia (Fig. 2f)	56	Tib. ant. R.	S.o.-trans. state, prolonged mean duration	23	125, 200	40, 64	320	Moderate atrophy of the interstitium
Facial paresis, 2 cases								
1	12	Facial L.	Reduced activity	4	Values between 400 and 1,600	Values between 40 and 1,000	2000	Moderate reduction of power in dorsal flexion in foot. Reduced deep sensitivity in foot joint
2	23	Facial R.	Slightly reduced activity, no denervated potentials	8	320-400	160	800-1000	Incomplete paresis of 2 days' duration
Peripheral lesion of ulnar nerve L.	28	Inteross. dors. I, man. L.	Highly reduced activity, several very polyphasic potentials, background activity	6	100, 200	40	200	After 11 days' regression of paresis. 16 days' anamnesis.
Suspected peripheral lesion of median nerve R.	28	Thenar L.	Several polyphasic potentials	6	500	200-250	800	3-year-old traumatic lesion

TABLE I—continued

Diagnosis	Age	Muscle	E.M.G. Findings	Number of Spectra	Peak Frequency Values in c./sec. (mean value)	Frequency Values		Remarks
						Min.—½	Max.—½	
Radial paresis L.	47	Extensor of left forearm	Reduced activity; sometimes only s.o. single denervated potentials	3	250, 250, 800	125, 160, 160	400, 400, 1600	Partial traumatic paresis 2½ m.
Polyneuritis ?	65	Quadr. femor. L.	Some very polyphasic potentials but not certainly pathological	9	200	40-80	320-400	Moderate general weakness. Left quadriceps and both calf reflexes missing
Prolapse of cervical intervertebral disk	54	Bic. brachii R.	Reduced activity, s.o. prolonged mean duration, some very polyphasic potentials	11	100	40	200	Excessive atrophy and highly reduced power
Myotonic dystrophy, 4 cases (Fig. 2h)	15	Tib. ant. R.	Typical findings with myotonic phenomena and spikes with short duration in simple or polyphasic potentials. Reduced activity, partly very irregular background activity	16	200	40, 80, 100	800	Only flicker of contraction in tib. ant. R.
1	56	Tib. ant. R.	" "	9	200, 320	Values between 50 and 200	400	Power of dorsiflexion of foot greatly reduced
2	37	" "	" "	9	200, 400	40, 125	Values between 320 and 2,500	" "
3	37	" "	" "	10	200	125-160	800, 1,250	" "
4	37	Tib. ant. R.	Highly reduced activity sometimes with s.o. A lot of rapid phases in simple or polyphasic potential	7	200-250	40, 80	500	Very low power of dorsiflexion
Progressive muscular dystrophy, 5 cases (Fig. 2i)	24	Deltoid R.	S.o.-trans. state, a lot of rapid phases in simple or polyphasic potentials	9	200	40	400, 2,000	Excessive atrophy of shoulder muscles. Very low power of deltoid
1	30	Quad. fem. L.	As in 1	13	40	40, 80	Values between 400 and 2,500	No data available
2	8	Tib. ant. R.	" "	9	200, 250	80	Values between 250 and 2,500	Greatly reduced power of dorsiflexion
3	47	Bic. brach. R.	" "	16	100-125, 200	40, 64-80	200-2,500	Greatly reduced power of flexion in elbow joint

distribution of half-values. The cases investigated are reported in Table I.

Results

A more detailed description of the generally known electromyographic alterations should not be necessary here. It is, however, of interest to establish in what manner the pathological lesions are reflected in the spectrum.

Normal.—The peak of the frequency in the examination of the large skeletal muscles is entirely clear at 200 c./sec. (Walton gives 100-200 c./sec.). No obvious change, except a uniformly increased amplitude, is introduced in the spectrum when the contraction is augmented from slight, when isolated action potentials are dominating the pattern, to strong, when an interference pattern is seen (Fig. 3). It is then justified to assume (a) that the motor units in the neighbourhood of the electrode are contributing with activities of similar spectra, and (b) that no considerable synchronization is present. At still more forcible contractions there is a variable change in the spectrum, the frequencies in the 40-50 bands being stressed. At this point the changes of the spectrum are explained in an uncomplicated

way by assuming a certain degree of synchronous activity in the motor units.

The rapid action potentials of the facial muscles deviate from those of the large skeletal muscles, which is reflected by a displacement of the maximum. The normal thin spikes of the rabbit muscles have their maximum at a higher frequency than the corresponding muscles in man.

Inactivity Atrophy.—Buchthal and Pinelli (1952) have found in similar cases a reduction of the mean duration. There may be a slight tendency to higher frequencies, for fairly high figures are represented in the peak values. The lower half-value also seems to be displaced towards a higher frequency, which means a change in the shape of the potentials.

Secondary Atrophy in Rheumatoid Arthritis.—The maximum and the half-values showed the same distribution as the normal muscles. In one case a strong tendency appeared in frequencies in the Piper range.

Neurogenic Degeneration of Anterior Horn Cells.—In post-polio myelitis paresis, amyotrophic lateral sclerosis and in cerebellar hereditary ataxia there was a rather striking displacement towards the low peak values, and correspondingly potentials of long

FIG. 3.—Histograms from normal muscle in (a) weak, (b) medium degree of contraction, in (c) very strong contraction with variable change in frequency distribution (Piper rhythm).

mean duration in the E.M.G., but in hereditary spinal progressive atrophy the values were as above, partly normal, with very rapid secondary peaks. In syringomyelia the spectrum was normal, which is in agreement with the findings of the ordinary E.M.G. analysis.

Neurogenic Diseases Probably without Affection of Anterior Horn Cells.—No characteristic deviations from the normal spectrum were seen.

In myotonic dystrophy, if anything, there was displacement to the left of the frequency peak, whereas in progressive muscular dystrophy displacements of the maximum towards higher frequencies were considerable. In those cases where normal or broadened action potentials are mixed with rapid, polyphasic potentials, as is seen in cases of myotonic dystrophy, and in the activity after denervation, we

have often observed that the higher frequencies are poorly represented in the spectrum in comparison with the lower ones, in spite of the fact that the polyphasic potentials are easily distinguished in ordinary analysis. This drawback might perhaps be helped somewhat if the analyser's amplification were not the same at different frequencies but were weighted in favour of the higher ones. On the whole, however, the E.M.G. results in the cases investigated are in agreement with Walton's findings and show that the shape of the action potential is mirrored in the frequency spectrum in such a way as to bring out the characteristic E.M.G. differences between neurogenic and myogenic atrophies. This is seen partly in the form of a displacement of the value of the frequency maximum, and partly by a change in shape of the spectrum. Nonetheless, there remains the primary question: Does the frequency analysis really facilitate the E.M.G. diagnosis? Our experience of this method is, it is true, not overwhelming, but we nevertheless dare to maintain that in its present approach the gain for the E.M.G. diagnostician as regards time and diagnostic safety is comparatively insignificant. This, however, does not exclude the possibility that the method of analysis applied in a different way might well be considered to provide information about the grouping of the impulses. We have already touched on the possibility of studying the motor units' mutual activity (problems on synchrony) with the technique of frequency analysis.

Summary

An audiofrequency meter has been used for analyzing E.M.G. recordings by Walton's method. It was found to be of a certain but limited value in diagnosis. It is suggested that this machine should be applied to the study of synchronization.

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