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Elements of Human Extraocular Electromyography

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The recording of potentials from the ocular muscles in man is a new technique which is providing a greater insight into ocular motility and innervation than we have had in the past. While the neurophysiologist considers electromyography a basically simple technique, it is fraught with difficulties in both the recording and the interpretation of the records for others who may not be sophisticated in electrophysiological methods. It is our goal to present the elements of the human electromyography of the extraocular muscles. We hope that this presentation will aid anyone who wishes to take an extraocular electromyogram himself but above all serve as a guide in aiding the reader to interpret and evaluate electromyograms, which are becoming commoner in the ophthalmic literature. Furthermore, this paper will serve as a basis for subsequent publications from this laboratory.

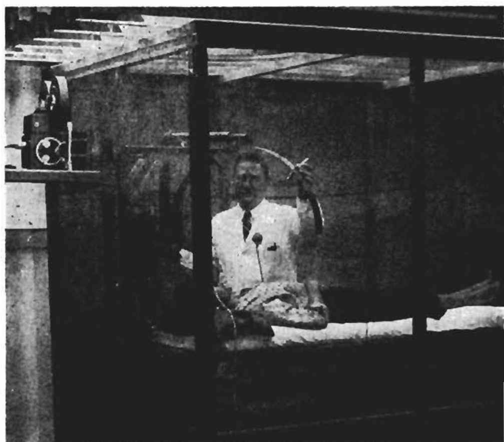


Fig. 1.—Subject supine on gurney in electrically shielded screen room. Eye-movement camera at upper left has no direct connection with electromyography.

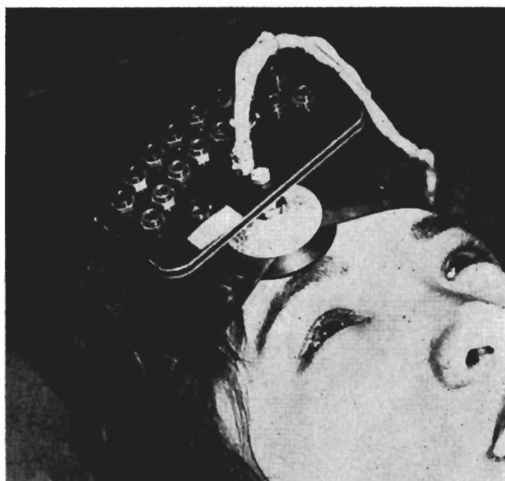
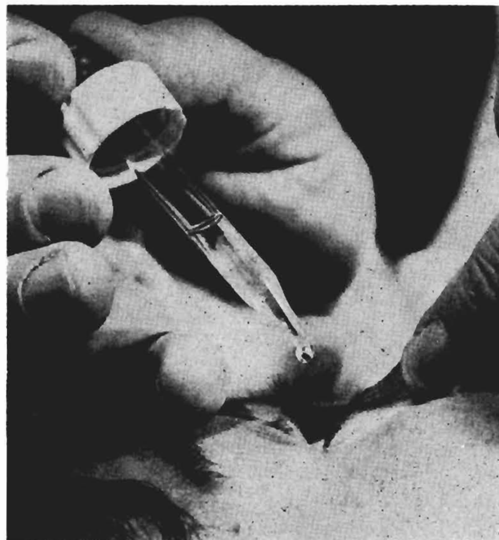


Fig. 2.—Headband, with jacks for leads from electrodes, in place on subject's head.

Fig. 3.—Instillation of drops. Tetracaine or proparacaine (Ophthaine) is used for topical anesthesia; methylcellulose, for prevention of corneal drying, and, sometimes, epinephrine for vasoconstriction.



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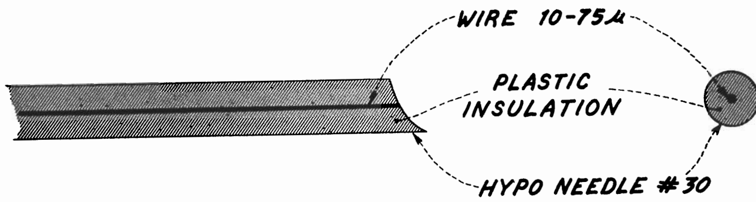


Fig. 4.—Schematic diagram of the muscle electrode, made from a 30-gauge hypodermic needle with an insulated central wire down the lumen.

For those who are going over this ground for the first time and find the terrain rocky, we suggest that the text be overlooked until the illustrations and their captions can be covered without excess effort. The well-trained neurophysiologist, however, will find no new electrophysiological principles in these pages. For those who wish to read more broadly, an extensive selected bibliography is added.

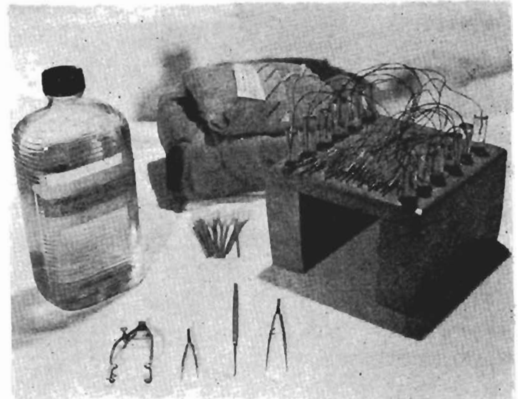


Fig. 5.—Electrodes sterilized in benzalkonium (Zephiran) nitrate. Instruments used are displayed in the foreground.

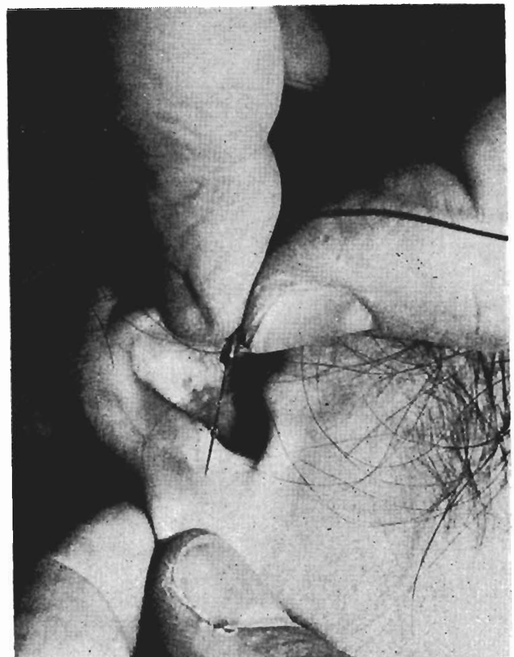
Pictorial Presentation of Ocular Electromyography

Some Details of the Extraocular Electromyograph

As in the apparatus which measures other bioelectric phenomena, such as the electroencephalograph and the electrocardiograph, the electromyograph consists of three basic parts: electrode, amplifier, and display.

The Electrode.—The electrode must be placed in the muscle to record individual units effectively. This dictates use of a needle with an electrically isolated tip. We use a concentric electrode (Adrian and Bronk, 1929) which consists of a 1 in. 30-gauge hypodermic needle in which lies an insulated Nichrome wire which is electrically exposed at the tip.*

Fig. 6.—Plain uninsulated needle is inserted in earlobe for electrically grounding the subject.



* Details on the construction of our electrode, block diagrams of the electromyograph and other supplementary material to this article have been deposited as Document No. 5822 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington 25, D. C. A copy may be secured by citing the document number and by remitting $2.50 for photoprints or $1.75 for 35 mm. microfilm. Advance payment is required. Make checks for money orders payable to, Chief, Photoduplication Service, Library of Congress.

Figure 7

Fig. 7.—The conjunctiva is lifted with a pair of fine forceps, and the needle is inserted through the conjunctiva into the belly of the muscle. A lid speculum is in place. Insertion is guided and judged by the audio response heard from the loudspeaker.

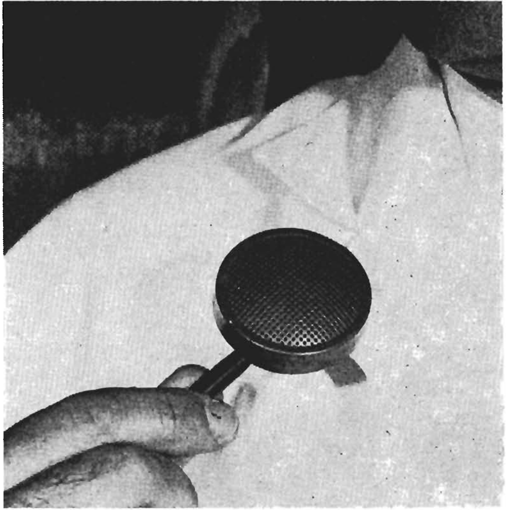


Figure 8

Fig. 8.—Experimental and test procedures are recorded through the lapel microphone worn by the experimenter.

Fig. 9.—Stimulus for fixation is guided by a perimeter or varied through a phorometer. Mirror in background allows simultaneous motion picture recording of eye movements.

Fig. 10.—Thorough shielding of all leads from the screen room is important. In the upper left cable the shielding is obscured by a plastic rubber covering.

Figure 9

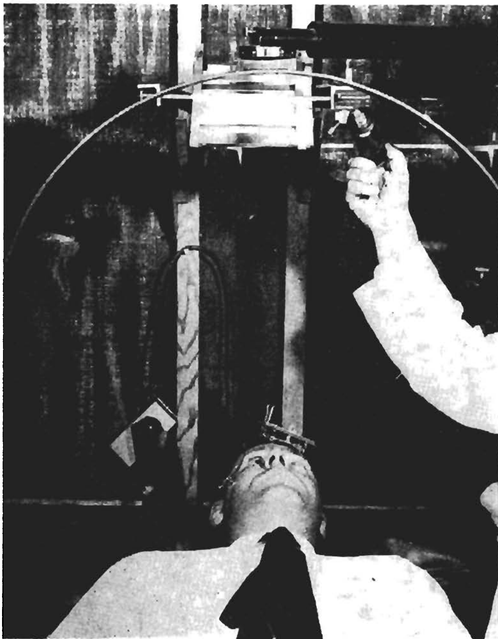
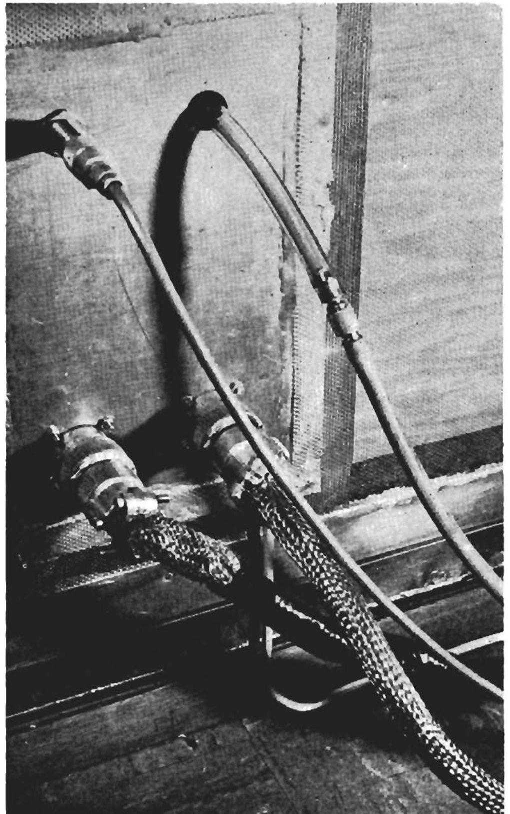


Figure 10



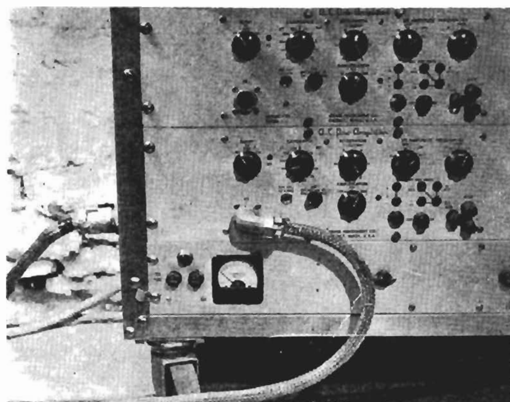


Fig. 11.—Two of a battery of amplifiers which make large potentials out of the small ones from the muscles. A separate amplifier is required for each muscle electrode. The third panel below is a battery charger.

Fig. 12.—The amplified muscle potentials are seen on the cathode-ray oscilloscope. In the foreground is a special camera for a permanent photographic record.

The concentric electrode described is the most convenient to use but difficult to fabricate. Another type, consisting of an insulated entomological pin (as used by Björk and Kugelberg, 1953) is more troublesome, since a second, indifferent electrode must be inserted elsewhere about the eye, usually in the conjunctiva. It has the disadvantage that it is more likely to pick up artifacts and is less durable. Its advantages are lower cost, ease of fabrication, less directional in pick-up, and smaller diameter, which reduces trauma.

Shielding.—Since the potentials which are recorded from the extraocular muscles are exceedingly small (of the order of 50μv. to 100μv.), it is necessary in almost all locations to provide adequate electrical shielding. In practice, this means that the subject must be enclosed in an electrically shielded

Figure 13

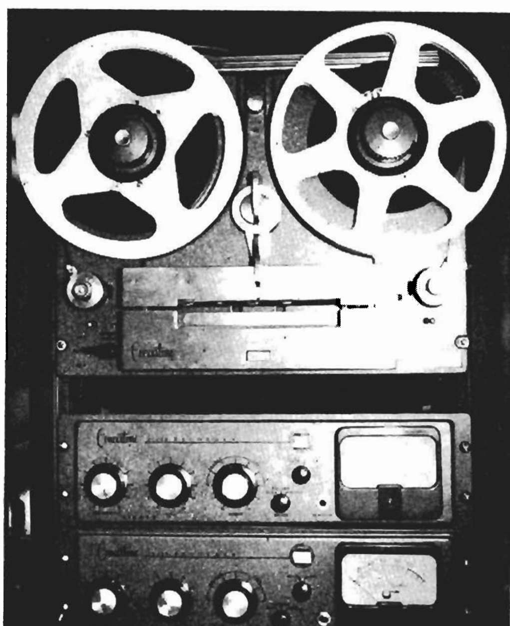
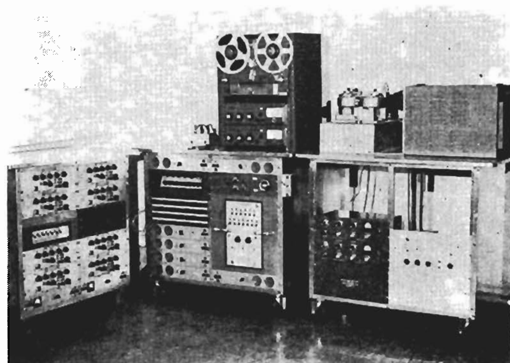


Fig. 13.—A two-channel tape recorder is convenient for recording the experimental procedure from the lapel microphone. The second channel may be used to record an electromyogram. Marking of events can be made on either channel.

Fig. 14.—The complete multichannel electromyograph. Included in this illustration, but not previously mentioned, are the electronic switch for multichannel display; the pulse generator for marking time; two direct-coupled amplifiers for electro-oculography; loudspeakers for listening to the electromyogram, and various switching and coding devices.

Figure 14



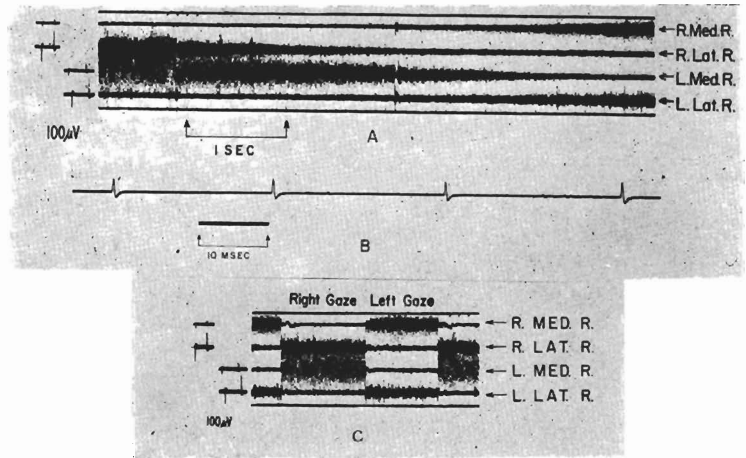


Fig. 15.—*A*, a typical electromyogram showing reciprocal innervation of two pair of opposing muscles of the two eyes. Individual units are not entirely or easily visible at this slow film (sweep) speed. *B*, high film (sweep) speed tracing of a single unit. The shape as well as the size and number of the individual units is seen. An electrode with a 10μ diameter central wire was used, which allows single units to be distinguished even during maximum contraction. *C*, a typical electromyogram at slow film speed, showing saccadic movements of the two eyes.

room, usually made of bronze or copper window screening. The screen room, or Faraday cage, is grounded to a good earth connection at one point, such as a cold water pipe. Without such screening, the electrical noise from light switches, fluorescent lamps, electric motors, television and radio transmitters, and, above all, diathermy machines, which are picked up by the subject's body and the electrodes, may largely mask or completely drown out the electromyogram from the extraocular muscles.

The Amplifier.—A shielded cable carries the electromyogram to an amplifier that makes it large enough to be displayed. The amplifier should have a relatively high impedance input, that is, of the order of 100,000 ohms to 10 megohms, and a frequency response of 2 to 10,000 cps (Buchthal, Guld, and Rosenfalck, 1954), although ordinarily the lower limit we use is 40 cps. It should have a balanced (push-pull) input and sufficient gain or amplification to give an adequate display. It is convenient if the amplifier incorporates a voltage calibration device. The noise level should be very low, that is, not exceeding 7μv. from the top to the bottom peak of the noise with the input leads shorted to ground. There are many such amplifiers available. We use a Grass P5 Preamplifier.

The Display.—The electromyogram can be displayed in two ways, visually and aurally. The auditory display is provided by a loudspeaker from which the electrical activity can be readily heard. In fact, it is far easier to hear an electromyogram than it is to see one, and the placement of electrodes is always done under auditory guidance. For permanent and quantitative records, however, a visual trace is preferable. Therefore, the amplifier is fed into a cathode-ray oscilloscope as well as a loudspeaker. At this point, the question may arise, "Why can I not use my pen-writing electroencephalograph for this work?" The answer lies in the speed of response. Pen-writing instruments usually cannot respond to frequencies greater than 100 cps because of their inertia, whereas the electrical activity recorded from the eye muscles is in the form of spikes which have a duration equivalent to about a thousand cycles per second. Hence, only relatively crude patterns of the response can be obtained from a pen-writer, and the individual units would be largely lost or distorted.

The cathode-ray oscilloscope may be photographed by a camera and, for any useful length of record, it is necessary to have a camera in which the film travels at a constant velocity, a feature of the so-called oscilloscope record camera. Thus, a signal from the muscle moves the oscilloscope beam vertically while simultaneously the film is traveling across the face of the dis-

play tube horizontally, providing a time base or sweep. We use a Grass oscilloscope record camera which has been modified to give a maximum film speed of 2 meters per second.

A cathode-ray oscilloscope is more versatile if it has two beams or tracings instead of one. We use a Tektronix Type 531 dual-trace oscilloscope, although for some types of recording a dual-beam oscilloscope, such as made by DuMont, Tektronix and Electronic Tube Corporation, may be preferable.

Generally, in order to provide more than two channels, it is necessary to have an auxiliary electronic switch which will chop the beam into a series of traces. For this purpose, we have a Burroughs Beamplexer, which can provide as many as 10 channels on one oscilloscope display. A separate electrode and amplifier is required for each recording channel.

An integrator can make the response from a muscle easier to visualize. There are several versions of electronic integrators which need not be discussed here. Suffice it to say that, in general, an integrator takes the potentials from the muscle and adds them with respect to time. The integrated trace would soon run off the face of the oscilloscope were it not, after a certain preset time, returned to baseline. The lower trace in Figure 17 is the integrated activity of the direct trace above it, the slope indicating the rate of activity. It is worth keeping in mind that noise, blinks, and other artifacts are nicely integrated concomitantly with unit activity. This can make such an impressive display misleading.

It is helpful to have a two-channel magnetic tape recorder which can simultaneously record (by means of the lapel microphone worn by the experimenter) information about the test as it is being performed and, at the same time, record any given channel of the electromyogram. The tape-recorded electromyogram, single or multichannel, can be kept as a permanent record and may be played back at a later time through the oscilloscope and photographed at any desired film speed, subject of course, to the frequency limitation of the tape recorder. A marker indicating the instant of various stimulus or response events can be recorded on either channel. We use a common telephone dial, which provides a marking code of 1 to 10 pulses as dialed.

Various miscellaneous stimulus equipment, such as a perimeter arc and a phorometer, is used, but requires no special description.

Unit Activity

An electrode in a muscle may record from a single unit which is recognized by its rhythmicity and its relatively constant size and shape. This unit is commonly thought to be a *motor unit,* that is, a small group of muscle fibers which fire or contract as a unit because they are innervated by the same nerve fiber. However, the size of the response of the individual motor fibers which summate or give a unit response is largely dependent on the distance to the electrode. Therefore, if the individual fibers are spread out spatially, some fibers will contribute to a large degree to the response whereas others will contribute little, if at all (Buchthal, Guld, and Rosenfalck, 1957; Krnjevic and Miledi, 1958). Professor Buchthal and his colleagues have recently suggested the term "sub-unit" for the group of fibers that are recorded in unit activity. It should be stressed that the sub-unit concept has been applied to skeletal limb muscles and is not necessarily applicable to extraocular muscles, where the ratio of motor fibers to nerve fibers is very low, probably a mean of 7:1. Nevertheless, until we know more about the histophysiology of the extraocular muscles, it is perhaps better to avoid speaking of the recording of motor units, since we may be picking up sub-units.

There is good evidence from skeletal muscles of the frog and cat that some muscle fibers are multiply innervated (Hunt and Kuffler, 1954). As yet there is no indication of this polyneuronal innervation in oculorotary muscles.

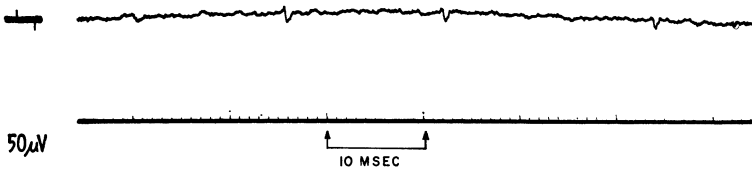


Fig. 16.—Recording from a paralyzed left lateral rectus muscle in extreme right gaze. These units are assumed to be fibrillation potentials because they are small, nonrhythmic, and not correlated with the position of the eye.

In fibrillation, small nonrhythmic spike potentials are seen some weeks after denervation. There is direct evidence that these spikes are from single muscle fibers (Nicholls, 1956; Li, Shy, and Wells, 1957) which fire without regard to attempted voluntary activity. Potentials from a paralyzed oculorotary muscle are seen in Figure 16.

Gradation of muscular contraction is accomplished in two ways. First, by a change of *frequency* of the individual motor units and, second, by the number of motor units active. As a larger number of motor units become active, they are said to be *recruited.* In general, both mechanisms are increased at the same time. There is some evidence of gradation by change of the number of active muscle fibers within single motor units, but the evidence is not yet very clear (Norris and Gasteiger, 1955).

When a single unit responds, we have a *simple pattern* as shown at the very beginning of Figure 17. If more units respond, but still the response is not so great that the individual units are masked, the picture is called a *mixed pattern,* shown toward the middle of the first line in Figure 17. Finally, if the response is so great that the individual units cover one another so that they cannot be individually resolved, the result is called an *interference pattern,* as seen in the third line of Figure 17. An interference pattern makes it generally impossible to determine the frequency response of single units at maximum degrees of contraction without special techniques.

It is believed that the frequency of some of the ocular muscle units reaches values as high as 175 spikes per second or more, but it is difficult to be certain, partly because of the interference pattern (Björk and Kugelberg, 1953; Reid, 1949; Gordon, 1951; Breinin, 1957) and partly because the wave form has not been examined to eliminate the possibility of synchrony of more than one unit giving an erroneous value.

As implied earlier, the amplitude or voltage of the response is largely dependent upon the distance of the electrode from the

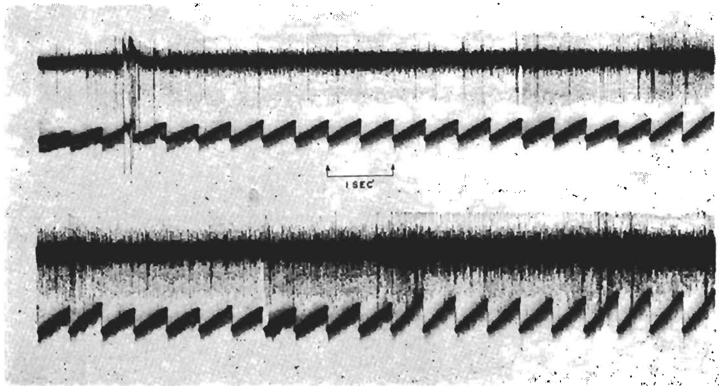


Fig. 17.—Upper tracing shows the activity of the right medial rectus from extreme relaxation to extreme contraction. A single unit pattern can be seen at the beginning of the record which blends into a mixed pattern and ultimately into an interference pattern, above which some units can be distinguished. The lower tracing is that of the upper tracing after it has been put through an electronic integrator which resets itself (returns to baseline) every half second. Note how the slope of these segments of the tracing increases as the muscle contracts.

active fibers. It is also dependent upon the size of the fibers, and therefore the response in limb muscles is many times greater than that of the extraocular muscles.

At times, instead of the diphasic response commonly found in extraocular muscles (Fig. 15*B*), there are four or more phases, or a polyphasic response. They are very rare in the extraocular muscles and are generally considered a sign of recovery from denervation, presumably because the nerve fibers have regenerated in a fashion not favorable for good synchronization of the response of the individual muscle fibers. In the past, it has generally been considered sufficient to identify a single motor unit as a train of uniform action potential spikes on a relatively smooth baseline. However, it is desirable that identification of a single motor unit be more complete, that is, not only that its frequency and its height be identified, but also its wave form. A relatively fast movement of the film or sweep speed is required for display of the wave form, as seen in Figure 15*B*. Notice that the wave forms are essentially all alike. Hence, it is reassuring to examine the wave form before assuming that a rhythmic series of uniform amplitude spikes arises from a single motor unit.†

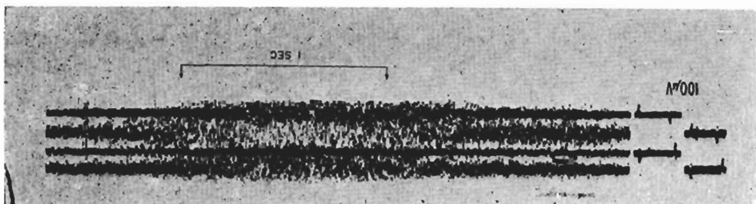
† No direct information can be obtained by the usual extracellular myographic technique about muscle spindles or intrafusal fibers. The small motor nerve system (γ-efferents) to the muscle spindle is well established (Granit, 1955) and recently has been exquisitely demonstrated physiologically in the extraocular muscles of the goat (Cooper and Daniel, 1957). However, any further discussion of this system is outside the scope of this paper.

A serious question arises in using electromyography as an indication of the total activity of a muscle. Is the response, recorded from a circumscribed volume (probably less than 1 mm. in diameter) representative of the activity of the muscle as a whole? In general, this seems to be true, although where there are units of lower threshold they may show activity sooner in a contracting muscle than recordings from other areas where higher threshold units may be found. This is seen in Figure 18, where we have multiple insertions in the same muscle. Upon contraction of the muscle, which presumably is contracting as a whole, there is activity recorded from one electrode before another. Hence, minor time differences during following movements between the recordings of different eye muscles can be misleading on this basis. Furthermore, the eye movement cannot be less than about eight degrees to demonstrate a perceptible change in the electromyogram even with good insertion.

Ocular Electromyography and Muscle Tension

There is no good direct evidence that the electromyogram of the extraocular muscles is directly proportional to the muscle tension. It has been found in limb muscles that there is a direct relationship between the integrated electrical activity and the tension of muscles in isometric contraction (Lippold, 1952; Inman et al., 1952; Bigland and Lippold, 1954; Edwards and Lippold, 1956), but the oculorotary muscles ordinarily do not contract without changing their length under normal conditions. The

Fig. 18.—Three electrodes in the same medial rectus muscle. Note that the activity appears to start in one trace earlier than in the others. When all traces are above threshold, the activity appears proportional in all channels. Hence the higher threshold units appear to lag behind the lower threshold ones but do not in actuality.



common, tacitly accepted, notion that the electrical activity of ocular muscles is a measure of isotonic muscle contraction is not unreasonable but is still merely an assumption.

Interpretation of Events

At a moderate or slow film (sweep) speed, a firing of a single unit results in a spike. This impulse appears on the baseline of the electromyogram, as seen in Figure 15*B*. If several units are being recorded, they will appear as separate impulses unless two or more happen to fire simultaneously. In this case, they will summate, or show the total of their individual amplitudes. It is usually easy to see with fast sweep speed that summation has occurred, because the summated wave form thus exhibited will show tell-tale notches or humps where the units have their individual maxima or minima. Regardless of whether summation occurs or not, however, the trace will return to the baseline within a few milliseconds.

If the amplifier has a long time constant, that is, if it can respond to relatively low frequencies, of the order of 1 cps, then slow potential changes which may be picked up in the electrode will result in a relatively slow drift of the baseline. This slow drift should not be interpreted as potentials resulting from firing of individual units. In fact, it can be eliminated by turning a switch and shortening the time constant of the amplifier, or, in other words, reducing the low frequency sensitivity. In Figure 19 are shown a series of simulated "spikes" in the form of square waves of 1,000 cps. In the upper trace of Figure 19*A*, we see a slow potential drift which is superimposed on the square wave spikes. Note that the simulated spikes show up as clearly as ever, but the baseline is displaced downward from the level of the drawn-in dashed line. In the lower trace of Figure 19*A* is the same signal which has been sent through the usual capacity-coupled amplifier used in electromyography. It is obvious that the simulated spikes appear as clearly as in the original tracing but that the baseline returns more quickly to the normal level, despite the original signal traced above. In Figure 19*B*, the upper trace is the same original signal. In the lower trace, the time constant is shortened and the slow potential drift returns to the baseline much more quickly. The time constant may be shortened further to eliminate almost entirely these unwanted drifts. An actual slow drift can be seen at the beginning of Figure 17 as a sudden baseline shift. It is over quickly because of our short time constant. We use a lower frequency limit of about 40 cps, which makes clearer records without being misleading. The sacrifice of these lower frequencies in the wave forms of single units does not seem to be of significance.

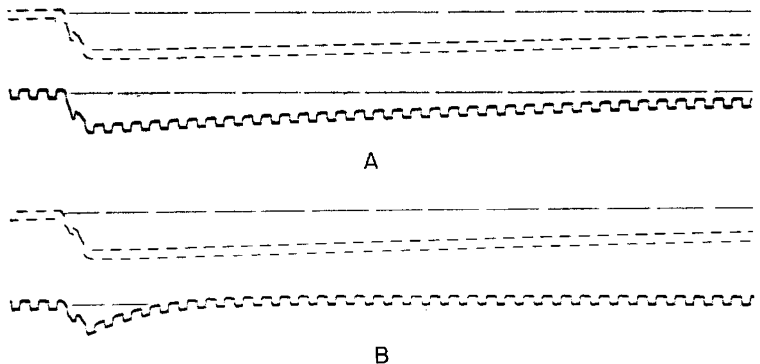


Fig. 19.—Simulated square wave "spikes" at 1,000 cps with superimposed slow potential demonstrating the effect of the amplifier time constant (low frequency response) on the recording of muscle units. *A*, upper tracing shows square wave signal simulating muscle spikes with superimposed slow potential which slowly returns toward dashed baseline. Lower tracing shows the above signal after it has been put through the usual capacity-resistance coupled (A. C.) amplifier. Note that the square wave simulated spikes are seen essentially undistorted whereas the return of the slow potential to baseline is faster than in the original signal. *B*, the same as *A*, except that a switch has been turned on the amplifier which shortens the time constant (raises the low frequency response.) The unwanted slow potential is now largely eliminated.

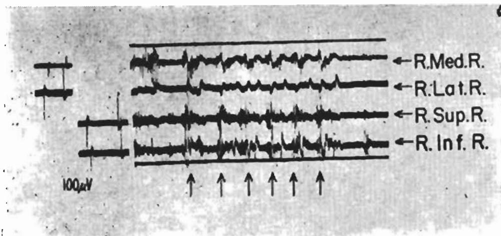


Fig. 20.—The vertical arrows point to the electrical records of the four recti muscles of the right eye during blinks. These artifacts are usually seen simultaneously on all channels.

A thin baseline with adequate amplification is desirable. If the baseline is thick or uneven in relation to the units recorded, then the equipment or location is noisy or else the insertion is poor. It is not a good practice to reduce the gain or amplication to show a better baseline, because in so doing electrical activity of the muscles is difficult to see and analyze.

Often, when the needle is touched by the lid one sees movement of the baseline. A high-speed recording will show that this movement is not characteristic of motor unit activity, and it is usually possible to make this distinction for blinks at lower sweep speed, as is apparent in Figure 20.

On occasion the electrode moves although there is evidence that little or no movement occurs. Specifically, a single unit can be recorded in a given eye position or degree of muscular contraction. After repeated excursions of the eye one can return to the threshold of this unit in what appears to be the same eye position as before. On other occasions, in returning the eye to the same position one does not find the same unit there unless the eye goes beyond this position and returns to it. This can be done repeatedly and indicates that if there is electrode movement here it must be a regular uniform and repeatable one.

It is obvious that when an eye moves the movement is a result of the balanced oculorotary muscular contraction. The electrical unit activity indicates the contraction but not the function of the muscle. For example, the contraction of an oblique muscle may be clearly recorded, but the electromyogram itself gives no hint as to the action, be it elevation or depression, abduction or adduction, intorsion or extorsion.

Advantages of Multiple-Channel Recording

It is useful to have available four or more channels for the recording of the extraocular electromyogram. If a blink should occur, it usually registers on all channels, which makes it easy to distinguish (Fig. 20). In general, distinctive activity by a single muscle stands out more clearly from artifacts during multiple recording.

Instances of coactivity or cocontraction can readily be measured by multiple channels, whereas a single or even a dual-channel apparatus does not give a complete picture. Furthermore, binocular function can be more directly and readily measured. In other words, the interrelations of the four or more muscles are directly seen by the use of multiple channels. Steadiness and maintenance of fixation can thus be readily monitored.

Clinical Value of Ocular Electromyography

Human extraocular electromyography is an important research tool but is of limited clinical value. If there is, at present, a practical usefulness of the technique, it lies in neuro-ophthalmological diagnosis and prognosis.

The selection of patients must be made with care. Generally, children cannot be examined and the personality of adults must be such that they are willing to undergo what to most persons is a somewhat frightening and not entirely painless procedure. Furthermore, elderly patients occasionally get subconjunctival hemorrhages that are cosmetically distressing.

Usually, limitation of eye movement by paralysis, paresis, or mechanical restriction can be diagnosed by clinical means such as observation of eye movements and the forced duction test under general anesthesia. Electromyography only confirms these findings. Therefore, electromyograms are, generally speaking, neither necessary nor helpful in usual practical motility prob-

lems. One cannot distinguish overactivity from underactivity, because the amplitude of the tracing is largely dependent upon the insertion. A moderate or severe paresis or paralysis which can be observed on the oscilloscope is obvious without the aid of electrical techniques.

Niles Roth, A.B., M.O., designed and constructed the electrodes; William Houweling and Bob Markevitch, B.S., M.S., constructed, maintained, and operated the electronic gear and designed the integrator, and Wilmer Renner did the photography.

Stanford University Hospital, Clay and Webster Sts. (15).

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