# HANDBOOK OF ELECTROENCEPHALOGRAPHY AND CLINICAL NEUROPHYSIOLOGY

EDITOR-IN-CHIEF A. REMOND

VOLUME 16

## Electromyography

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Institute of Neurophysiology, University of Copenhagen, Copenhagen (Denmark)

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PART B

## Neuromuscular Diseases

EDITOR: J. A. SIMPSON

Department of Neurology, University of Glasgow, and
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ELSEVIER

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**International Federation of Societies for EEG and Clinical Neurophysiology**



A great need has long been felt for a Handbook giving a complete picture of the present-day knowledge on the electrical activity of the nervous system.

The International Federation of Societies for EEG and Clinical Neurophysiology is happy to be able to present such a Handbook, of which this is a small part.

The decision to prepare this work was made formally by the Federation at its VIIth International Congress. Since then nearly two hundred specialists from all over the world have collaborated in writing the Handbook, each part being prepared jointly by a team of writers.

The Handbook begins with an appraisal of 40 years of achievements by pioneers in these fields and an evaluation of the current use and future perspectives of EEG and EMG. The work subsequently progresses through a wide variety of topics—for example, an analysis of the basic principles of the electrogenesis of the nervous system; a critical review of techniques and methods, including data processing; a description of the normal EEG from birth to death, with special consideration of the effect of physiological and metabolic variables and of the changes relative to brain function and the individual's behaviour in his environment. Finally, a large clinical section covering the electrical abnormalities in various diseases is introduced by a study of electrographic semeiology and of the rules of diagnostic interpretation.

The Handbook will be published in 16 volumes comprising 40 parts (about 2500 pages altogether). For speed of publication most of the 40 parts will be published separately and in random order.


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PART B

# NEUROMUSCULAR DISEASES

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# Preface

From the requirements for improved diagnostic and prognostic methods in the care of patients with peripheral nerve injuries in the Second World War, clinical electromyography (EMG) developed in different directions according to the interests of a small number of individual workers and their associates. For the specialists in neurology and physical medicine the differential diagnosis between neurogenic and myogenic causes of muscular weakness led to the exploitation of needle electrodes and recording with the cathode-ray oscilloscope to analyze the innervation ratio and recruitment patterns of muscle and later to the development of methods of measurement of nerve conduction velocity. Anatomists and orthopaedists have found surface electrodes and multichannel pen recording suitable for their requirements. The interests of clinicians and kinesiologists converge in the study of reflexes, dyskinesias, dystonias and in quantitative techniques which are now being developed.

An unfortunate consequence of this historical development is that clinical electromyography has been advanced independently by enthusiasts in different parts of the world, using different techniques to study selected aspects of the field. The newcomer to electromyography has, of necessity, to obtain training from a senior electromyographist or to search a widely scattered and somewhat uncritical literature, and in effect to rediscover everything for himself.

Following an Assembly at Strasbourg in 1960, a major step bringing together the various interests was made at the 1st International Congress of Electromyography in Pavia, Italy, in September 1961. The proceedings of that Congress (Electroenceph. clin. Neurophysiol., 1962, Suppl. 22) are a landmark in the rise of EMG to acceptance as a major division of clinical neurophysiology. More importantly, an informal international group ("the Pavia Committee") was assembled to arrange for further international meetings and to set up working parties to make recommendations on the standardization of electromyographic terminology and techniques. This informal organization promoted further successful meetings in Copenhagen (1963) and Glasgow (1967) between the International Congresses in Vienna (1965) and in San Diego (1969). At the 7th International Congress of Electroencephalography and Clinical Neurophysiology held in San Diego, California in September 1969, electromyography and its scientific societies were given full representation in the Federation of EEG and Clinical Neurophysiology and the report of the "Pavia" subcommittee on EMG terminology was formally adopted (see Appendix). The informal Pavia Committee thereupon dissolved itself and national societies representing EMG (usually in common with EEG) are now directly affiliated to the Federation, which has an elected Committee on Electromyography.

With the growth in scientific stature of clinical EMG and its related techniques, the time has come to prepare a handbook for the guidance of those entering the field. It is intended to present the corpus of information on which there is a substantial measure of agreement between workers in different countries. Controversial topics and esoteric techniques are not discussed in detail, but references are provided for further reading. Inevitably, the references are selective and reflect the awareness of the contributors. In an attempt to provide consensus opinion, the Theme Leader has integrated the contributions of a number of authors as an alternative to providing signed Sections, but each author has made his main contributions to those aspects in which his main interest has lain.

J. A. SIMPSON
Theme Leader

# Section I. The Electrophysiology of Muscle and Nerve in Man from the Pregalvanic Era to about 1930

## A. THE BEGINNING OF ELECTROPHYSIOLOGY

The birthday of electrophysiology falls on September 20th 1786 when Galvani, the professor of anatomy, physiology and obstetrics at Bologna University, enjoyed the mild evening on the terrace of his home, the Palazzo Zamboni. He watched the remarkable dance of some frog legs placed on the iron balustrade of the terrace when the wind made the copper hook through the spinal cord touch the iron. Galvani (1791) assumed erroneously that the fence acted as the conductor which allowed discharge of electricity stored in the muscle. He was strongly opposed by Volta (1792), the physicist of Pavia, who correctly attributed the source of the electricity to the contact between two different metals. However, five years later Galvani demonstrated "animal electricity" showing that demarcation currents of nerve or muscle could make muscles twitch in the absence of any metal. He was confirmed by von Humboldt (1797) and Matteucci (1844).

Even before Galvani, the stimulating effect of electricity on animals and man had been reported. The Parisian physician Abbé Nollet (1753), demonstrated before the king the effect of the discharge of a Leyden jar on 180 soldiers of the guard. As they stood hand in hand the first of the line touched the brass knob connected to the tin foil of the inner coating and the last touched the tin foil of the outer coating of the jar. They were taken by surprise and all jumped at once. Other experiments demonstrated the stimulating effect of electrical current on the nerve and muscles of amputated limbs and of bodies a few minutes after execution (Aldini 1804). Electrical stimulation of muscles in living man was taken up systematically by Duchenne (1867). His pioneer work on the mechanics of individual muscles *in situ* is still up to date.

## B. ELECTRICAL SIGNS OF VOLUNTARY ACTIVITY

A principal advance after Galvani was when the frog leg was replaced by a measuring instrument, the galvanometer, to show animal electricity. Du Bois-Reymond (1843), who improved the sensitivity of this instrument, was the first to perform experiments which suggested that muscles develop electrical activity during voluntary effort in man (1849, 1884). One finger on each hand of the subject was connected to the leads of a needle galvanometer. As the arms were flexed there was a deflection of the needle. The deflection increased with the strength of the contraction. It was larger when the right arm was flexed in right-handed subjects; it increased when the epidermis was removed and decreased at the onset of fatigue (Du Bois-Reymond 1884). He made his observations on distinguished subjects: "In spite of my old age and my weak arms, the deflections of the needle of the galvanometer were quite obvious", writes von Humboldt (1849), "though much smaller than those produced by our great anatomist, Johannes Müller, and by von Helmholtz, the author of important physiological papers". A decrement in the action potential of normal muscle during activity, which was assumed by Du Bois-Reymond (1843), was disproved by Hermann (1878b) who mistakenly held that the electrical activity observed by Du Bois-Reymond, originated not from muscle, but rather from secretory glands and sweat. He introduced the term "action current" and gave the first unambiguous demonstration of muscle action potentials in man. Hermann (1878a, b) stimulated the brachial plexus in the axilla and recorded from the surface of the forearm. Already von Helmholtz (1854) had certain experimental evidence that the electrical activity of muscle was associated with excitation rather than with contraction. This was convincingly demonstrated by Burdon Sanderson (1895) who showed that the wave of excitation ("Reizwelle", Bernstein 1871) precedes the mechanical response. On the other hand, the relation of the discontinuous electrical phenomena and the smooth mechanical response of voluntary effort remained uncertain for another thirty years. From the sound associated with voluntary effort, compared by Wollaston (1810) to the "sound perceived which resembles most nearly that of carriages at a great distance passing rapidly over a pavement", it was concluded that every contraction, however continuous it may appear to be, is in reality discontinuous (von Helmholtz 1864). It was soon realized that discontinuous nerve impulses need not be reflected in a simultaneous increase and decrease in force because different muscle fibres are not activated synchronously (Brücke 1877).

From recording of action potentials during voluntary effort, Piper (1907, 1912) claimed a constant frequency of discharge of 47–50/sec independent of the strength of contraction. He thought this to be the rhythm of the nerve impulses, a theory which gave rise to many disputes with those who considered the frequency of discharge to be inherent in the muscle ("Eigenrhythmus", Garten 1908, 1910). At any rate Dittler and Garten (1912) found frequencies up to 200/sec and Florence Buchanan (1908) using "about a dozen Oxford undergraduates as subjects" found the frequency of the electromyogram "far from constant" during different degrees of contraction and in different subjects. She realized that no conclusion could be drawn from the interference pattern as to the mechanism of natural innervation. Buchanan (1908) and Piper (1909a) compared the synchronized action potentials evoked by stimuli to the nerve at 50/sec with the irregular response during voluntary effort. From counts of spikes during voluntary effort Wachholder (1923a) assumed a double rhythm of 10–50/sec, increasing with increasing strength of contraction on which was superimposed a 160–190/sec rhythm. More important are his extensive studies of kinesiology by means of the electromyogram (Wachholder 1923b), following a single report by Gregor and Schilder (1913).

The solution of the problem, how different degrees of effort are reflected in the electrical activity of muscle, came at the end of the twenties when Sherrington, Denny-Brown, Adrian and Bronk laid the foundations of modern electromyography. In

1925 Sherrington introduced the concept of the motor unit: "the term motor-unit includes together with the muscle fibres innervated by the unit, the whole axon of the motoneurone from its hillock in the perikaryon down to its terminals in the muscle". Eccles and Sherrington (1930) furnished a quantitative anatomical basis for this concept, and Denny-Brown, while studying the stretch reflex of the soleus muscle, observed that mild degrees of stretch applied to the tendon caused a regular sequence of galvanometer deflections, the motor unit potentials (1929a). Finally in 1929 Adrian and Bronk introduced the concentric electrode and recorded motor unit potentials during voluntary effort, demonstrating the change in frequency as a mechanism of gradation.

### C. REFLEX ACTIVITY

The study of electrical activity associated with reflex activity had an early successful beginning. P. Hoffmann (1910, 1918, 1922) taking as his starting point Sherrington's work (1907) on the stretch reflex, demonstrated the monosynaptic reflex in man by its muscle action potential (H-reflex) (p. 16B–103).

### D. FIBRILLATION

As to spontaneous activity of denervated muscle, it was observed in the tongue of the dog five days after section of the hypoglossal nerve (Schiff 1851). This observation was forgotten until Langley and Kato (1915) drew attention again to fibrillation in denervated muscle.

### E. THE VELOCITY OF CONDUCTION ALONG MOTOR AND SENSORY NERVE

The time required for the transmission of volition and sensation has occupied physiologists for more than 200 years. In 1762, Albrecht von Haller refers to adventurous calculations by Sauvage who calculated the velocity of the nerve impulse to more than 100,000 m/sec. Von Haller himself tried to determine the velocity by reading the Aeneid aloud. He counted how many letters he could pronounce within 1 minute. Among the 1500 letters per minute "R" was assumed to require 10 successive contractions of the styloglossus muscle, indicating that a muscle can contract and relax 15,000 times per minute. From this he supposed each contraction to last 2 msec and that it took the nervous agent 2 msec to travel the 10 cm from the brain to the muscle. Thereby he arrived at a velocity of 50 m/sec, a value "not a little remarkable", as Du Bois-Reymond (1866) states, "in its wonderful coincidence with von Helmholtz' measurements of conduction velocity, considering that every single step in von Haller's reasoning was erroneous. In this case the Aeneid really has proved a book of oracles".

Others have shared this critical attitude and early in the 19th century the action of nerve was still explained as a psychical principle spreading with infinite velocity "just as the velocity of a thought". In his "Handbook of Physiology" Johannes

Müller (1834) concludes that the determination of the velocity of the nervous impulse "probably is denied us for ever". Within 20 years the velocity had been measured by his outstanding pupil, Hermann von Helmholtz (1850).

In his first studies von Helmholtz used an electromagnetic method which Pouillet (1844) had designed to measure the velocity of a bullet. Then von Helmholtz developed his own procedure and determined the conduction velocity of motor nerve in frog and in man by recording on a myograph the difference in mechanical latency of the muscle when stimulating successively at two points on the nerve. He gives the motor conduction velocity in the frog in two experiments as $31.4 \pm 7$ and $38.4 \pm 10.6$ m/sec (20° C). In the median nerve of the human arm the motor conduction velocity was found to be $61.0 \pm 5.1$ m/sec and in the leg $62.1 \pm 6.7$ m/sec; 17 years later he found 31.5389 and 37.4927 m/sec (1867) and attributed the difference between 30 and 60 m/sec to differences in temperature in winter and summer. Conduction velocity was higher in the proximal than in the distal segments of the median nerve (von Helmholtz and Baxt 1870).

At about the time of his first experiments on motor conduction, von Helmholtz (1850) determined the conduction velocity in sensory nerve in man to be 60 m/sec by measuring the difference between the reaction time to two subsequent tactile stimuli presented at different distances from the brain. This was the first of a series of papers on this subject, some of them by astronomers with the time measuring equipment used in observatories; they found a velocity of 30 m/sec (Hirsch 1865; Donders 1886). These values were often given with astronomical accuracy (29.634 m/sec, Schelske 1864). Kohlrausch (1866–67) found a velocity of sensory nerve of 94 m/sec and apparently suspected a calculating error to be the cause of von Helmholtz' lower values—but "Herr Hofrath von Helmholtz was kind enough to look at my figures and thought an error of this type in his experiments was unlikely". Later observers again found around 30 m/sec (von Wittich (1868): 35.82 m/sec; Oehl (1892): 35.18 m/sec and Kiesow (1904): 30.609 m/sec) and suspected a considerably lower velocity in sensory than in motor nerves.

Though the order of magnitude for both motor and sensory conduction found in these early studies was the same, the differences in velocity reported by various investigators worried physiologists and neurologists. Thus Sir William Gowers (1903) commented on a paper by Alcock (1904, read in 1903) who found the rapidity in the median nerve in tall and short individuals to be about 65 m/sec. Sir William refers to the velocity of 33 m/sec given by Sir Michael Foster in his "Textbook of Physiology" of 1888 (part I, p. 76). "The difference is considerable and places us in a dilemma: (1) either Sir Michael or Dr. Alcock is widely wrong or (2) the rate of transmission has become greatly accelerated during the last 15 years. Of the two the latter seems to be the simpler explanation."

Piper (1908, 1909a, b) was the first to use the muscle action potential in man as an indicator of the arrival of nerve impulses evoked by stimulation of the median nerve at two points 16–17 cm apart. He reported a velocity of 117 m/sec and believed the high rate to be due to the warm weather in June. Münnich (1916) attributed Piper's high velocity to inaccuracy caused by the short distance between the stimulating and recording electrodes; in critically evaluated experiments he came to a motor conduction velocity of 60–65 m/sec, of the same order as that found by Hodes *et al.* (1948), who were the first to determine motor conduction velocity in neurological patients.

The velocity of sensory nerve in man was still approached only indirectly. In 1922 Schäffer found a velocity of 60–65 m/sec. He used an ingenious method recording the time intervals between latencies of the H-reflex recorded at different levels of the leg. The method has the drawback that H-reflexes usually can only be evoked from the calves.

In continuation of the separation of whole nerve into groups of fibres with different diameter (Erlanger and Gasser 1924; Gasser and Erlanger 1927), Heinbecker *et al.* (1933) tackled the study of sensory nerve in man by recording action potentials 30 min after excision of a cutaneous nerve (saphenous). At a stimulus strength which gave pain on the tenth repetition of stimulation *in situ*, they found a fast component conducting at 100 m/sec, a slower conducting at 25 m/sec and at a stimulus strength sufficient to stimulate all fibres of the nerve, an additional component conducting at 1.5 m/sec.

# Section II. Principles of Recording. Limitations and Artefacts

Action potentials from muscle and nerve are recorded by placing two metal electrodes in the electric field set up by the action currents and by amplifying the potential difference between these electrodes. When action potentials are used for measurement it is necessary that distortion and disturbances are kept at a minimum throughout the whole recording system, from the tip of the electrode to the final trace. With proper construction of the difference amplifier and the recording system it will be possible to record without significant distortion the signals passed by the input stage. From this it follows that the choice of electrode and the properties of the input stage require special attention.

## A. RECORDING ELECTRODES

The choice of electrodes depends on the aim of the investigation. Small electrodes with an area of the same order as the cross section of muscle fibres (0.001 $mm^2$) are chosen to obtain a selective recording from a single or few fibres when many fibres are active. Electrodes used in clinical electromyography to record motor unit activity and spontaneous activity from single or few fibres have areas from 0.01 to 0.2 $mm^2$ as in concentric, bifilar, unipolar or multielectrodes. To obtain a measure of the number of active fibres in a muscle or nerve, and also for the study of the pattern of activation of different muscles, electrodes with a metal-area larger than 1 $mm^2$ are placed on the skin, subcutaneously, within the muscle, or close to the nerve.

The impedance of metal electrodes is determined by electrochemical processes in a thin surface layer between metal and electrolyte. It is inversely proportional to the electrode area and varies with frequency (Gesteland *et al.* 1959). Electrode impedance is reduced by passing a small alternating current across the surfaces with the needle in saline (Guld *et al.* 1970). For a concentric electrode with an area of 0.07 $mm^2$ the impedance declines from 100 kΩ at 10 c/sec to 4 kΩ at 10,000 c/sec (Fig. 1, Buchthal *et al.* 1954a; Guld *et al.* 1970). Small selective electrodes with tip areas of 0.0015 $mm^2$ have a higher impedance (75–150 kΩ at 1000 c/sec, Vallbo 1970), whereas the impedance of large steel-needle electrodes with bared tips of 3 mm (diameter 0.6 mm) can be reduced to 1000–2000 Ω (20–5000 c/sec) (Buchthal and A. Rosenfalck 1966a; Andersen and Buchthal 1970).

The impedance of the large surface electrode used to connect the patient to the ground terminal of the difference amplifier is about 1500 Ω at 50 c/sec and 400–1000 Ω at 500–5000 c/sec (Møller 1966).

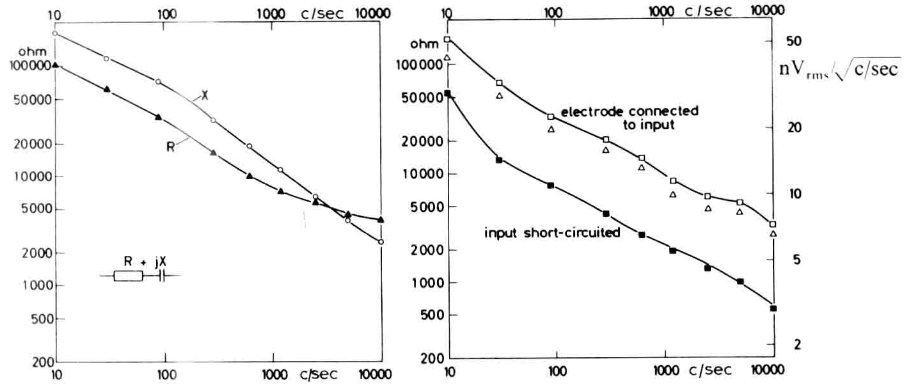


Fig. 1. Left: Impedance of a concentric electrode (area of core 0.07 $mm^2$) in 0.15% NaCl as a function of frequency. ▲ resistive component (R). ○ reactive component (X). The impedance was measured by means of a phase sensitive detector (Brookdeal Electronics 411) with a voltage over the electrode of less than 20 mV. Right: The shortcircuit noise of an FET amplifier (■) and the noise of the amplifier with the concentric electrode of Fig. 1 (left) connected to input (□). Left ordinate: equivalent noise resistance in ohm; right ordinate: $nv_{rms}$ per $\sqrt{c/sec}$. △ difference between equivalent noise resistance of amplifier with electrode and with shortcircuited input for comparison with the resistive component of the impedance in Fig. 1 (left).

### B. FREQUENCY RESPONSE (WITH ELECTRODE)

The frequency response of the input stage is largely determined by the ratio between the electrode impedance and the impedance between the two input terminals of the amplifier. To avoid distortion the input impedance should be at least 100 times greater than the electrode impedance. High impedance electrodes require that the cable to the input stage is shielded (p. 16B–17). The use of grounded shields adds capacitance to ground of 100–200 pF/m. Therefore, special precautions should be taken (driven shield arrangements) to reduce the effect of this capacitance.

The result of using an electrode with a small area, *i.e.*, with a high impedance, without increasing the input impedance of the amplifier, is a narrowing of the frequency response.

To record faithfully action potentials from single motor units or a few muscle fibres the transmission characteristic of the recording system including the electrode should be flat over a frequency range with −3 dB points at 2 c/sec and 10,000 c/sec. A decrease in high frequency limit would cause a prolongation of spike duration and loss of spike amplitude (Buchthal *et al.* 1954). A change in low frequency limit from 2 to 20 c/sec may add a tail to muscle action potentials (Buchthal *et al.* 1954a) and to stimulus artefacts (Andersen and Buchthal 1970).

The distortion which arises from frequency limits and non-linearities in a recording system can be studied by applying a signal to the electrode and displaying this signal and the transmitted signal on a double beam oscilloscope (Fig. 2 and Guld *et al.* 1970). The best test signal would be a replica of the action potential but valuable information can be achieved by testing with transient square or triangular symmetrical waves in addition to the classical determination of 3 dB frequency limits to sine wave signals (Schoenfeld 1964; Guld *et al.* 1970).

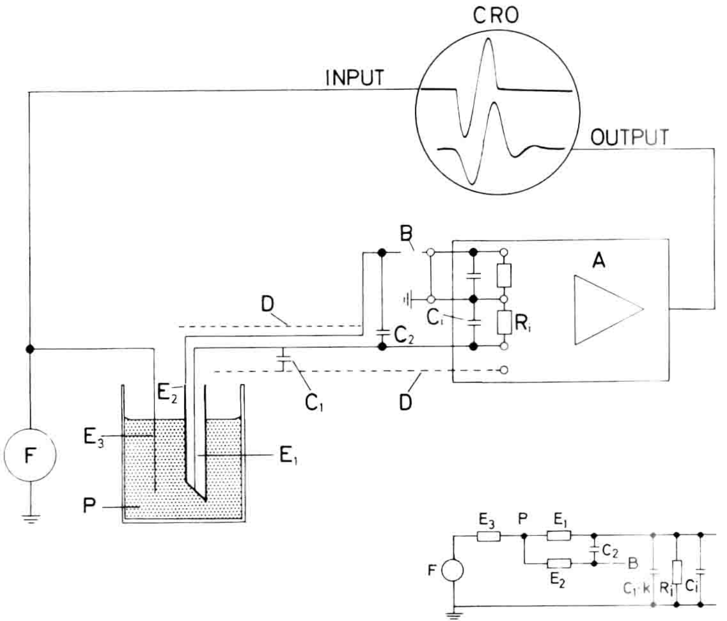


Fig. 2. Set-up for check of the frequency and pulse response of a recording system including a concentric electrode and its shielded input cable. $E_1$, $E_2$: concentric electrode; $E_3$ large area electrode; P: 0.15% NaCl or muscle; D: driven cable shield; $C_1$: capacitance between inner core and cable shield; k: reduction factor for driven shield; $C_2$: capacitance between inner core and cannula. A: difference amplifier with one side grounded in the input stage; $C_i$: input capacitance; $R_i$: input resistance; F: function generator, output impedance $< 1000\Omega$; CRO: cathode-ray-oscilloscope. B: the cannula was disconnected in the plug. Below: equivalent diagram of the set-up. $E_1$, $E_2$, $E_3$ represent the impedance of the respective electrodes. The shunting effect of $C_2E_2$ was negligible.

The frequency range of the system should be chosen to be as wide as necessary for undistorted recording and as narrow as possible for the reduction of interference and blocking time (p. 16B–17). However, when disturbances from base-line shifts and noise are prohibitive for recording, a reduction of the bandwidth of the amplifier is needed. The choice of slope of the frequency response curve (*e.g.*, 20 or 40 dB per decade) beyond the cut-off frequency is a compromise between distortion and interference. The effect of the filters is best evaluated by comparing action potentials recorded with the total bandwidth (2–10,000 c/sec) and with the bandwidth reduced.

Similarly, the effect of recording action potentials on instruments with a limited bandwidth (paper recorders, UV recorders and magnetic tape recorders) can be evaluated by recording the same potentials from cathode-ray-oscilloscopes. In the case of magnetic tape recording (conventional or FM) action potentials or transient test pulses reveal the distortion from the restricted frequency band as well as from the phase shifts (Fig. 3).

However, many components of the noise, stimulus artefact and interference potentials have the same frequency content as the action potentials and precautions other than limiting of the frequency band should therefore be considered.

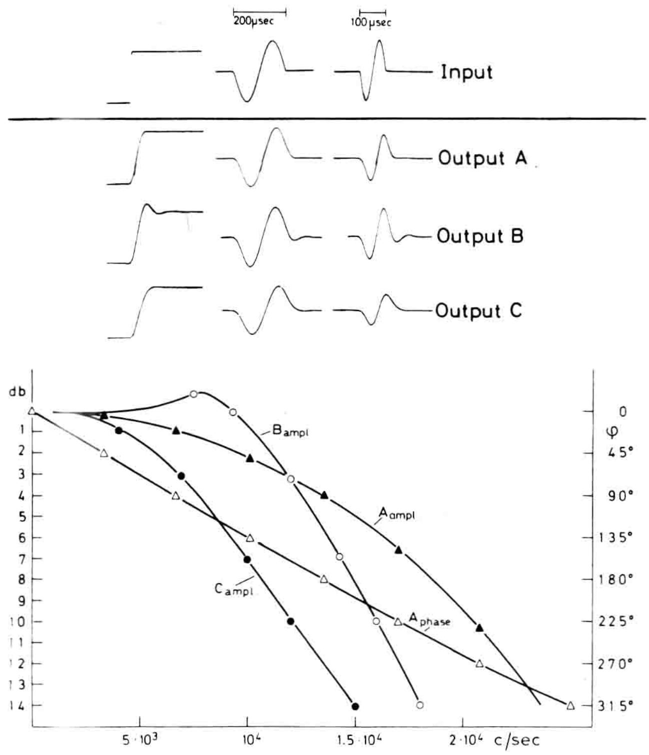


Fig. 3. Results of tests of recording systems with a step function and with two single periods of sine wave. Above: input from function generator. Middle: outputs from three different recording systems A, B and C. Below: amplitude and phase characteristics for system A and amplitude characteristics for B and C. Note that the peak-to-peak deflection in the 200 $\mu$sec pulse is full size in A and B whereas the 100 $\mu$sec pulse is cut in amplitude and prolonged in all cases.

C. NOISE

The thermal noise from the tip of an electrode depends on the ohmic component of the electrode impedance (for references see Offner 1967). At room temperature (15–30° C) the noise voltage of the electrode resistance (R ohm) is: $0.13 \cdot \sqrt{R}\ nV_{rms}$ per $\sqrt{\text{bandwidth in c/sec}}$. For the concentric electrode in Fig. 1 the noise resistance varies from 100,000 to 5000 ohm from 10 to 10,000 c/sec and the noise voltage from 40 to 8 $nV_{rms}$ per $\sqrt{c/sec}$. This corresponds roughly to a peak-to-peak noise of 10–13 $\mu$V or 2–3 $\mu V_{rms}$ in the frequency range 2–10,000 c/sec.

The shortcircuit noise of an amplifier with junction field effect transistors (FET) in the input stage can be kept to half these values. This is illustrated in Fig. 1 (right) which shows the shortcircuit noise of an FET amplifier and the noise with a concentric electrode connected to the input. The noise was measured with a wave-analyzer (Radiometer FRA 3, noise bandwidth of filters 9 c/sec) and the values converted to equivalent noise resistance. It can be seen that the electrode has only added the thermal noise due to its own ohmic resistance. With an FET amplifier there is no increase in amplifier noise when the electrode is connected. In contrast, the measure-