

**MANUAL OF SURFACE ELECTROMYOGRAPHY**

*John F. Davis, M.D., M.ENG.*

*Laboratory for Psychological Studies  
Allan Memorial Institute of Psychiatry  
McGill University*

*DECEMBER 1959*

(This is a republication of a report originally published by the  
US Army in 1952, under Contract No. DA-49-007-MD-70)

Project No. 7184

Task No. 71580

AEROSPACE MEDICAL LABORATORY  
WRIGHT AIR DEVELOPMENT CENTER  
AIR RESEARCH AND DEVELOPMENT COMMAND  
UNITED STATES AIR FORCE  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

# Contrails

## FOREWORD

This report was originally prepared by John F. Davis, M.D., M.Eng., under Contract No. DA-49-007-MD-70 between The Surgeon General, U. S. Army and McGill University (Dr. R. B. Malmo, Principal Investigator). Reproduction in whole or in part for any purpose of the U. S. Government is authorized. Permission to reproduce this report was obtained from The Surgeon General, and from Dr. John F. Davis. It is being reissued as a report of the Psychology Branch of the Aerospace Medical Laboratory, Directorate of Research, Wright Air Development Center, under a project identified by Research and Development Project No. 7184, Task No. 71580, "Criteria for the Design and Arrangement of Displays" with Mr. Charles A. Baker acting as task scientist. The reissued report was prepared for publication by the Engineering Psychology Research Project, Antioch College under Contract No. AF 33(616)-6095 with the approval of the Chief, Aerospace Medical Laboratory, Wright Air Development Center.

This manual\* was actually the product of the closely knit efforts of a whole group of workers in the Laboratory for Psychological Studies at the Allan Memorial Institute of Psychiatry. The author would like to thank especially Dr. R. B. Malmo, Director of that Laboratory, for his many concrete suggestions and his moral and physical support in the preparation of the manual. Acknowledgement is also made to the following former members of his staff for their assistance: Mr. R. E. Quilter, Mrs. D. Hubel, Mrs. W. Kohlmeyer, Mrs. W. W. Surwillo and Miss D. Casdim.

The author would also like to thank Mr. John Wing of the Engineering Psychology Research Project at Antioch College, for his efforts in producing the second printing of this manual, and Mrs. Marie Payton of that Project, for her efforts in modifying the format of the report and doing the complete retyping of it. The text remains almost identical to the original (1952), although it could have been greatly expanded in the light of more recent experiences. However, time for rewriting has not been available and we hope that the basic story presented here is still valid.

---

\*The term "manual" is retained in the title of this report in order to be consistent with the first printing. This is not, however, an official Air Research and Development Command manual and is issued for information purposes only.

The methodology and instrumentation of surface electromyography are presented in detail. Principles (and applications of principles) of electrode placement are given along with certain standard placements. Various types of ink-writing electromyographs and accessories are evaluated and specifications are outlined for a satisfactory research instrument. These specifications include type of power supply, type of recorder, and desirable characteristics for the pre-amplifiers, the main amplifiers, and the control panel. Basic principles are given for layout and construction of laboratory rooms so as to minimize artifacts in the EMG record. Finally, the manual discusses the operation of EMG instruments, including methods of eliminating various artifacts, and the measurement of both primary and integrated records. Illustrations of electrode placements and construction and schematics of ink-writing electromyographs are provided.

*Contrails*  
TABLE OF CONTENTS

	<u>Page</u>
PREFACE . . . . .	1
PART I: METHODOLOGY - SURFACE ELECTROMYOGRAPHY	
A. Why Surface Electrodes? . . . . .	2
B. Principles of Electrode Placement. . . . .	7
1. Anatomical considerations. . . . .	7
2. Depth of the muscle. . . . .	7
3. Spacing of electrodes. . . . .	9
4. Separation of activity . . . . .	10
5. The orientation of the vector. . . . .	10
C. Application of these Principles. . . . .	12
D. Standard Lead Placements used in this Laboratory . . . . .	15
1. Forehead . . . . .	16
2. Massater . . . . .	18
3. Chin . . . . .	20
4. Sternomastoid. . . . .	20
5. Neck . . . . .	22
6. Trapezius. . . . .	24
7. Biceps . . . . .	24
8. Triceps. . . . .	26
9. Forearm flexor . . . . .	26
10. Forearm extensor . . . . .	28
11. Leg. . . . .	28
PART II: INSTRUMENTATION - THE INK-WRITING ELECTROMYOGRAPH AND ITS ACCESSORIES	
A. Electrodes . . . . .	31
1. EKG or plate type. . . . .	31
2. "Bentonite" or mud type. . . . .	33
3. "Sponge" type. . . . .	34
4. "Collodion" type . . . . .	36

*Contrails*  
TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
5. "Needle" type . . . . .	38
6. "Saline bridge" type. . . . .	41
7. Other types . . . . .	41
8. The story of chloriding . . . . .	41
B. Electrode Attachments . . . . .	43
1. Adhesive cement . . . . .	44
2. Adhesive tape . . . . .	44
3. Elastic belts and bands . . . . .	45
4. Lastonet. . . . .	45
5. Stress relief . . . . .	46
C. The Problem of Skin Resistance. . . . .	46
1. Method of attack. . . . .	47
a. Cleansing . . . . .	47
b. Abrasion. . . . .	47
c. Massage . . . . .	48
D. General Remarks on Amplifiers, Recording Methods, and Integration . . . . .	48
1. Amplifiers. . . . .	48
2. What do the amplifiers measure? . . . . .	51
3. Choice of a recording method. . . . .	53
4. Integration . . . . .	55
E. Block Diagram of Instrumentation. . . . .	57
1. The electrode plug-in box . . . . .	61
2. The selector switches . . . . .	61
3. The calibrator switch . . . . .	62
4. The preamplifiers . . . . .	62
5. Gain controls and filter controls . . . . .	65
6. The main amplifiers . . . . .	68
7. The integrators . . . . .	73

*Contrails*  
TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
8. Galvanometers and chart drives. . . . .	75
9. Internal and external calibrators . . . . .	76
10. The integrator timer and discharging relay. . . . .	78
F. Disadvantages of Some Commercial EEG's for EMG Use. . . . .	81
G. Specifications for a Research EMG . . . . .	83
H. Laboratory Design and Layout. . . . .	87
1. Privacy . . . . .	87
2. Quiet . . . . .	89
3. Low electrical interference . . . . .	90
I. Costs . . . . .	91
 PART III: OPERATION - PRACTICAL POINTS IN THE USE OF THESE INSTRUMENTS  	
A. Application and Care of Electrodes. . . . .	93
1. Measurement of electrode resistance . . . . .	94
2. The ohmmeter. . . . .	95
3. Electrode maintenance . . . . .	96
B. Connecting the Subject to EMG . . . . .	98
C. Grounding Problems. . . . .	98
D. Artifacts in the Primary Record . . . . .	100
1. "60-cycle" artifact . . . . .	100
2. "EKG" artifact. . . . .	104
3. "EEG" artifact. . . . .	106
4. "Eye-blink" artifact. . . . .	106
5. "Pulsation" artifact. . . . .	107
6. "GSR" artifact. . . . .	107
7. "Electromechanical" artifact. . . . .	108
8. "Open circuit" artifact . . . . .	108
E. Artifacts in the Secondary Record . . . . .	109

*Contrails*  
TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
F. Equalization, Calibration, and Other Daily Adjustments. . . .	111
G. Getting a First-Class Recording . . . . .	113
H. Measurement of the Records. . . . .	115
I. Routine Equipment Checks. . . . .	119
REFERENCES . . . . .	121

LIST OF ILLUSTRATIONS

<u>Figures</u>		<u>Page</u>
1	EMG amplitude vs. dynamometer pull. . . . . (Data furnished by R. B. Malmo)	5
2	Surface activity and depth of muscle. . . . .	8
3	Effect of electrode spacing . . . . .	8
4	Differentiation of muscles at varying depths. . . . .	11
5	Orientation of electrodes over a muscle . . . . .	11
6	Flexor-extensor differentiation . . . . .	14
7	Longitudinal vs. transverse placement . . . . .	14
8	Standard forehead lead. . . . .	17
9	Standard masseter and sternomastoid leads . . . . .	19
10	Standard chin lead. . . . .	21
11	Standard neck lead. . . . .	23
12	Standard trapezius lead . . . . .	25
13	Standard biceps lead. . . . .	25
14	Standard triceps lead . . . . .	27
15	Standard forearm flexor lead. . . . .	27

*Contrails*  
LIST OF ILLUSTRATIONS (Cont'd)

<u>Figures</u>		<u>Page</u>
16	Standard forearm extensor lead. . . . .	29
17	Standard leg lead . . . . .	29
18	Table of electrodes used in electromyography. . . . .	32
19	Construction of "sponge" electrode . . . . .	35
20	Construction of "collodion" electrode . . . . .	37
21	Construction of "needle" electrodes . . . . .	39
22	Block diagram of instrumentation. . . . .	58
23	Comparison of preamplifier circuits . . . . .	63
24	Circuits and data: Low frequency filters . . . . .	69
25	Circuits and data: High-frequency filters. . . . .	70
26	Comparison of main amplifiers . . . . .	72
27	Functional diagram of integrator. . . . .	74
28	Basic timer for integrator. . . . .	79



The preparation of this manual was in response to a number of requests from other investigators for detailed information concerning our use of electromyography (EMG) in psychological studies. Limitation of space in journal publications prevents the investigator from presenting many details of instrumentation and procedure which are of considerable importance to others in the field. Unfortunately, the kind of "know-how" which an investigator acquires in working with specialized instruments is rarely passed along in print to others; it often lies buried in the store of personal experience of the investigators themselves. The major aim of this manual is to pass along such useful information to others.

A word should perhaps be said about singling out EMG technique for special consideration and the failure to deal with other physiological measures. This concentration on EMG does not mean that this measure is to be used by itself in psychophysiological investigations, nor that it is superior to other measures. There are at least two very good reasons why Dr. Davis should devote an entire manual to EMG. In the first place, he has contributed significantly to the development of techniques for recording and quantifying EMGs, and this manual affords him opportunity to describe the details of this important developmental work. In the second place, relatively few psychophysicologists have employed EMGs, probably because the techniques for recording them are more difficult to master, and the need for spelling out the essentials of reliable EMG recording is therefore greater than it is in the case of other techniques that have been more widely used.

As a matter of fact, the manual deals with certain general methodological considerations that extend beyond the limits of EMG recording. In addition to its practical value, Dr. Davis' manual is a splendid example of how important the contribution of biophysics is to a research program in the field of psychophysiology.

R. B. Malmo, Ph.D.  
Principal Investigator

## METHODOLOGY - SURFACE ELECTROMYOGRAPHY

## A. WHY SURFACE ELECTRODES?

In muscle potential work, one should think of the muscle as a source of electrical activity surrounded by a low-resistance conducting medium (the interstitial fluid, blood, and other tissue), usually referred to as a "volume conductor." This, in turn, is surrounded by skin, a two-layer membrane consisting of a metabolising layer of living cells, glands and accessories, and having a relatively low electrical resistance, and a non-metabolising layer of horny, dead, and dying cells which has a high electrical resistance.

The problem of instrumentation, then, is to get at and measure the electrical activity of muscle with as little interference from other factors as possible. And the practical solution to the instrumentation will depend upon what kind of information is to be obtained from the muscle. For example, if a careful study of the muscle action-potential is to be made, then an intramuscular electrode of near-microscopic dimensions will be needed in order to pick up potentials from a single muscle fibre, and a D-C amplifying system would be needed to reproduce the long-lasting after-potentials. Or, where the "spike" of a muscle action-potential (i.e., the initial rapid component - monophasic or diphasic) is of interest, then the intramuscular electrode must still be used but an ordinary A-C amplifier will do. And thirdly, if the details of individual spikes are not important, but a broad survey of the action potentials from a whole group of muscle fibres, or a whole muscle, is of interest, then a subcutaneous or surface electrode located over the muscle will pick up the desired information. In the last case, an A-C amplifier is perfectly adequate because the after-potentials from many fibres tend to cancel each other out when they are all firing asynchronously and repeatedly, whereas the spikes occur so

---

Author released manuscript January 1959 for publication as a WADC Technical Report

WADC TR 59-184

2

rapidly that relatively few of them cancel out and the pattern merely becomes coarser and of higher amplitude as the muscle becomes more and more active. This ability to pick up spikes from many muscle fibres makes the surface electrode particularly valuable for studying muscle tension, since in this field it is the whole muscle one is interested in rather than a microscopic part of it. Lindsley has stated that surface leads are preferable in the study of tension associated with emotional reactions.

The clinical electromyographer ordinarily employs the intramuscular needle type electrode which automatically eliminates most of the problems arising from non-muscular tissues and the skin, and at the same time gives information about the shape of individual action potentials which is of diagnostic value. We, however, are not primarily concerned with the details of individual action potentials and find that surface electrodes are admirably suited to our needs. This relatively non-traumatic method of electrode connection also makes it possible for us to attach many electrodes to a subject without submitting him to undue stress (when the electrode placement routine is operating smoothly!).

We recognize, of course, that individual spikes are distorted by the effect of attenuation in passing through the conducting media, but it is mainly the high-frequency component which is distorted and, since the ink-writer cannot follow the higher frequencies anyway, we are not much concerned about their loss. Empirically, one finds that most of the available ink-writers do record a very useful electromyogram from surface electrodes and one is immediately struck with the fact that the envelope of the EMG wave (i.e., the peak amplitude) appears to change in proportion to the amount of muscular activity. Also, the complexity of the wave form suggests immediately that it is a summation of the electrical activity from a relatively large section of muscle tissue. Although interesting patterns and wave forms are seen, it can readily be appreciated that the cathode-ray oscilloscope would reveal an even richer wave form so that studies of the electromyogram structure are best left for a different instrumentation.

The important basic assumption that amplitude of the EMG is closely related to the strength of muscle contraction or degree of muscle tension

# Contrails

was checked in an experiment conducted by Dr. R. B. Malmo. Records were taken from surface electrodes over the flexor muscles of the forearm while the subject pulled with fixed amounts of tension on a hand dynamometer of the spring type. Normal males and females yielded data for the curves illustrated in Figure 1. In the upper ranges of tension it can be seen that the graphs tend to be more exponential than linear, which is of interest, but this is in the range of very strong muscle contraction. The relationship between EMG and kilograms of pull is practically linear in the range below 6 kg. A further study was carried out of EMG amplitude vs. spring tension in the range 0-2 kg. This was done with a standard spring scale, operated by flexion of one finger. In this range the function proved to be very linear and no sex difference was demonstrated. Most of the activity recorded in our work would be well down in the linear part of these curves.

Although we are satisfied that the amplitude of the EMG gives a satisfactory indication of tension in a muscle we recognize that rather gross variability about a mean amplitude is to be expected even when conditions are such as to maintain the tension nearly constant. Thus, in the above dynamometer study one subject may have produced EMG potentials double or treble those of a second subject for the same pull. Even the female group average yielded a curve about 50% higher than the male group average in the range of strong muscle pulls. In fact, many different factors enter into the production of the EMG potential. Some of these might be:

- Type of muscle tissue (smooth or striated)
- Use of the muscle (postural or otherwise)
- Size of muscle (normal, atrophic or hypertrophic)
- Sex of individual
- Degree of individual development
- Degree of fatigue present
- Number of muscle fibres per bundle (i.e. per nerve fibre or motor unit)
- Number of muscle bundles
- Oxygenation, metabolism and bloodflow.

Thus, although we actually make measurements on individual EMG spikes or small groups of spikes, it is only by averaging many measurements that

# Contrails

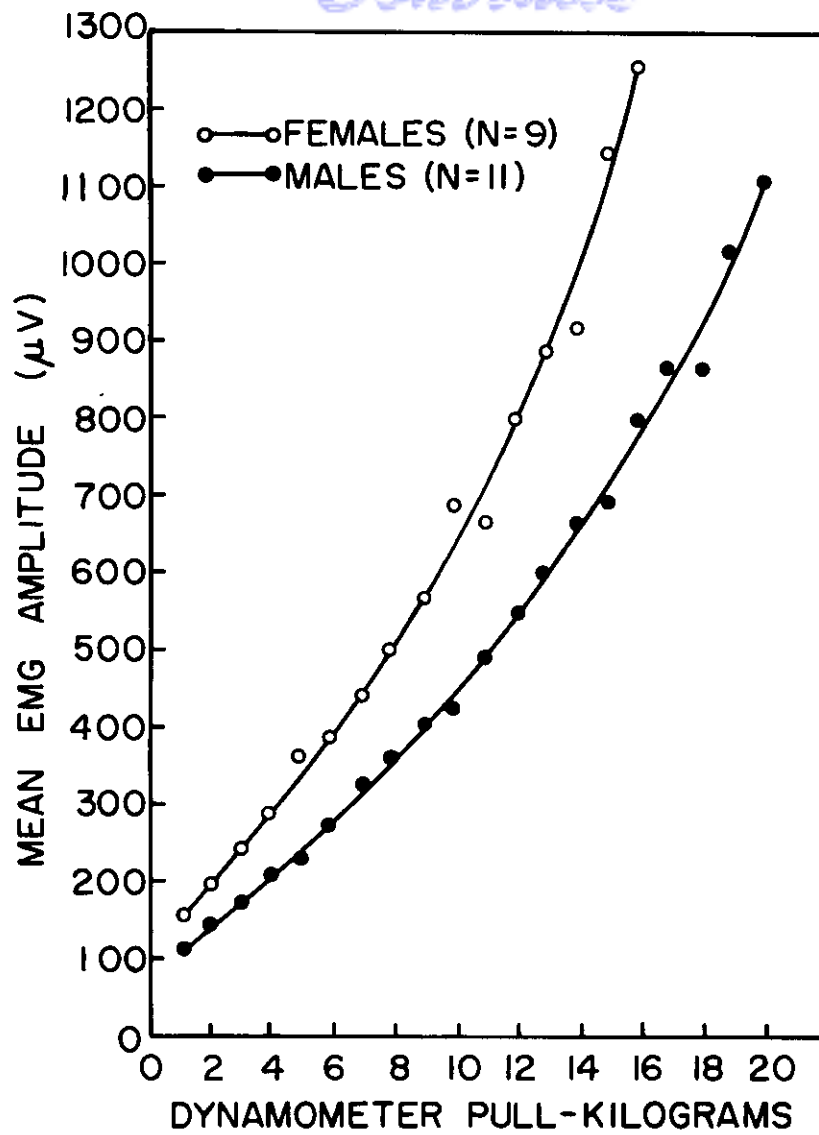


FIGURE I. EMG AMPLITUDE VS. DYNAMOMETER PULL

DATA FURNISHED BY R.B. MALMO

# Contrails

reliable comparisons can be made either from individual to individual or in the same individual from time to time. And, although the absolute amplitude of the EMG may give a rough idea as to the degree of muscular activity, it is the change in amplitude which yields the more interesting information.

Spike-counting was tried in some of our earlier investigations. The object was to try to establish a correlation between clinical variables and spike-frequency changes independent of the amplitude changes. The practical difficulties proved insurmountable at the time and this line of measurement was given up. The problem with hand-counting of spikes was two-fold. Paper speeds had to be very high (at least 50 mm/sec) to separate the spikes for counting, and it was difficult, with the ink-written record, deciding what was a spike and what wasn't. For example, by increasing the recording sensitivity (say, doubling the amplitude) without any other change, one could count more spikes than at the lower amplitude - simply because the friction of the paper or the inertia of the pen did not permit a measurable deflection of the pen for a very small, very fast spike at the lower gain. Also, it was found that for very wide ranges of tension, provided the recording sensitivity was kept adjusted for approximately constant signal output, frequency counts fell within a rather narrow band (from 40 to 60 spikes per second) and with a more random distribution than we had hoped for. It was concluded that ink-writers could not be satisfactorily used for this type of quantification.

A further attempt to secure frequency counts was made at the time of constructing our first muscle-potential integrators. In these, a special electronic circuit was included which, by means of sharpening, peak clipping, and differentiating elements, was supposed to feed uniform pulses to a counting-down circuit, and the final count appeared on a mechanical counter. The system would respond to spike-frequencies as high as 150 or 200 per second and thus could follow EMG spikes which were not recordable by the ink-writer. The system worked very well as long as the input signal remained fairly constant but with wide amplitude variations such as are common in electromyography, the errors were large. We were thus again frustrated in our attempt to separate frequency and amplitude. No further work has been done but it is not inconceivable that future progress in

frequency-analyzing integrators may provide the key to this problem. Meanwhile, of course, we feel that the results from the use of the amplitude variable alone are so rich as to warrant its continued use.

Surface electromyography, with all its difficulties, has come to be the most useful single tool in our battery; it is thus important to apply it in the most efficient manner possible.

## B. PRINCIPLES OF ELECTRODE PLACEMENT

The limitations of surface electrodes as regards the electrical detail of muscle action potentials have been mentioned above, but this works mainly to our advantage in that the EMG wave picked up represents a kind of summated electrical activity from a whole section of muscle tissue. We would like now to go into some detail in the matter of the anatomical limitations and other factors which govern electrode placement.

1. Anatomical considerations. Large muscles or muscle groups whose electrical activity spreads over a wide anatomic area are easy to tap with surface electrodes. A small muscle located just under the skin may lay down a surface electrical field strong enough to give clearly defined recordings with skin electrodes. But a similar small muscle located deeply under the skin may produce a very weak and poorly defined surface electrical field and, therefore, may be difficult or impossible to study with surface electrodes. Further limitations of the technique are met when the electrical activity from the desired muscle becomes inter-mingled with activity from a muscle not under study or from other sources of electrophysiological potentials. Examples of situations such as these will be commented upon in the section on Standard Lead Placements.

2. Depth of the muscle is an important variable. Figure 2 shows pictorially how we may think about this matter of attenuation. Actually, the conducting medium acts as a partial short circuit to the electrical output of the muscle. Two muscles are shown which are about equally active, as indicated by the length of the vectors drawn inside the muscles, but they

# Contrails

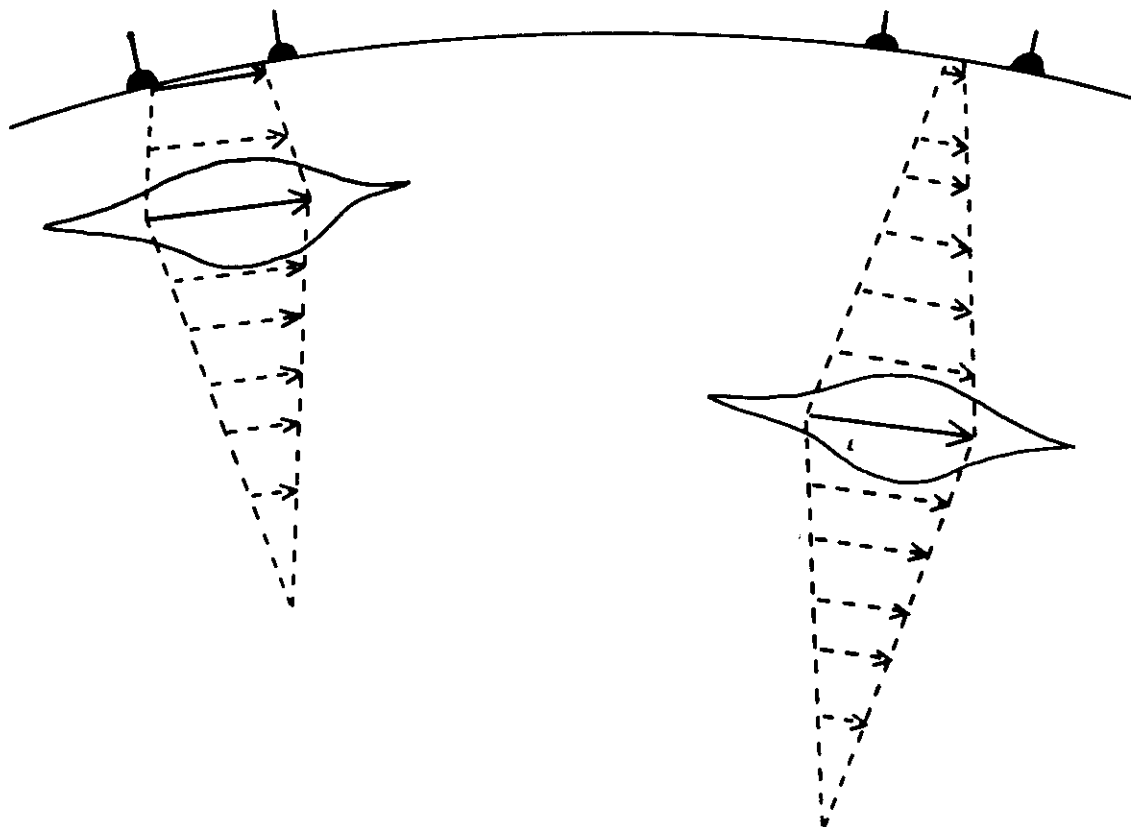


FIGURE 2. SURFACE ACTIVITY AND DEPTH OF MUSCLE

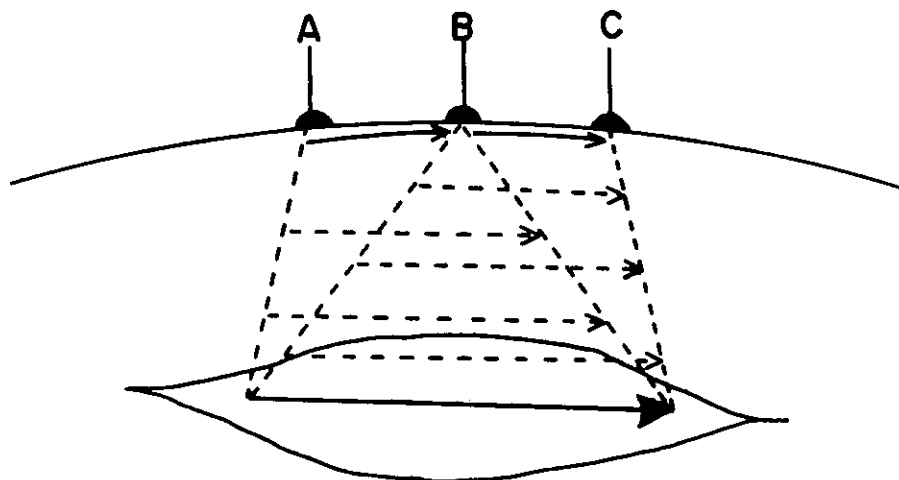


FIGURE 3. EFFECT OF ELECTRODE SPACING



# Contrails

lie at different depths under the skin and, therefore, the amount of conducting medium lying between the skin and the muscle is different in the two cases. This results in different degrees of attenuation of the vectors from the two muscles. The two muscles are shown surrounded by groups of vectors which become smaller with increasing distance from the muscle, and it is easy to see that the surface electrode over the deep muscle will pick up considerably less electrical activity than the one situated over the muscle closely located under the skin. Another way of thinking about this picture is to say that the electrical activity at the surface is inversely related to the depth of the muscle. Whether this relationship is inversely proportional to the depth or whether it varies according to the inverse square of the depth or some other power of the depth of the muscle is not known and probably varies a lot with the individual case. Since the irregularly shaped human body acts as a volume conductor, it is evident that the electrical field of the muscle vectors will be squeezed and distorted in various ways, according to the relationship of the muscle to the skin and other anatomical structures. We would, therefore, not expect to find any simple law relating surface activity to depth of muscle.

3. Spacing of electrodes on the surface over a muscle is another important variable in this work. The little vectors just under the skin, shown in Figure 2, and which represent the amount of electrical potential reaching the skin, do not, of course, appear only at one small point. They appear in varying degree all over the skin nearby but, in general, are largest immediately over the muscle involved. Figure 3 shows three electrodes placed immediately over a muscle. If the pair of electrodes AB and the pair BC are of similar spacing and are more or less symmetrically placed over the muscle, one would expect to get about the same amount of electrical activity from each pair. This is shown by the two small vectors of equal length immediately under the skin. If we now consider the outside pair of electrodes AC, we are really adding electrically the two small vectors AB and BC, and we would expect to get about twice as much electrical activity from this third pair. Thus, where fairly large muscles are involved we anticipate some proportionality between the electrode spacing and the amount

# Contrails

of electrical activity picked up. Indeed, this expectation is confirmed by the empirical finding that narrowly spaced electrodes do yield lower potentials than do widely spaced ones. Also, as we widen the electrode spacing, information from deeper layers becomes measurable - which may or may not be advantageous, depending on the problem.

4. Separation of activity from neighbouring muscles is probably best accomplished with electrodes spaced close together over the desired muscle. In the case of two muscles with equal activity at different depths (see Figure 4), we may speculate as to what sort of mixed signal will be picked up by electrodes of different spacing. With narrowly spaced electrodes one will obtain a certain ratio of desired to undesired signals from the two muscles. As the spacing is increased, both the desired and undesired signals increase so that the ratio remains constant for a time and there is no gain or loss in differentiation. However, as the spacing between electrodes approaches and exceeds the physical size of the desired muscle (the one closest to the surface), the desired signal no longer increases in proportion to the increasing electrode spacing. The signal from the undesired muscle may, at the same time, continue to increase in proportion to the spacing, since the surface electrical field from this deeper muscle may be more uniform. In this way, the ratio of desired to undesired signals may actually be reduced by the wider spacing. By carrying this argument to the logical limit, if extremely wide spacing is used (spacing much greater than the size of the muscles involved) the ratio between the two signals becomes practically unity if the two muscles are equally active, so that there is no effective separation of the two signals. Referring again to Figure 4, the electrodes XY evidently would discriminate against the signals from the deeper muscle better than would the electrodes WZ.

5. The orientation of the vector of electrical activity of a given muscle should be important if there actually is a vector. Figure 5 represents a view of four electrodes attached to the skin, looked down upon from above. The broken line is the outline of a muscle under the skin and the broken vector is the activity of this muscle. In a case as clear-cut as this geometrically, one would get a maximum of electrical activity from the electrodes GH and a minimum or no activity at all from the pair JK. Now in

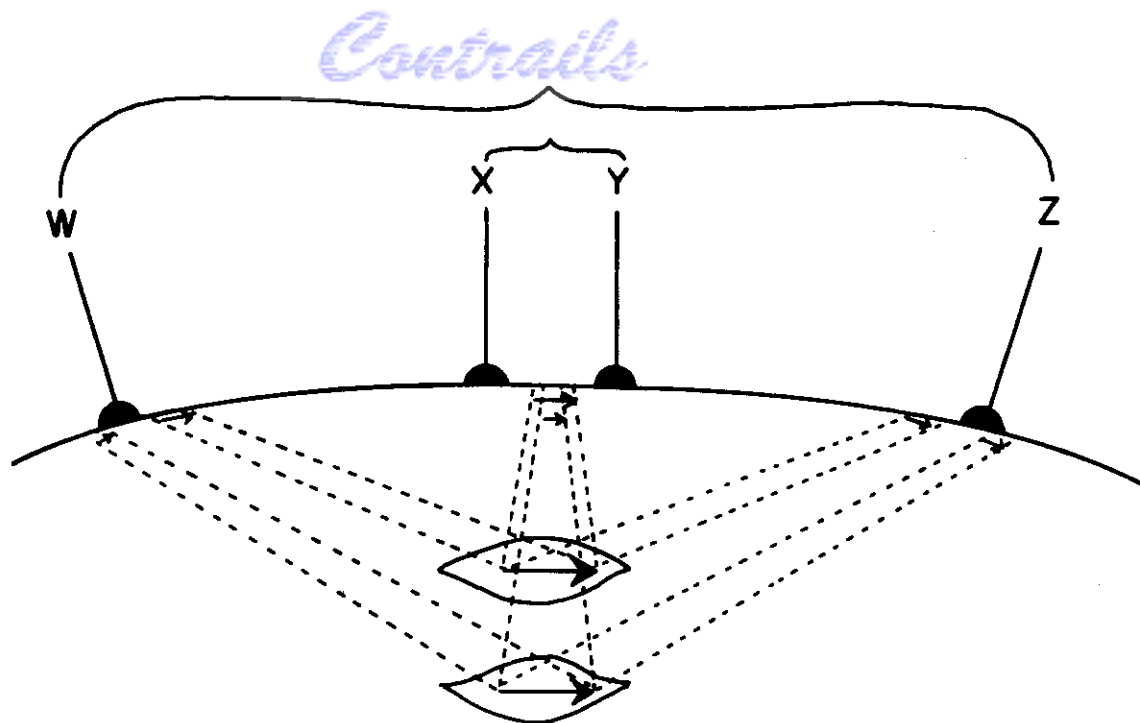


FIGURE 4. DIFFERENTIATION OF MUSCLES AT VARYING DEPTHS

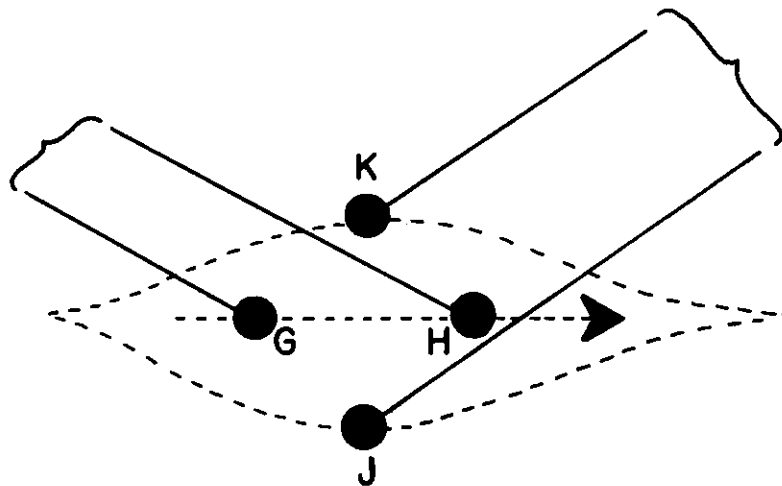


FIGURE 5. ORIENTATION OF ELECTRODES OVER A MUSCLE

# Contrails

practice, of course, there is no position over a muscle where a pair of electrodes will pick up zero activity. This is because the muscle has breadth as well as length and the fibres on one side of the muscle do not contract in perfect synchrony with those on the other side. However, one does find larger potentials in one direction than in another, the direction of the largest signals usually being parallel with the muscle fibres. Thus, orientation can be an important variable in determining electrode placement.

We have spoken glibly of vectors of activity, of inter-electrode spacing, of partial short circuits, and so on .... How important are all these things in a practical sense? We cannot perform very accurate geometrical operations upon something as variable and as flexible as the human anatomy; neither the measurement in the dimension of depth nor the measurement upon the surface of the skin can be relied upon to remain constant either from individual to individual, or in the same individual from moment to moment, in anything but the resting state. Whenever physical movement is carried out, the muscles slide upon one another in various ways and the skin slides over the muscle layer to a considerable extent. Thus, an accurate placement one minute may be quite inaccurate the next minute, and a vector pointed in one direction one minute may change considerably the next minute. However, in spite of these various sources of error, the principles are well worth remembering and yield fruitful results in many cases.

It is to be hoped that the reader will not think of these diagrammatic illustrations of surface electromyography as being mathematical derivations. They are intended only to help in the choice of electrode placement. A much more rigorous analysis of the electrical fields involved would form the subject matter of a technical monograph on the subject.

## C. APPLICATION OF THESE PRINCIPLES

Now we shall proceed to a few concrete examples based on laboratory experience which, on the whole, support the principles set forth in the preceding section.

# Contrails

Example 1 - Differentiation between flexor and extensor activity in recording from muscles of the forearm. Figure 6 shows diagrammatically the human forearm with a number of electrodes attached. When we first set out to record separately from flexor and extensor muscles, we reasoned that placement such as MS and PS should give fairly well differentiated records, because, we argued, the tendons located at S represent a relatively inactive area as far as these muscles are concerned and, therefore, should be an inactive reference point, with all the active potentials coming from the electrodes M and P. However, on actually recording two channels from these two electrode pairs, one could detect practically no difference in the shape of the wave coming from the MS pair as compared with the PS pair. In the light of the foregoing discussion, it can now be seen why this was; evidently, the E muscle contributed just about as much activity to the PS recording as did the F muscle because the wide electrode spacing tended to pick up as much "deep" activity as "superficial" activity. In attempting to record flexor activity, of course, the extensor muscles represent a deeper group and vice versa. Later experimentation showed that very much better discrimination between flexor and extensor groups could be achieved by the use of such pairs of electrodes as MN and PQ. Here again, in the light of our discussion of the relative depth of the muscles in relation to the spatial separation of the electrodes, it can be seen that the F group of muscles would be expected to contribute much more activity to the PQ recording than would the E group of muscles.

Example 2 - Direction of orientation of the muscle potential vector. Early in our experimentation, we found that we consistently got higher electromyographic potentials when our electrodes were placed along lines longitudinally related to the arm than if the electrodes were placed along lines transversely drawn on the arm. In Figure 7, placements such as YY invariably gave higher potentials than placements such as XX. No further investigation of this phenomenon was conducted at the time nor has been since, but it is possible that in the future we may investigate the vectorial axes more fully with a view to exploiting this aspect of muscle activity even further. It is possible, for instance, that there is an optimal axial

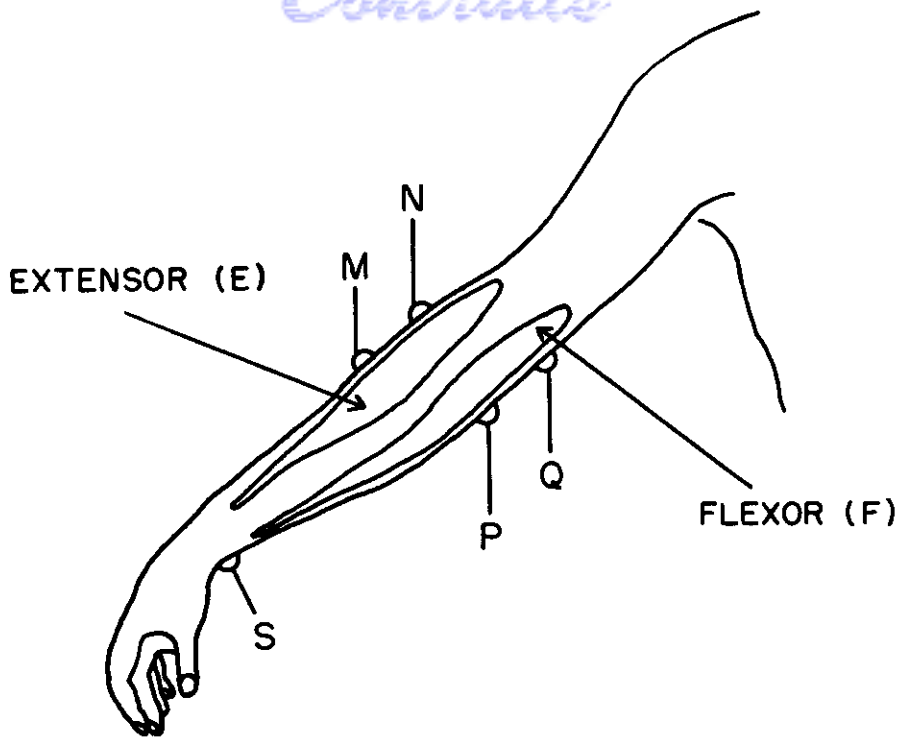


FIGURE 6. FLEXOR-EXTENSOR DIFFERENTIATION

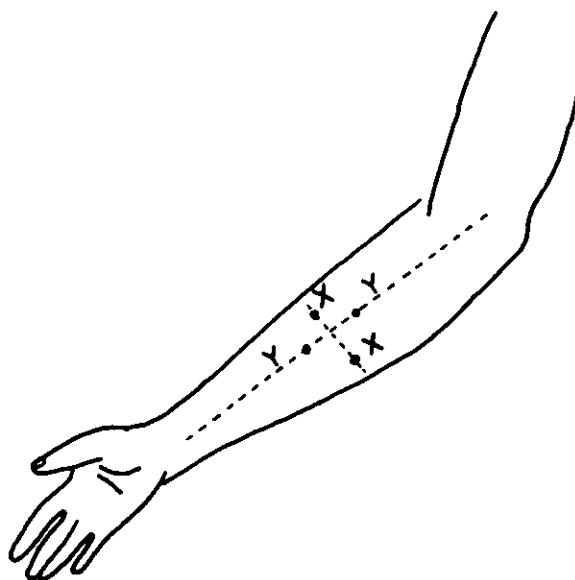


FIGURE 7. LONGITUDINAL VS. TRANSVERSE PLACEMENT

# Contrails

placement other than the purely longitudinal or the purely transverse which may give even better discrimination of a particular muscle group than we have achieved up until now. Vectorial axes of muscles in the region of the shoulders are, of course, very complicated and a field study of this region would undoubtedly be worthwhile.

## D. STANDARD LEAD PLACEMENTS USED IN THIS LABORATORY

Before proceeding to the details of leads commonly used in this laboratory, it might be useful to include a very brief discussion of leads in general. First, it should be noted that a "lead" normally consists of two electrodes. This usage of the term follows the practice of electrocardiography (EKG) and electroencephalography (EEG).

It is the electrical potential difference between these two electrodes which is led to the amplifier as the input signal. Each of the two points is usually active electrically (i.e., there is a voltage from each point to some common reference point such as ground) so that it is important to remember that it is only the voltage difference between the two points which is recorded. This situation is described as a bipolar lead, that is, recording from two points, each of which is active. If one of the points is known to be inactive with respect to the common reference point, then all of the recorded activity must originate in the other electrode and the lead could be called a monopolar lead.

In surface electromyography nearly all of the really useful leads are bipolar, both electrodes being located over the active muscle. It is perfectly possible, of course, to make a lead monopolar as far as the muscle is concerned simply by removing one of the electrodes to a remote point. But such a lead loses its usefulness by the introduction of large EKG artifacts (see Part III, Section D below) and the other advantages of close spacing described above would be lost. Note that one cannot make a bipolar lead monopolar by making one of the two active points ground. This merely unbalances the amplifier input so that it operates half grounded and half free and it would lose much of its ability to discriminate against certain

# Contrails

kinds of 60-cycle artifact with this lop-sided input connection (see Part II, Section G below). And besides, the voltage between the two points would remain unchanged anyway. Monopolar leads, however, are used to great advantage in electrocardiography (chest lead, monopolar limb leads, and augmented monopolar limb leads) and some use has been made of the same principle in electroencephalography with the introduction of the "average electrode".

Detailed descriptions of our eleven standard lead placements will be given. In each case we describe in some detail the anatomical localization of the first electrode of the pair and then follow with instructions for placing the second electrode. References will be made to the type of electrode which we use in each case and to the kind of electrode attachment. Any appropriate remarks concerning common artifacts to be found in each lead, etc., will also be included. For further details regarding electrodes and electrode attachments the reader is referred to Part II, Section A, Part II, Section B, and Part II, Section C following. For hints on the practical point of applying electrodes, please refer to Part III, Section A following, and for a general discussion of the artifact problem, see Part III, Section D.

## 1. FOREHEAD (Frontalis muscle)      See Figure 8

First electrode: Using as a guide the nasion and theinion (see Figure 9), draw a line through the center of the forehead, from nasion to hair-line. Draw a horizontal line on the right side of this central dividing line two inches in length and approximately one inch above the eyebrow. Center of the first electrode should be placed over this point.

Second electrode: Repeat above procedure on the left side of central dividing line for the second electrode.

Type: Sponge.

Attachment: Lastonet (product of Lastonet Products Ltd. of Cornwall, England - A product not generally available in the U.S.A. We obtain our supply from J. F. Hartz Company Limited, 5265 Van Horne Avenue, Montreal).



# Contrails

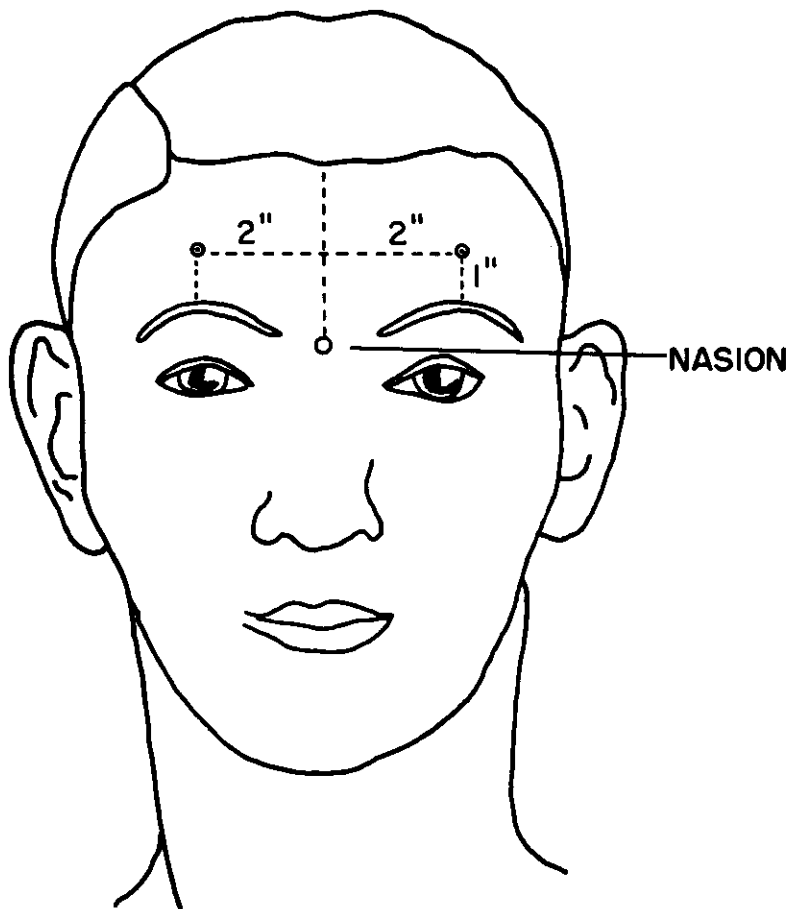


FIGURE 8. STANDARD FOREHEAD LEAD

# Contrails

Dimensions: two inches by six inches. Two strips of cotton tape are sewn on each end of the bandage which is pulled taut over the forehead and tied at the back of the head. Adhesive tape attachments are also used, and have given fair success over a long term.

Comments: In this situation, of course, one would expect to see quite a bit of eyeblink artifact, and it is true this artifact is commonly seen. But it is not as serious as might be expected because the axis of the muscle lead is horizontal whereas the axis of the eyeblink potential is vertical. Side-to-side movements of the eyes, however, do produce large slow-wave artifact in this lead. EEG artifact is also very common and quite troublesome because, being a frontal lead, the beta frequencies of the EEG are most prominent and these correspond to the low end of the muscle frequency band so that there is considerable room for confusion in interpreting this lead at times.

## 2. MASSETER See Figure 9

Posture: For lead placement on right side of face, turn head slightly to the left.

First electrode (A): Mark a point  $3/4$ " anterior to and  $1/2$ " above the angle of the jaw. This point should be one of maximum palpable contraction when teeth are clenched and relaxed. The center of the first electrode should be placed over this point.

Second electrode (B): Measure two inches directly above the center of the first electrode and mark this point for the second electrode.

Type: Sponge.

Attachment: Adhesive tape holder.

Comments: A kind of artifact which occurs with blinking of the eyes is seen in this lead, but this is not true eyeblink artifact. It is the result of tugging of the adhesive tape attachment which invariably gets close to the corner of the eye and it can usually be alleviated by cutting away that part of the adhesive which overlaps the eye muscles.

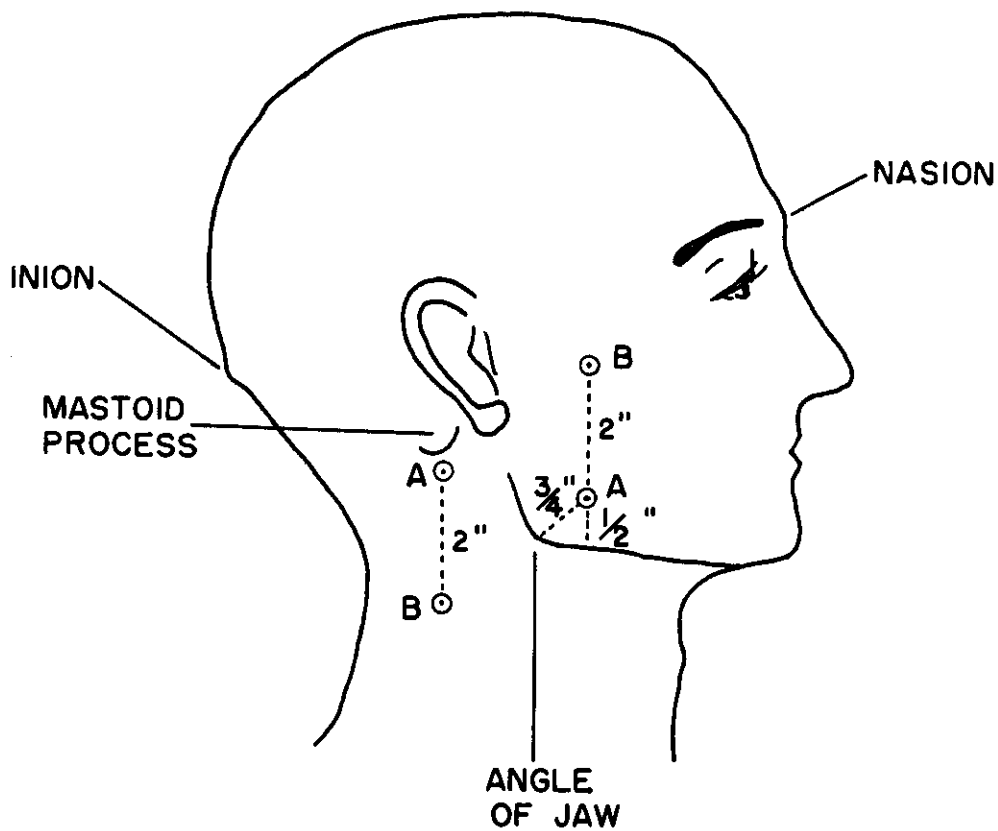


FIGURE 9. STANDARD MASSETER AND STERNOMASTOID LEADS

# Contrails

Pulsation artifact is also seen in this lead owing to the fairly prominent pulsation in some individuals just in front of the ear.

3. CHIN (Muscle potentials mainly from Depressor labii inferioris, Genioglossus, the Digastric muscles, and Platysma). See Figure 10

Posture: The head is held slightly back.

First electrode (A): On the midline of the chin, mark a point  $3/4$ " above the point of the chin and place the center of the first electrode here.

Second electrode (B): On the midline under the chin, mark a point  $3/4$ " below the point of the chin. This should be immediately behind the mandible. Place the center of the second electrode here. One should be able to palpate contraction at this point when the tongue is pressed against the lower teeth.

Type: Sponge.

Attachment: Lastonet. Dimensions: Four inches by five inches. Two strips of cotton tape are sewn on each end of the bandage which is pulled taut over both sponge electrodes and tied at the top of the head. Adhesive tape attachment was used until recently, but the lastonet appears to be superior.

4. STERNOMASTOID See Figure 9

Posture: For lead placement on the right side of the neck, turn head slightly to the left. This is intended to bring the sternomastoid into a vertical line.

First electrode (A): Place the first electrode directly below the mastoid process.

Second electrode (B): From the center of the first electrode measure two inches vertically downwards and mark the point for the second electrode.

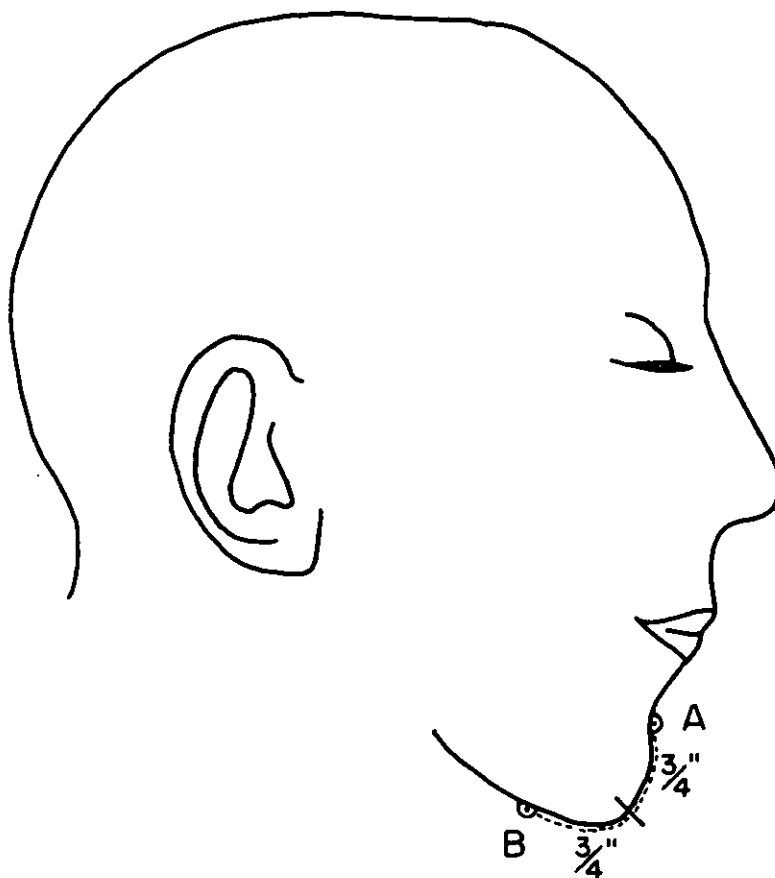


FIGURE 10. STANDARD CHIN LEAD

Type: Sponge.

Attachment: Adhesive holder.

5. NECK (Semispinalis capitis muscle and Splenius capitis muscle). See Figure 11

Posture: Bend head slightly forward.

First electrode (A): Locate and mark the second cervical spine, which may be found by counting from the prominent seventh cervical spine. The second cervical spine is usually directly below the hairline. Measure 1-1/8 inches outward from the second cervical spine (perpendicular to backbone), and mark this point for the first electrode.

Second electrode (B): Measure 1-3/4 inches from the second cervical spine vertically downwards and mark this point. From this point, measure 7/8 inches laterally and mark this point for the second electrode.

Type: Metal disc.

Attachment: Collodion.

Comments: Movement artifact of various kinds can be expected in this location unless special care is taken. Any collar or clothing around the neck must be loosened and pulled away from contact with these electrodes and the lead wires must be arched upwards and outwards so as not to touch the clothing at all. If the electrode marking, as outlined above, should place either electrode in a hollow, then a slight shift of the electrode, usually in the lateral direction, should bring it onto a more prominent area. It is difficult to secure proper electrode pressure against the skin if the electrode is in a hollow. A certain amount of EKG artifact is normal in this lead and in general it will be found to be worse on the left side than on the right. Placement of a ground electrode plate nearby on the neck is the best means of reducing this EKG artifact and is definitely recommended, unless for some other reason the ground must be located elsewhere.

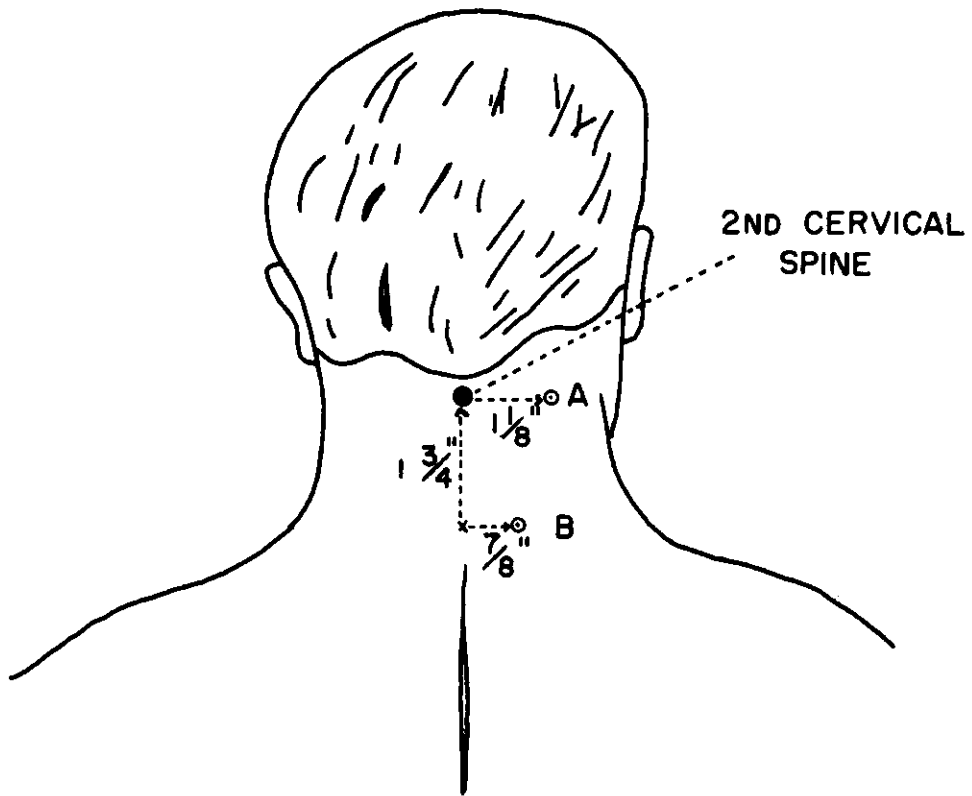


FIGURE II. STANDARD NECK LEAD

# Contrails

## 6. TRAPEZIUS See Figure 12

Posture: Subject is seated with finger tips resting on the collar bone (arms uncrossed).

First electrode (A): Draw a horizontal line running through the space between the spines of the first thoracic and the seventh cervical vertebrae. Mark a point 1-5/8 inches outward from the midline. Place the center of the first electrode here.

Second electrode (B): Draw a horizontal line running through the space between the spines of the second and third thoracic vertebrae to the posterior edge of the head of the humerus. The center of the second electrode is placed on the point which lies half-way between the backbone and the posterior edge of the head of the humerus. This placement should be one of visible strain when the head is moved down and to the opposite side and should show contraction on hunching shoulders together.

Type: Sponge.

Attachment: Adhesive tape holders.

## 7. BICEPS See Figure 13

Posture: Place arm on a table, palm up, with elbow slightly flexed and the body erect.

First electrode (A): Mark a point one half of the distance from the anterior fold of the axilla to the cubital fossa. Measure one inch proximally from this point on the line and place the center of the first electrode here.

Second electrode (B): Place the center of the second electrode two inches distally to the center of the first on the same line. This placement should be one of visible contraction with flexion of the elbow.

Type: Sponge.

Attachment: Adhesive tape holder or Lastonet sleeve.



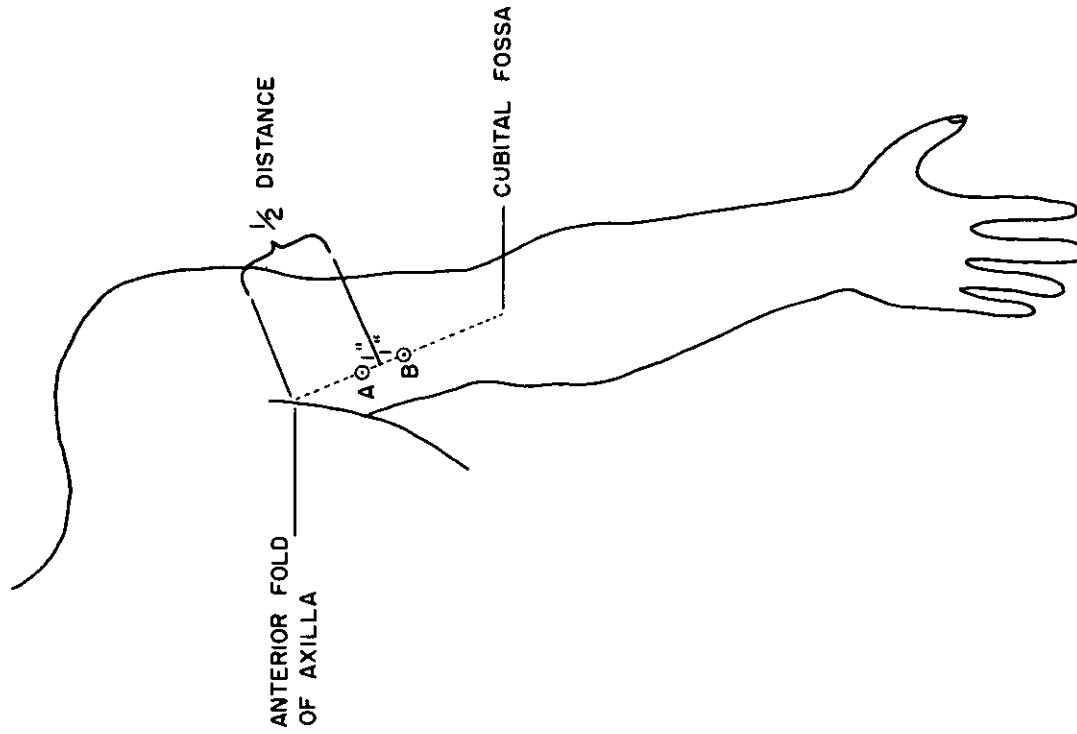


FIGURE 13. STANDARD BICEPS LEAD

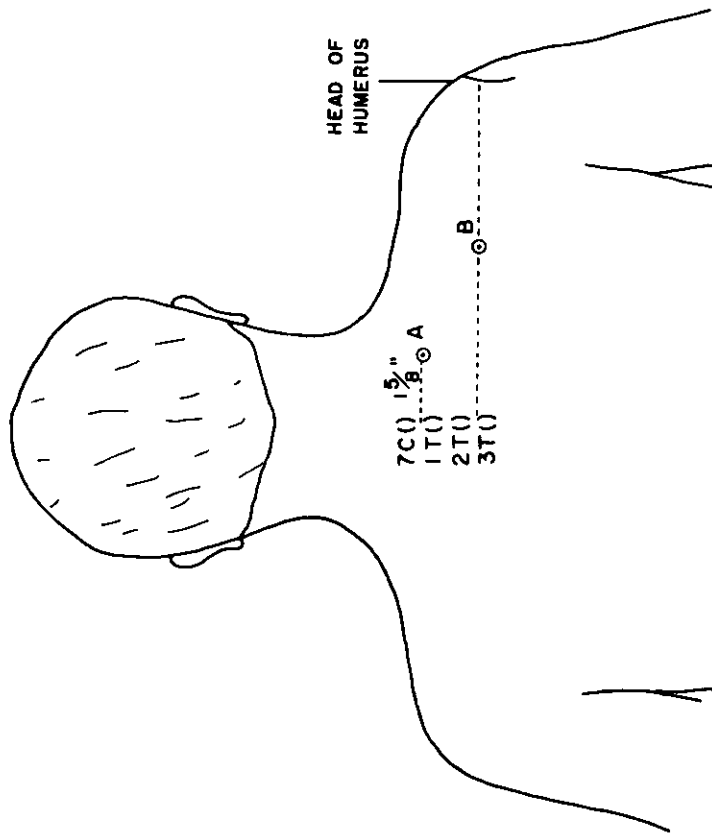


FIGURE 12. STANDARD TRAPEZIUS LEAD

8. TRICEPS See Figure 14

Posture: Place the outstretched arm on a table, palm down, with the anterior aspect of the shoulder against the table surface.

First electrode (A): Mark a point one half of the distance from the posterior fold of the axilla to the lateral epicondyle of the humerus. Measure one inch from this point proximally along the line and place the center of the first electrode here.

Second electrode (B): Place the center of the second electrode two inches distal to the center of the first on the same line. This placement should be one of visible contraction with forcible straightening of the elbow.

Type: Sponge.

Attachment: Adhesive tape holders or Lastonet sleeve.

9. FOREARM FLEXOR (Flexor carpi radialis and Flexor digitorum sublimis muscles). See Figure 15

Posture: Place the forearm on a table, palm up.

First electrode (A): With tape measure, determine the distance from the medial humeral epicondyle to the styloid process of the radius. Mark the point which is one third of the distance from the epicondyle to the styloid process. The center of the first electrode should be placed over this point.

Second electrode (B): From the center of the first electrode mark a point two inches in the distal direction along the same line. The center of the second electrode should be placed over this point. The placement determined in this way should be one of visible contraction with flexor movement of the middle finger.

Type: Sponge.

Attachment: Lastonet sleeve. The Lastonet sleeve is four inches wide and the circumference should be about 80% that at the upper forearm. Each

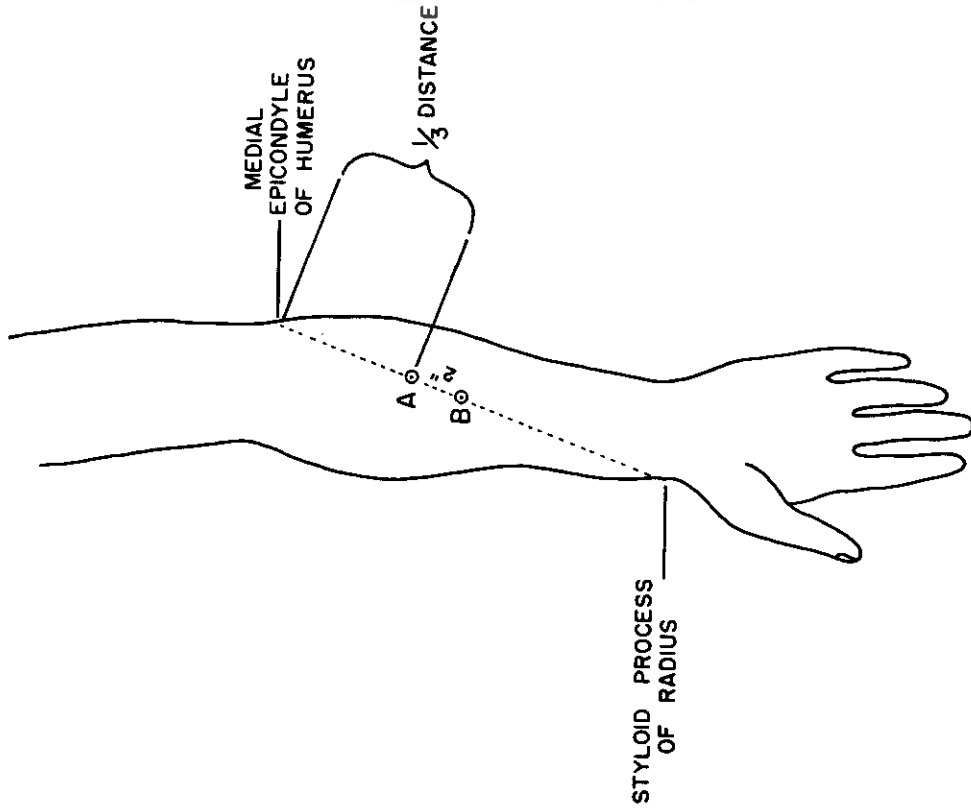


FIGURE 15. STANDARD FOREARM FLEXOR LEAD

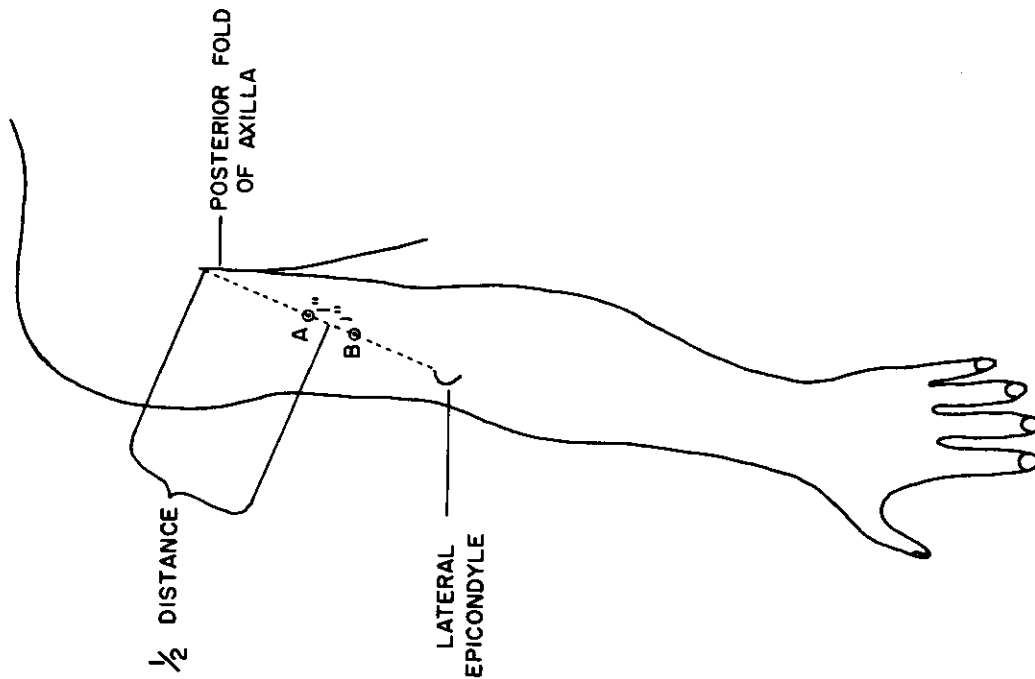


FIGURE 14. STANDARD TRICEPS LEAD

# Contrails

sponge may be inserted with tweezers into a rubber holder with a small hole in it for contact of sponge with skin. Or the sponge may be slipped under the edge of the Lastonet without any other holder. Elastic arm-bands made of rubber were used until recently, with good success.

Comments: EKG artifact is generally larger on the left arm than on the right, but it is usually not large enough to be a serious disadvantage. Placing a ground plate at the elbow or at the wrist of the same arm will usually reduce or eliminate the EKG artifact provided that the ground does not have to be placed in some other location.

10. FOREARM EXTENSOR (The superficial extensor muscles of the forearm).  
See Figure 16

Posture: Place the forearm on a table, palm down.

First electrode (A): Mark a point one third of the distance from the lateral humeral epicondyle to the styloid process of the ulna. The center of the first electrode should be placed over this point.

Second electrode (B): From the center of the first electrode mark a point two inches in the distal direction along the same line. The center of the second electrode should be placed over this point. The point determined in this way should be one of maximum visible contraction with extensor movement of the middle finger.

Type: Sponge.

Attachment: Lastonet sleeve with or without rubber holders. Note that it is quite possible to use a single Lastonet sleeve to hold down both the flexor and extensor electrodes.

11. LEG (Peroneus longus and Peroneus brevis muscles). See Figure 17

First electrode (A): Measure the distance from the head of the fibula to the lateral malleolus. Mark a point which bisects this line. Place the center of the first electrode at this point.

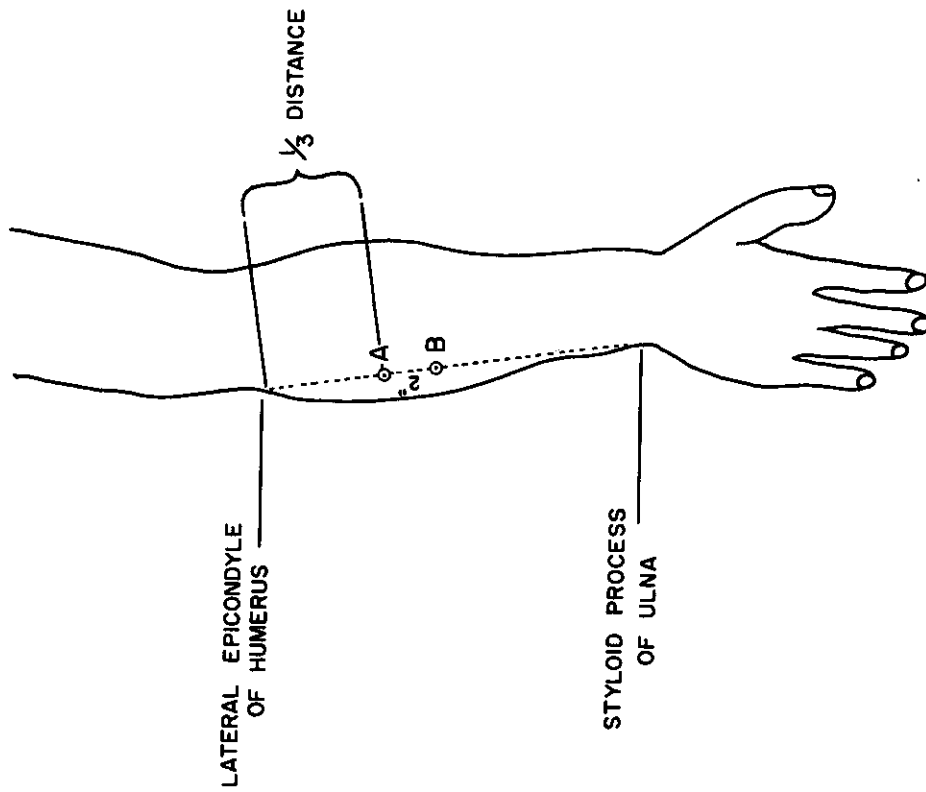


FIGURE 16. STANDARD FOREARM EXTENSOR LEAD

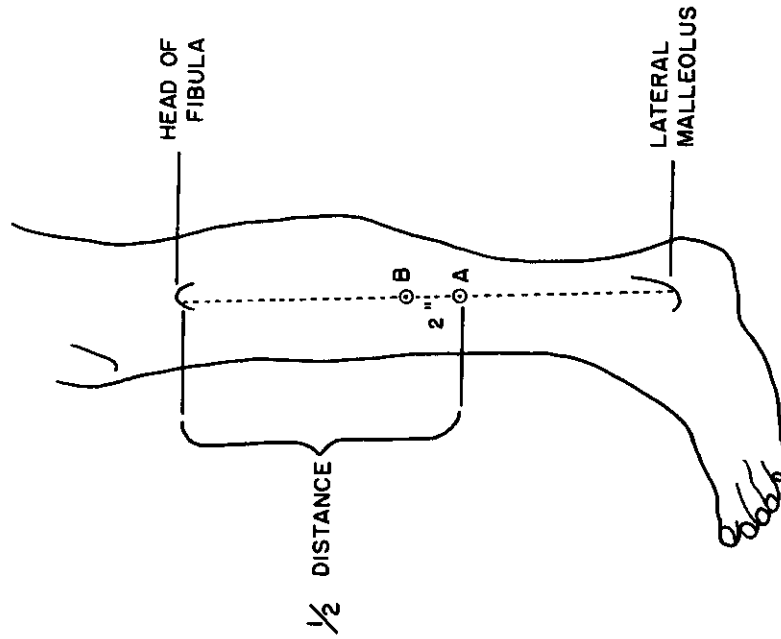


FIGURE 17. STANDARD LEG LEAD

# *Contrails*

Second electrode (B): Place the center of the second electrode on the same line, two inches proximal to the first. This placement should be one of visible contraction with eversion and/or dorsiflexion of the foot against pressure.

Type: Sponge.

Attachment: Adhesive tape holder or Lastonet sleeve.

Comment: Leg recordings have not been entirely satisfactory. This is partly due to postural shifts which occur spontaneously in the legs, even in fairly well relaxed individuals. Other unusual artifacts have been observed in leg recordings which have not yet been explained.

### INSTRUMENTATION - THE INK-WRITING ELECTROMYOGRAPH AND ITS ACCESSORIES

#### A. ELECTRODES

A satisfactory "lead" for recording muscle potentials depends upon the following four factors:

1. Choice of the best electrode site.
2. Selection of the most suitable type of electrode.
3. Use of the most efficient attachment device.
4. Careful preparation of the skin.

We have discussed in some detail the first of these factors under Part I on Methodology. The remaining three factors are really instrumentation problems and will be discussed in the order given above in this and the following two sections.

Figure 18 shows a table with comparative data on a number of popular types of electrode used in this work and giving the estimated area covered by each electrode, the range of electrical resistance to be expected for a pair of electrodes, the minimum practical distance between the centers of electrodes, and the degree of anatomical localization possible. In addition to the information given in this table, a few general remarks might be made about each type.

1. EKG or plate type. These are usually made of either Standard Silver, Stainless Steel, or German Silver.\* These are all alloys and are chosen for their relative noncorrodibility and chemical inertness as compared

---

\* Standard Silver is 92.5% silver and 7.5% copper. Stainless Steel is 90% iron, 8% chromium, and small amounts of manganese and carbon. German Silver is 60% copper, 25% zinc, and 15% nickel.

E.M.G. ELECTRODES IN COMMON USE - COMPARATIVE DATA

ELECTRODE TYPE	CONTACT AREA (CM <sup>2</sup> )	RESISTANCE PER PAIR (KILOHMS)	MINIMUM SPACING	LOCALIZATION	MEANS OF ATTACHMENT
"EKG" (PLATE)	10-25	1-2	2½"	FAIR	ELASTIC BELT
"BENTONITE" (MUD)	5-10	2-10	2"	FAIR	SELF-ADHESIVE
"SPONGE"	2-5	5-30	2"	GOOD	LASTONET, ADHESIVE TAPE ELASTIC BELT
"COLLODION"	0.5-1	3-30	1"	EXCELLENT	ADHESIVE CEMENT (COLLODION)
"NEEDLE"	0.02-0.1	1-5	½"	EXCELLENT	SUBCUTANEOUS OR INTRAMUSCULAR
"HOLLOW NEEDLE"	MICRO-SCOPIC	50-500	BOTH ELECTRODES IN LUMEN OF NEEDLE	MICRO-SCOPIC	INTRAMUSCULAR

FIGURE 18. TABLE OF ELECTRODES USED IN ELECTROMYOGRAPHY



# Contrails

with other metals. The main advantage of this type of electrode is the ease with which it is put on, and the main disadvantage is the limitation that it should be used only on the extremities because of the fact that it is best held on by means of an elastic band or belt.

These electrodes are best obtained from any maker of a standard electrocardiograph. They usually consist of a plate about three centimeters by five centimeters with smoothed or rounded edges and a rather concave construction so that it fits snugly against the surface of the arm. Most of them are provided with a screw-type binding post which is used for connecting the lead wire. Our experience has been that this binding post makes the electrode unnecessarily heavy and in most cases we have removed it by cutting the metal plate down somewhat in size and soldering the lead wire directly to the outside surface of the plate. This soldered joint, by the way, should be covered over with a plastic cement of some kind so that electrode jelly will not come in contact with the solder metal. This serves the double purpose of protecting the lead wire from excessive corrosion just at the point where it joins the metal plate and eliminates the "battery effect" which is bound to result if the solder and the electrode metal both come in contact with the electrode jelly.

2. "Bentonite" or mud type. These depend upon the natural stickiness of any clayey mud. Finely divided powdered clays such as Bentonite or Fuller's earth are electrochemically inert and when mixed with potassium chloride, calcium chloride, or sodium chloride solution, act as a conducting medium by virtue of the ionized electrolyte. The main advantages of these electrodes are: that they are fairly quickly attached, that they wash off completely with water and leave very little deposit (in the subject's hair, for example). The disadvantages are: that the mud dries fairly quickly, and its conductivity goes down slowly during recording, so that they are not practical for more than an hour or so. Also, although the adhesion is good enough for quiet subjects who are resting or moving only to a small degree, they do not stick on well enough for a test where the subject is required to perform tasks, and they do not stick well onto earlobes or the inferior surfaces of arms, chin, etc.

# Contrails

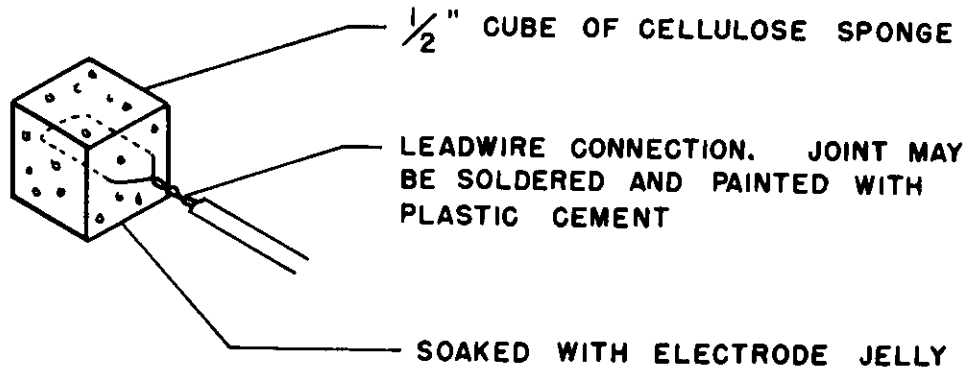
The mud for these electrodes must be made up freshly every few days because it tends to dry out and lose its adhesive qualities. A stock bottle of saturated aqueous solution of calcium chloride and a stock of the dry Bentonite powder should be kept on hand. A little experimenting soon reveals how much of each is required to produce a paste of the maximum stickiness. Little pyramids of this substance about one centimeter in each direction are built up directly on the skin surface by means of a tongue depressor. The lead wire, terminated in a silver disc or cup about 1/4 inch in diameter, is then buried in this pyramid. Again, at the soldered connection between wire and disc, plastic cement should be used to insulate the solder from the Bentonite mud.

3. "Sponge" type. In this case, the interstices of the spongy substance are filled by electrode jelly or saline. Natural sponge or cellulose sponge may be used, but sponge rubber or foam rubber is not at all suitable because the little bubbles of air inside the rubber do not communicate very well with each other and, therefore, conduction occurs more around the outside of the sponge than through the middle of it. The sponge is held on by means of adhesive tape, Lastonet, or a rubber band, and the elastic property of the sponge itself keeps the electrode in contact with the skin. The advantages are: that the electrode has a small area and gives good localization, and at the same time has fairly low electrode resistance. The disadvantages are: that if sponges are not kept in use continuously there is a tendency for the formation of mold in the sponge and of verdigris on the wire that passes through the sponge. Also, fairly large tapes must be used in certain locations to hold these sponges on, and if they are too large they tend to interfere mechanically with one another and pick up mechanical artifacts from arterial pulsations, etc.

It was once thought that even smaller electrode areas could be achieved with this type of electrode by preparing the skin in advance with a film of collodion, leaving a small area of uncovered skin in the middle. Tests soon showed that this type of skin preparation made no difference whatsoever in either electrode resistance or apparent electrode area, and on further study it was found that skin with a very thin layer of collodion had the same resistance as skin without any collodion. It should have been realized

# Contrails

(A)

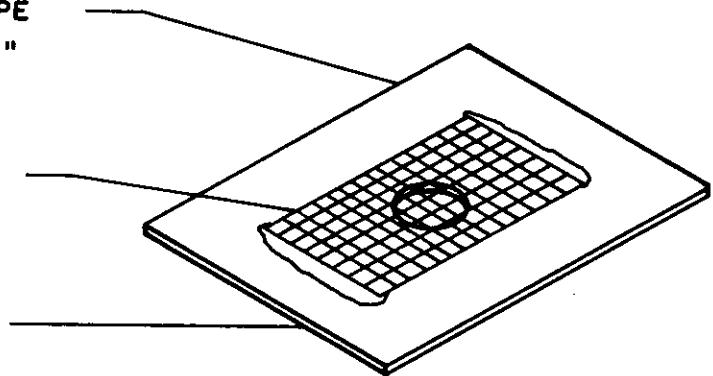


(B)

"GRINOLINE" ADHESIVE TAPE  
 $1\frac{1}{2}$ " X 2" WITH A  $\frac{5}{16}$ "  
HOLE CUT CENTRALLY

$\frac{3}{4}$ " X  $1\frac{1}{2}$ " FOLDED  
GAUZE PAD GLUED BOTH  
ENDS TO TAPE

STICKY SIDE UNDER



(C)

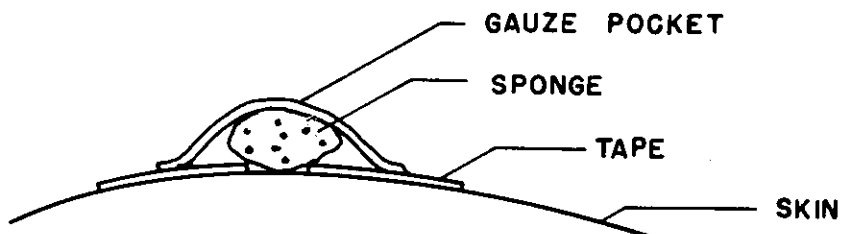


FIGURE 19. CONSTRUCTION OF "SPONGE" ELECTRODE

# Contrails

at the time that very thin films of collodion act as dialyzing membranes which allow free passage of water and electrolyte ions and, therefore, should not affect the measurement of skin resistance at all.\* However, the idea of restricting the area of the electrode by means of a non-conducting film might still be exploited by the use of some such material as rubber cement or the "liquid glove" used in dermatological practice (kerodex).

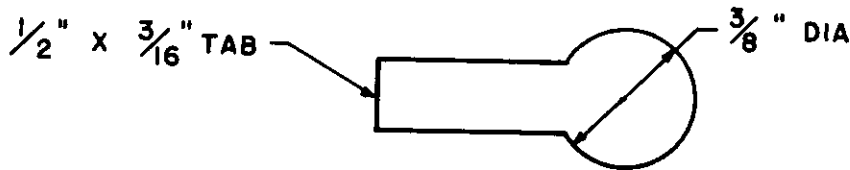
Construction of the sponge electrode is outlined in Figure 19. A 1/2-inch cube is cut from a cellulose sponge and two holes are pierced through the cube by means of a spike. The twisted strands of the lead wire are then passed through one hole, looped back through the other, and twisted. We usually solder the twisted wires for better mechanical strength and have not run into much trouble due to the exposure of the solder to the electrode jelly. However, the soldered joint should actually be covered over with plastic cement of some kind. A refinement which would reduce the amount of corrosion in the wire loop would be to use silver wire through the sponge rather than ordinary tinned copper wire, but we have not as yet found it necessary to go to this length. Figure 19 also shows a sketch of the adhesive tape attachment which has been widely used with this sponge electrode. Such electrodes can also be held on by means of adjustable rubber belts and by the newer material, Lastonet.

4. "Collodion" type. Here, a small cap-shaped electrode of silver or chlorided silver is glued to the skin by means of a film of collodion. Even pressure against the skin is maintained by means of a small jelly-soaked felt pad between the skin and the electrode. Since air is pretty well excluded from the point of contact, the electrode has no tendency to dry out by evaporation and remains moist for a long time. Even after several hours of recording, such electrodes can be revived merely by the addition of more jelly. In this case, the collodion does not act as a good dialyzing membrane simply because it is put on rather liberally and is quite thick after drying. The main advantage of this type of electrode is that it is a very small electrode and gives extremely good anatomical localization for subcutaneous electrical activity. The disadvantages are:

---

\* Note, however, that thick layers of collodion which accidentally separate electrode from skin can cause trouble in the form of high skin resistance or even an open circuit.

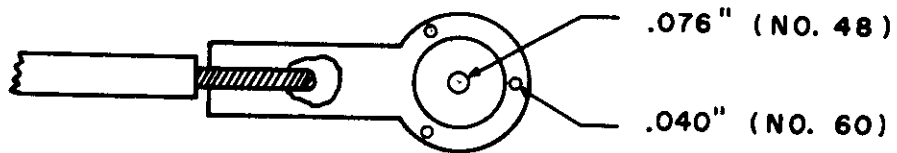
(A) PUNCHING FROM STANDARD SILVER SHEET (.020" THICK)



(B) CROSS-SECTION OF FORMED ELECTRODE



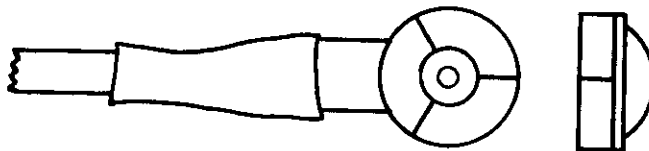
(C) DRILLING & SOLDERING (TOP VIEW)



(D) PLASTIC CEMENT INSULATION



(E) FELT WASHER & PROTECTIVE SLEEVE (BOTTOM VIEW)



(F) COLLODION ATTACHMENT (SECTION)

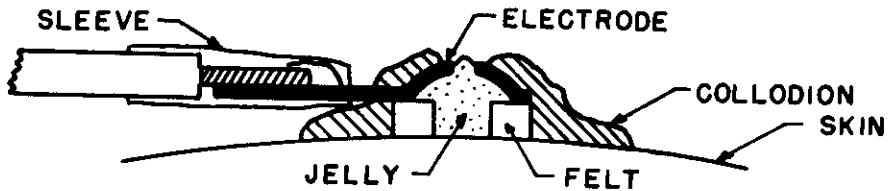


FIGURE 20. CONSTRUCTION OF "COLLODION" ELECTRODE

that it takes special equipment (air blowers, etc.) to put on these electrodes, that they leave crusts of collodion in the hair which are rather difficult to remove, and that collodion (which is dissolved in ether) has the same objectionable odor that ether itself has.

The construction of the collodion type electrode is shown in Figure 20. A special shape consisting of a disc with a tab on it is punched out of Standard Silver sheet (or better still, fine silver sheet - 99.9% pure silver) by means of a special steel die. The disc is then shaped by means of a second die such that one side of the disc becomes concave and the other side convex, and the rim remains flat. The disc is then drilled with four holes; a central hole large enough to admit a wooden applicator stick and three small holes around the periphery of the disc. The lead wire is then soldered to the tab. A ring of outside diameter equal to that of the disc is cut from a piece of thick felt and sewn to the disc, using the three small holes. The soldered joint is then covered over with plastic cement. The electrode may be chlorided or not, as desired. For EEG use the chloriding is an advantage, but there is little advantage in EMG use.

5. "Needle" type. The subcutaneous needle electrode gives information very little different from a small sized surface electrode, but has lower resistance and does not pick up galvanic skin responses (GSR) or other D-C or slow waves from the area. It consists of a single insulated unshielded needle which does not penetrate the muscle layers but lies between the muscles and the skin. The advantages of this type of needle are: good localization, and minimization of problems related to skin resistance. But these points are not usually important enough to compensate for the disadvantages of additional trauma to the subject and necessity of using sterile technique. It is worthwhile noting that in some centres the advantages of this type electrode are considered important enough to warrant their use in routine EEG recording, where up to 16 subcutaneous needles are inserted in the scalp.

The intramuscular needle electrode is a hollow, standard intramuscular needle with one or two insulated conductors passing down through the middle. Usually the hollow needle itself is used as a shield and is grounded at the

*Contrails*

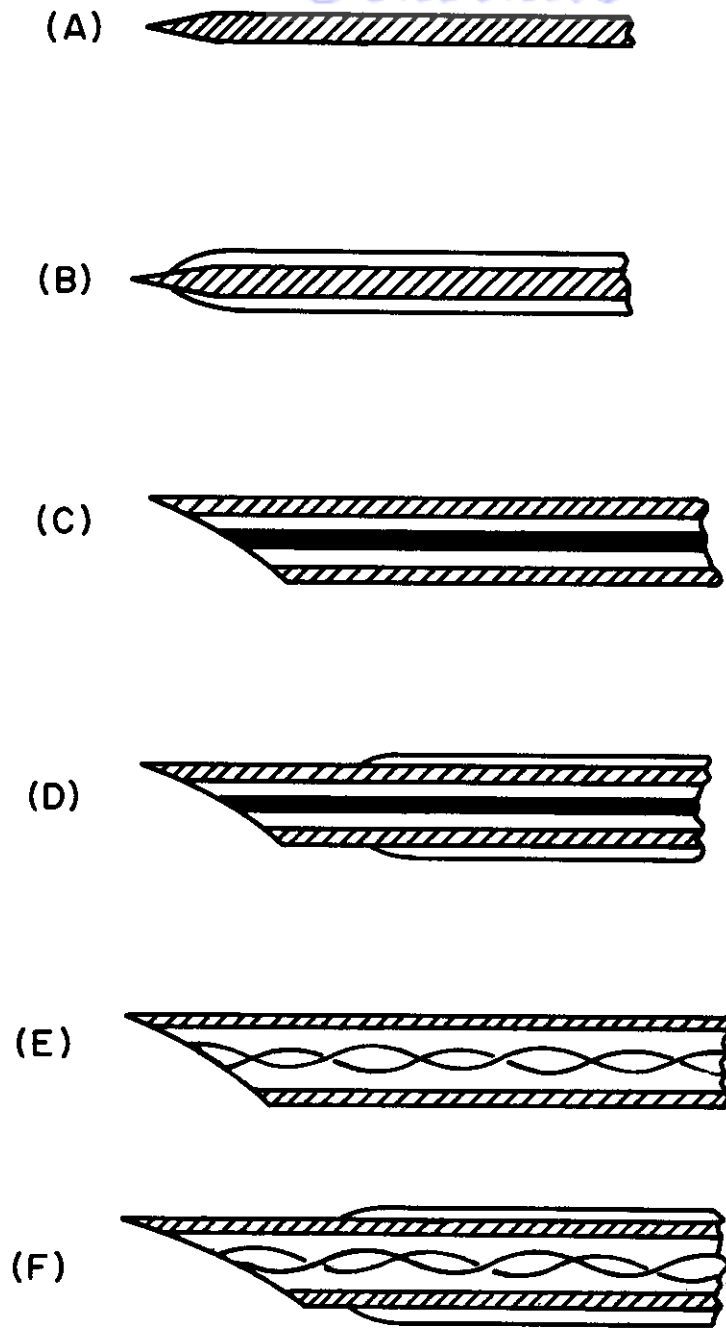


FIGURE 21. CONSTRUCTION OF "NEEDLE" ELECTRODES

# Contrails

amplifier input. The conductors inside the needle are then used to feed single-ended or push-pull amplifiers, as the case may be. The extremely minute anatomical localization achieved by the exposed ends of the conductors at the tip of the needle naturally causes the electrode to pick up an entirely different kind of information from that picked up by surface electrodes. These intramuscular electrodes get at the activity of individual muscle fibres, and since this type of activity contains frequencies well above the recording range of ink-writing recorders, such electrodes are best used with electro-myographs using the cathode-ray type of display (with photographic recording). Further disadvantages, of course, are that the electrical resistance of these electrodes is extremely high because of their very small size (necessitating amplifier inputs of special design) and that sterile technique must be used with these needles as with any other injection procedure.

Figure 21 shows some construction details of various types of needle electrode. Very much magnified views of the tips of these needle electrodes are shown, drawn in longitudinal section for the purpose of showing the internal construction. A is a simple steel sewing needle or surgical needle, unshielded and uninsulated. B is similar to A, but with the addition of a thin layer of plastic cement covering the entire needle down to within one or two millimeters of the tip, but still not shielded. C is a hollow hypodermic or intramuscular needle with an enamelled copper wire running through the middle of it and the rest of the lumen filled up with plastic cement. The tip of this needle must, of course, be reground after making it in order to preserve its sharpness and present a clean face across the tip. In this case, the outer conductor or needle acts as a shield to the inner conductor. D is similar to C except that a layer of insulating plastic has been added, leaving only the tip of the hypodermic needle uninsulated. E is similar to C except that in this case two enamelled copper wires are passed down through the middle of the needle and their ends exposed only at the tip. Again, the lumen of the needle is filled up with insulating plastic after the central wires have been positioned. F is similar to E with the addition of a layer of insulating plastic on the outside of the hypodermic needle.

Rather large potentials occur in relation to the skin in certain parts of the body, although these are for the most part composed of very low



*Continued*

frequency and slowly changing D-C potentials, and are consequently not a serious source of trouble in electromyography. However, if one wishes to eliminate these potentials completely from the circuit, one must use the needles with the plastic insulation on the outside, such as B, D, and F.

6. "Saline bridge" type. In this type, the metallic electrode, usually silver or chlorided silver, is not in contact with the organ or membrane being studied but is connected to it electrically by means of a rubber or plastic tube filled with electrolyte, such as sodium chloride or potassium chloride. The electrodes used in electrogastrography are typical examples of this type. Here, the saline inside the plastic tube can be kept from diffusing into the hydrochloric acid of the stomach by means of a small pad of cotton fixed in the end of the tube. Two purposes are served by this type of electrode: the delicate layer of chloride is protected from being rubbed off by contact with the pharynx, esophagus, or stomach, and also the liquid diffusion potential arising at a barrier between electrolytes of varying ion content and concentration is kept constant and in this way minimized as a variable. The use of long tubes full of saline is attended by the nuisance of bubble formation inside the tube, so very short tubes are recommended.

For construction details of electrogastrograph (EGG) electrodes the reader is referred to the work of W. S. Martin.

7. Other types. In physiotherapy and electroconvulsive therapy (ECT), the problem is not to reduce skin resistance and skin potentials because of their interfering effect during the recording of a physiological potential, but simply to achieve minimum skin resistance in the path of the treatment current. For example, in ECT, large convex metal discs or balls of stainless steel mesh are used under heavy physical pressure maintained by a strong rubber band around the head or by the operator's own manual pressure. In physiotherapy, the use of large metal foil electrodes with or without saline pads is customary for large flat body areas. For extremities such as hands and feet, buckets full of saline are sometimes used.

8. The story of chloriding. We used to think that the use of chlorided silver electrodes was most important in eliminating electro-

chemical artifact from practically all electrophysiological recording. Now we believe that where chloriding is not done or where metals other than silver are used, virtually no such electrochemical artifact occurs in the frequency range above 10 cycles-per-second. It would thus appear that for electromyographic recording which does not involve frequencies much lower than 20 cycles-per-second, chloriding should not be necessary. Also, in the upper half of the EEG band, chloriding may not contribute much improvement in accuracy, but in the lower half below 10 cycles-per-second it may be of some importance. Certainly, in recording constant or slowly changing potential gradients such as are met with in the Galvanic skin response (GSR) and the electrogastrogram (EGG), chloriding is of considerable importance. It should be realized that the argument in favor of using the silver-silver chloride electrode is a theoretical one, the main idea being to prevent formation of gas films at the surface of the electrodes, i.e., to prevent polarization which sets up counter-electromotive forces opposite in direction to the voltage measured. Most of the so-called silver-silver chloride electrodes that have been in use and are in use in laboratories of this kind rapidly develop a grayish, purplish, or brownish tint, and there is some reason to believe that this discoloration is not chloride at all (which is a white substance) but either silver oxide or reduced silver itself, and from a theoretical point of view these other substances are in no way good substitutes for the silver-silver chloride. However, in the practical sense, a pair of electrodes is acceptable for this kind of work if they are "in balance" which means that the electromotive force generated by the pair when placed in a saline solution is close to zero ( $\pm 3$  to 5 millivolts is usually acceptable). And since these "off-color" electrodes are frequently found to be in balance, and often remain so for days or weeks at a time, they continue to be used and give little trouble.

All that is needed for chloriding electrodes<sup>\*</sup> is a standard 1-1/2-volt dry cell, a bottle of Normal Hydrochloric Acid solution (3.7%), a 1000-ohm

---

\* Although the chloriding technique described here worked satisfactorily for us for many years, we have now changed it somewhat in order to keep the current more constant during the deposition period. The new technique will be published soon.

*Continuity*

resistor, and a silver cathode. The electrode to be chlorided, of course, must be of standard silver (or better) and all solder, tin, or copper wires connected to it must be coated with a waterproof plastic cement (Tygon Plastic Paint, for example). With the silver cathode connected to the negative terminal of the dry cell and partially inserted in the acid, the electrode is connected through the series resistance to the positive terminal of the dry cell and is completely immersed in the acid. The electro-deposition is allowed to continue for one or two hours. Actually 15 seconds gives a very serviceable chloride coating, but by continuing the current for the longer duration a heavier deposit is formed which is less susceptible to being rubbed off. On the other hand, if the chloriding is continued for many hours, I believe that the chloride coat becomes so thick as to be in danger of flaking or chipping off.

#### B. ELECTRODE ATTACHMENTS

A perfectly good electrode, placed on well prepared skin, may give a recording full of artifacts if the attachment is unsatisfactory. Just as the selection of the proper electrode type depends mainly upon the anatomical location, so does the choice of attachment device depend on anatomical factors. We have listed under our "standard lead placements" the kind of attachments we use in any given location, but the investigator can work out his own solutions if he keeps in mind the requirements, which might be listed as follows:

1. The most important consideration is to provide some mechanical means of maintaining pressure of the electrode against the skin. This pressure should remain relatively constant for the full duration of a recording.

2. The presence of the electrode attachment must not, of course, mechanically inhibit the action or response one is trying to measure. Experimental psychologists call this "backward action"; electrical engineers call it "loading".

*Continued*

3. There must be no interference with circulation in the general area.

4. There should not be sufficient irritation from the attachment to produce reflex elevation of tension in nearby muscles or any degree of subjective discomfort. Ideally, the subject should be almost unaware of the presence of the electrodes after the first few minutes.

We have used many different devices for attaching electrodes and are seeking improvements all the time. It is worth while including a paragraph on each of the methods which are currently in use in our labs.

1. Adhesive cement. The cement used must adhere to skin reasonably well and must dry rapidly. The natural choice is collodion, although there are suitable substitutes for this material. For very small-sized electrodes, the use of collodion cement is ideal because the electrode disc may be pushed against the skin to form a depression and held there while the collodion is spread over the surrounding skin and all over the electrode (except for an access hole for saline jelly). This technique insures that tight contact between skin and electrode is achieved. Where very close spacing of electrodes (less than two inches) is desirable, the use of the collodion method is almost mandatory. With all other types, the likelihood of spreading of the saline jelly is very great and "conducting bridges" between electrodes result.

2. Adhesive tape. The problem of attaching an electrode to a relatively flat surface is a common one and although it can always be solved with the use of the collodion method, one may wish to use a simpler attachment. Adhesive plaster can be used to hold on plate-type or sponge-type electrodes, and we have used this method a great deal. There are distinct disadvantages, though, and one can expect a certain amount of electrode trouble from this method.\* It is difficult to apply tape in such a way that it exerts pressure on the electrode, but by drawing the skin together somewhat before putting on the tape one can make use of the elasticity of the skin itself. Also, by using bulky electrodes (sponge type or a plate with a wad of cotton wool behind it) better pressure can be achieved. When the skin is prepared before putting on the tape (as is usually done) it may be somewhat moist or jelly

---

\* See footnote p. 31.

*Continued*

may have spread too far during massage, with the result that the tape will not stick to the moist skin. The use of a rather large piece of tape is sometimes necessary to hold an electrode on a vertical surface (side of face, for example). This may cause trouble by overlapping onto moving areas (corner of mouth, corner of eye) and may pick up mechanical artifact from such movements or from arterial pulsations (external carotid artery and its branches). Cutting away parts of the tape sometimes helps when such artifacts are seen.

A special tape construction is used to hold on sponge electrodes, the sponge coming in contact with the skin only through a small hole cut in the tape. The sponge is held in a pocket made from gauze and glued to the outside face of the tape. Figure 19 illustrates the construction.

3. Elastic belts and bands. As used in clinical electrocardiography, we have used plastic and rubber belts for attaching electrodes (both plate type and sponge type) to arms and legs. Again, in the case of the sponge type, we constructed special pockets to hold the sponges which then made contact with the skin only through small holes in the belt. The idea was to make the effective area of the electrode as small as possible in order to secure good localization. Capillary spread of the jelly under the belt negated this effort to some extent. Plastic belts were found to be less satisfactory than rubber because of their poorer elasticity. We rarely use any belts now except for the application of large ground plates.

4. Lastonet. Our latest development in electrode attachment devices promises to be the best advance yet in our struggle for artifact-free recordings.\* A recently introduced material known as "Lastonet" (which is nylon-covered rubber thread woven into an open mesh-work) is intended for use in surgical hose. We have made simple sleeves of this material of suitable sizes for slipping over the hand or foot onto the arm or leg. The sponge or plate electrodes may be slipped under the edges of these sleeves and are held firmly against the skin by the "two-way stretch"

---

\* In early experiments by Dr. R. B. Malmo different attachment devices were compared. He found this material by far the best for the purposes. See bottom of page 16 for source information.

*Conrad's*

properties of this Lastonet. A sleeve circumference made to 80% of the circumference of the limb gives about the right degree of tension with no discomfort. A hammock made of the same material is fitted over the point of the chin and secured in place by pigtailed tied at the back of the head like a surgeon's mask. This device has given much better recordings of chin potentials during speech than our former adhesive tape attachment. This new material promises to eliminate almost all rubber belt and adhesive tape attachments.\*

5. Stress relief. Connecting wires to the electrode should not in any way interfere with the ability of the attachment to hold the electrode against the skin. Mechanical distortion of the electrode or the adjacent skin can cause artifact and, therefore, any stress on the lead wire should be relieved by fixing it within about six inches of the electrode to the skin or some other relatively fixed object such as a pillow, clothing, etc.

#### C. THE PROBLEM OF SKIN RESISTANCE

It has been mentioned in an earlier section that the skin consists of a membrane of two layers: the deep, living, metabolizing layer, and the more superficial dead and dying layer of cells. Of these two layers we may almost neglect the contribution of the deep, living layer. It is conceivable that the resistance offered by this layer may be reduced (in particular by pharmacological means or by the application of local heat or massage), but since it probably accounts for only about 10% or 15% of the resistance of a given electrode, there is no urgent need to investigate this type of treatment at the present time. Rather, our attention should be concentrated on the horny layer which we believe offers most of the resistance involved.

---

\* The latest improvement in our adhesive tape attachment is the use of "Elastoplast" (elastic adhesive bandage) instead of ordinary adhesive tape. This material adheres better to the skin and its elasticity provides added pressure against the electrode. In this technique a 1-1/2-inch square of waterproof adhesive tape with a hole in it is first applied to the skin and the sponge electrode is then held on by a piece of Elastoplast somewhat larger than the first piece of tape.

Resistance of the horny layer of the skin is made up of the following electrical non-conductors: the oily secretion of the sebaceous glands which spreads out thinly all over the skin; the dry remnants of cells which have not yet been shed by the skin; the dried sweat and dirt, not to mention such things as cosmetic creams and powders. One would expect to find large individual variations in the resistance of various types of skin, both from subject to subject (for example, blond vs. brunette, racial differences in pigmentation, different degrees of tanning, etc.) and in a single subject, from one body area to another (for example, palmar or plantar skin vs. hairy skin; covered vs. uncovered skin, etc.). This variation is found in practice and, indeed, extremes of skin resistance are found which would not appear to be explicable on the basis of the above factors alone. Thus, the problem of skin resistance has not been entirely worked out and there is room for further experimentation in this field.

1. Method of attack. In our attempt to reduce skin resistance as made up by the factors listed above, we use the following approach at the present time. With minor modifications, this method is applicable to any electrode used in surface electromyography.

a. Cleansing. The main object in this is to remove the oil from the skin. At the present time we use ether and most other labs use a mixture of ether and alcohol or ether and acetone. We are currently trying to switch from ether to some other cleansing agent because the powerful smell of ether is strenuously objected to by normal subjects as well as by most patients. I believe the answer is to be found in one of the newer detergents, possibly "Phisoderm", which has the property of penetrating deeply into the skin between the cells of the horny layer. In this way, even particles of oil deeply embedded in the skin should be removable. The difficulty associated with these detergents is that they leave the skin wet and this makes it difficult to attach adhesive tape or collodion later, if these particular methods of attachment must be used in a particular case.

b. Abrasion. The purpose here is to loosen and rub off the dead cells of the horny layer and to expose a more deeply situated layer of skin, presumably less dehydrated than the exterior layer. Some operators lay down in their protocol that this rubbing should only be carried to the point



*Contrails*

where a slight erythema or blush of the skin is observed, but it is difficult to see that there is any relationship between this erythema and the problem at hand, because the cells that we are trying to rub off are transparent, or at least translucent, and the erythema occurs in the deep, living layer of the skin.

c. Massage. In this phase, a conducting jelly or saline jelly is massaged into the skin to force the conducting medium into the crevices between the cells. Here again, one cannot tell when enough has been done by the appearance of the skin and it is almost certain that different types of skin require different amounts of massaging to achieve maximum penetration but, in general, if this massaging is carried on for a period of one full minute with an adequate amount of jelly, it is unlikely that the resistance can be made much lower.

Over the period of the past four years we have noted fairly consistently that high electrode resistance seemed to recur in the late winter season. It is probably related to the fact that most of us live and work in relatively overheated and underhumidified buildings and houses, and our skins probably become progressively drier as the winter wears on. The horny layer of the skin probably becomes thicker and tougher, and there is a concomitant increase of electrical resistance of the skin. Thus, it is wise to take extra care in massaging the jelly into the skin at this season of the year.

#### D. GENERAL REMARKS ON AMPLIFIERS, RECORDING METHODS, AND INTEGRATION

1. Amplifiers. There are many different applications of the principle of vacuum-tube amplification and the standard references on this subject can do no more than outline these principles and give a few examples. The examples usually chosen are either audio-frequency amplifiers or radio-frequency amplifiers, as used in the communications industry. The EEG amplifiers which are used in surface electromyography will not be found in such reference books and merit a little discussion here. For a very readable and



*Continued*

thorough coverage of such recording equipment and techniques the reader is referred to Chapter II of the symposium "Electroencephalography" edited by Hill & Parr.

Like any other amplifier, the EEG-EMG must be designed to fit the special circumstances of input signal and output load. The range of signals which might be fed into it would be from one microvolt to ten thousand microvolts. The frequency spectrum would be from 0.5 to 80 cycles per second (and higher in the case of EMG spikes). The source impedance of the signal would be from one thousand to one hundred thousand ohms. The output load is usually a recording galvanometer of impedance from one thousand to three thousand ohms (although in certain cases lower or higher impedances have been used). The output power requirements of such a load vary from 0.5 to 5 watts for full scale deflection, and the voltage required to drive the galvanometer to full scale will be in the range from ten to fifty volts. This information determines the overall characteristics of the amplifier, but the way in which it is to be used also affects the design. Because the instrument may be used with very small signal inputs or with fairly large ones, the overall sensitivity or gain of the amplifier must be under the operator's control. Because different physiological potentials are composed of different frequency components, it is also useful to have the frequency response of the amplifier under the operator's control. Since there are usually several channels of amplification in such an instrument, it is important that all the channels may be adjusted to operate at exactly the same sensitivity or gain, and thus, equalizing controls must be provided so that amplification can be made identical in all channels.

The main difference between the amplifiers in this instrument and those used in conventional communications work would be as follows:

a. Much greater amplification is required and this brings with it special problems in the selection of the proper type of vacuum-tube for the input stage in order to achieve the lowest possible noise level and a minimum of microphonics (sensitivity to vibration).

b. Very low frequency response is required in EEG work, but in EMG work the low frequency response does not need to extend below ten or twenty cycles per second.

c. The amplifier must be able to discriminate against fairly large in-phase signals at the input (this protects the amplifier against certain kinds of 60 c.p.s. pickup). The balanced differential amplifier which was introduced commercially by Offner achieved this effect. Several modifications of this circuit are now available.

d. Great stability of frequency response and amplification must be provided so that spontaneous changes of gain will not occur in the middle of a test.

As can be seen from studying the input and output signals from this amplifier, the amplification provided must be of the order of three million. This is a tremendous amount of amplification and ordinarily requires from three to six stages of vacuum tubes to achieve it. Actually, all stages but the final one are involved in this job of bringing the signal up to the useful level of about fifty volts. All of these stages would be classified as voltage amplifiers because they use very small currents and do not deliver any appreciable amount of power. However, in order to drive the galvanometers, a considerable amount of power is necessary, so that once the voltage has been brought up to the proper level it must be fed to a final power amplifier stage which draws sufficient current at that voltage to operate the galvanometers.

This brings us to the terms "preamplifier" and "power amplifier" which are very commonly used in this field. For reasons to be given later, the preamplifier usually consists of the first or the first and second stages of voltage amplification mounted in a separate unit of some kind. The power amplifier, also sometimes called the "main amplifier", actually consists of two or three more stages of voltage amplification plus the final single stage of power amplification.

We might also comment here on the terms "D-C amplification" and "A-C amplification". These are not good terms but they are in such common use that it is important to be conversant with them. The D-C amplifier (direct-coupled or direct-current amplifier) normally amplifies D-C voltage (not D-C current!) and it does this because there are no condensers between the stages of amplification. This simply means that all voltage changes at the

*Continued*

input, including steady voltage drifts as well as rapidly changing signals, are handed on from stage to stage and appear at the output. The A-C amplifier actually amplifies only the A-C components of the input voltage, and it does this because there are condensers coupling each stage of amplification to the next one, and whatever slow voltage drifts or very low frequency components are present are "blocked" by the coupling condensers. In this way, only the more or less rapid oscillations of the signal appear at the output of the amplifier. Now, in practice, it has been found impractical to build D-C amplifiers with sufficient sensitivity to use them in the EEG and EMG field. To be sure, some EEG amplifiers consist of a D-C amplifier of the maximum practical amplification plus a preamplifier of the A-C type, but most EEG amplifiers are condenser-coupled throughout.

The discussion of the D-C vs. A-C amplifiers above must not be confused in any way with the distinction between D-C operated and A-C operated amplifiers. Everyone has heard the term "AC-DC radio". This means that the radio may be operated from either an alternating-current line or a direct-current line and, of course, the terms D-C and A-C here refer to the source of power and not to the signal at all (which in the case of the radio will be radio-frequency and audio-frequency signals). In the same way one finds that all EEG amplifiers are at least in part A-C operated and most are completely A-C operated. In those which are partly D-C operated, wet cells are used to operate the heaters of the first two stages and dry batteries are used to supply the plate current of the same tubes. In those which are A-C operated throughout, these batteries are replaced by voltage-regulated power supplies.

2. What do the amplifiers measure? This brings us to several questions which may be elementary to the initiated reader but it might be of interest to include some discussion of them here. The amplifiers, of course, are just tools for measuring the biological electrical activity and I have frequently been asked the question: Just what is it we are measuring here, is it voltage or is it current? The answer is that we are trying to measure voltage. In order to do this with conventional vacuum-tube circuitry, it is necessary to allow some current to flow in the lead wires, but we keep this to an

*Continued*

absolute minimum by using very high input impedances to our amplifiers. The source of the biological potential itself has a relatively high internal resistance, which means that if very much current is allowed to flow, it loads the source electrically so heavily that the potential is actually decreased. This "loading loss" may be kept to about 1% by making the input resistance to the amplifier one hundred times as great as the internal resistance of the electrodes. The loss would be about 10% if the input resistance were only ten times as great as the electrode resistance, and the loss would be 50% if the input resistance of the amplifier were equal to the electrode resistance. Since the average lead has an electrode resistance between ten and twenty thousand ohms, and since the amplifiers have input resistance between one and ten megohms, it can be seen that this loss is kept in practice in the insignificant range. An exception to this is the needle electrode which may have a resistance from one hundred thousand ohms to one megohm, and specially designed amplifier inputs should be used with these. In general, it should be said that the loading effect should always be kept to an absolute minimum in measuring any biological potential. After all, we are trying to measure an electrical attribute of biological activity; we are not trying to use the biological system as a battery to extract as much energy as possible from it. Perhaps the approach would be slanted differently if we were dealing with the electric eel!

Another question which follows more or less directly and which I have been asked occasionally is this: What is the difference between action currents, action potentials, and action voltages? The latter two terms, of course, are practically identical because the potential referred to here is the electrical potential, and to all intents and purposes this is the same thing as an electrical voltage, so that the distinction to be made is actually between action currents and action voltages. Now, any electrical current, of course, refers to a movement or flowing of electrons or ions and, therefore, the true action current accompanying a biological event will simply be the flowing of ions in and around the source of the electrical activity through the tissue fluids or electrolytes. Now this will usually be a very complicated three-dimensional pattern of ion flow and will, as a consequence, be an extremely difficult

thing to measure without interfering seriously with the current itself. Also, measuring currents from skin electrodes has very little meaning because it is demanding that a system with very little energy to give should supply energy to an external circuit. Even the measurement of action currents from the cut end of a nerve preparation is a very artificial situation because the loading effect of the current-measuring device is far from negligible and probably distorts the current waveform considerably. For these reasons, it is the action potential or the action voltage which we always try to measure and this applies equally well to nerve muscle preparations as to the surface of the skin. As long as the input impedance or the input resistance of the electrical measuring device is high compared with the internal impedance or resistance of the biological system, one may be assured that a fairly undistorted measurement of the action potential will be achieved.

3. Choice of a recording method. Why did we finally settle on the ink-writing galvanometer as the most practical solution to our recording problem? The use of this medium dates back to the earliest experiments done in this laboratory, at which time the recording setup of the EEG department of the hospital was used by us on a part-time basis. However, it is no mere accident of circumstance that has resulted in our using more and more ink-writing galvanometers, because when the time came for us to write specifications for a research electromyograph, we had the whole field of graphic recorders to choose from. Just to run over this argument very briefly, we will first list the available methods of recording and then list the most important factors affecting the choice of method.

Recording Oscillographs:

- a. Photographic methods
  - (1) String galvanometer
  - (2) d'Arsonval mirror galvanometer
  - (3) CRO with recording camera
- b. Galvanometers with ink-writing styli
- c. Galvanometers with non-inking styli

- Continued*
- (1) Thermo sensitive plastic-coated paper and special heated stylus.
  - (2) Electrolyte-coated paper and special stylus voltage.
  - (3) Plastic-coated paper and high voltage sparking stylus

Factors Affecting Choice of Graphic Recorder:

a. Design features

- (1) Electrical characteristics (frequency response, sensitivity, damping, tolerance to overvoltage)
- (2) Mechanical characteristics and dimensions, and adaptability to multi-channel operation
- (3) Ease of replacement and repair

b. Costs

- (1) Initial outlay
- (2) Cost of recording material
- (3) Amount of recording material to be used

The only recorders in the above list whose electrical characteristics are almost ideally suited to the recording of muscle potential waves are the photographic types. Both the string galvanometer and the mirror galvanometer have very low inertia and therefore respond to fairly high frequencies. Also, of course, the cathode-ray oscilloscope has practically no inertia and has better response than the amplifier itself. However, these methods all suffer from the disadvantages that the record is made in the form of an undeveloped photographic film which must be developed before viewing the result. Not only are the photographic methods very expensive when lengthy records are taken, but they are completely impractical for this type of experiment because the direct viewing of the record as it progresses is of utmost importance so that the operator may make minute-to-minute adjustments in his equipment. Even a delay of ten seconds before the developed pattern can be viewed (as in some recent recorders) makes gain adjustments and monitoring rather difficult.

*Continued*

The galvanometers with styli other than the inkwriting type may be built with electrical characteristics just as good as those with inkwriters, and although these galvanometers in general are not ideally suited to the EMG recording because they do not respond to frequencies much above one hundred cycles per second, still they can be made to record very faithfully the frequencies below this figure and, as we have noted in an earlier section, this produces a very presentable electromyogram. All the methods of recording without ink have the disadvantage in common that they require a specially prepared recording paper and, of course, this is considerably more expensive than ordinary paper. The cost of the recording material is of considerable importance in this field because psychological studies usually require that many experiments be performed on different individuals or that repeated experiments be performed on the same individual. And, with continuous recording throughout each experiment, it can be seen that the amount of paper used is very large. In this laboratory, a fairly simple series of tests might use three hundred feet of recording paper on each of fifty subjects. A rough calculation shows that this represents five cubic feet of paper, which, while not inexpensive, is much less costly than photographic materials.

This pretty well eliminates all graphic recorders except the straight inkwriters and the choice then has to be made on the basis of their electrical and mechanical characteristics. Some more will be said in a later section on the subject of the electrical characteristics; for now, suffice it to say that practically all inkwriters will record some electromyographic potentials, but only a few of them will respond to high enough frequencies to record a really useful EMG.

4. Integration. Accurate quantification of an EMG record brings one face to face with the problem of measuring the individual amplitudes of many muscle potential spikes and then adding these up to represent a kind of total electrical activity for a given period of time. When this has to be done for a large number of sample periods in a given test, it becomes a very time-consuming period even to obtain results from a single channel of EMG record. If, as is often the case, it is desirable to record simultaneously four, six,



or eight channels of EMG from different muscle groups, the manual measurement of the data becomes completely impractical.

An accepted method for totalizing muscle potentials is the use of an electronic integrating circuit of one form or another. The basic integrating circuits were represented in convenient form by Clarke in 1944. They depend upon the fact that the voltage across a condenser is the integral of the current flowing into it, and the current in an inductor is the integral of the voltage applied across it. Of the two common circuits, the condenser integrator is the better adapted to the bio-electric frequency spectrum owing to the great difficulty of constructing lossless inductors with large reactance at low frequencies. Several investigators in this field have described integrators based on the charging of condensers (Freeman & Hoffman in 1940, Jacobson in 1940, Stevens in 1942, and R. C. Davis in 1948). However, none of the circuits described up until that time were considered to fit the exact needs of the instrumentation program here and the development of new integrators was undertaken. The early models were intended for use with rather lengthy time intervals (1, 3, 10, and 30 seconds, respectively). The integrations were carried out automatically but the operator had to read the result from a meter and no permanent recording was produced by the instrument. Later models were built for completely automatic operation, and integrations every tenth of a second or every half second, as desired, are recorded automatically by a series of galvanometers much like the recorder of an EMG. All of these integrators are of the condenser type. The development of these instruments and their characteristics were described by the writer in 1949, but the latest circuits now in use have not yet been published and manuscripts are in preparation (see Davis, J. F., Operators Manual - AMI Integrator System. Montreal, 1956, Allan Memorial Institute of Psychiatry, McGill University, 34 pages, mimeo.).

The hand method of integrating EMG potentials is really a totalization of the peak amplitudes of the muscle spikes. Electronic integrators, on the other hand, actually measure the mean amplitude of the spikes over a given time and do not operate on the peak amplitudes of the waves at all (it would be considerably more difficult to make an electronic instrument which would totalize the actual peak amplitudes). Mathematically speaking,



integration means measuring the "area under the curve", i.e., the area between the curve being studied and some baseline as a reference. In the case of the EMG wave, the baseline is the straight line drawn through the middle of the wave, and this line divides the function in such a way that the total area under the positive waves is equal to the total area under the negative waves, even though the shape of the positive and negative waves may be quite different. Of course, the electronic measurement of the average amplitude of the spikes is not at all the same measure as the peak amplitude which is measured by hand, but we would expect the two measures to be highly correlated and in actual practice they are.

#### E. BLOCK DIAGRAM (FLOW SHEET) OF INSTRUMENTATION

The basic instruments which are permanently wired into our Test Suite No. 1 are shown in block form in Figure 22. The setup in Test Suite No. 2 is practically identical, with the exception that the EMG is made by a different manufacturer (Edin Special EMG in Suite No. 1, Offner Type D EEG\* in Suite No. 2), and there are differences in the functioning of this part of the equipment. In the interests of simplicity, most of the accessory equipment which we use has been eliminated from the diagram. The only blocks included in the diagram are those which are absolutely necessary for the proper recording of electromyograms and integrated EMG records, together with accessories for calibration and the recording of time signals necessary for synchronizing the two records.

The block diagram is shown divided into four main compartments (dotted outlines). These correspond to: (1) electrical apparatus in the room with the subject himself, (2) the component parts of the main electromyograph console, (3) the units located at the integrator station, and (4) the timer and external calibrator units. The little arrows connecting one block with another show the direction of flow of information from one unit to another, and the figure in parenthesis beside each of these arrows gives the number of channels of information which are available for simultaneous use.

---

\* Now superseded by Grass EEG Model IV.

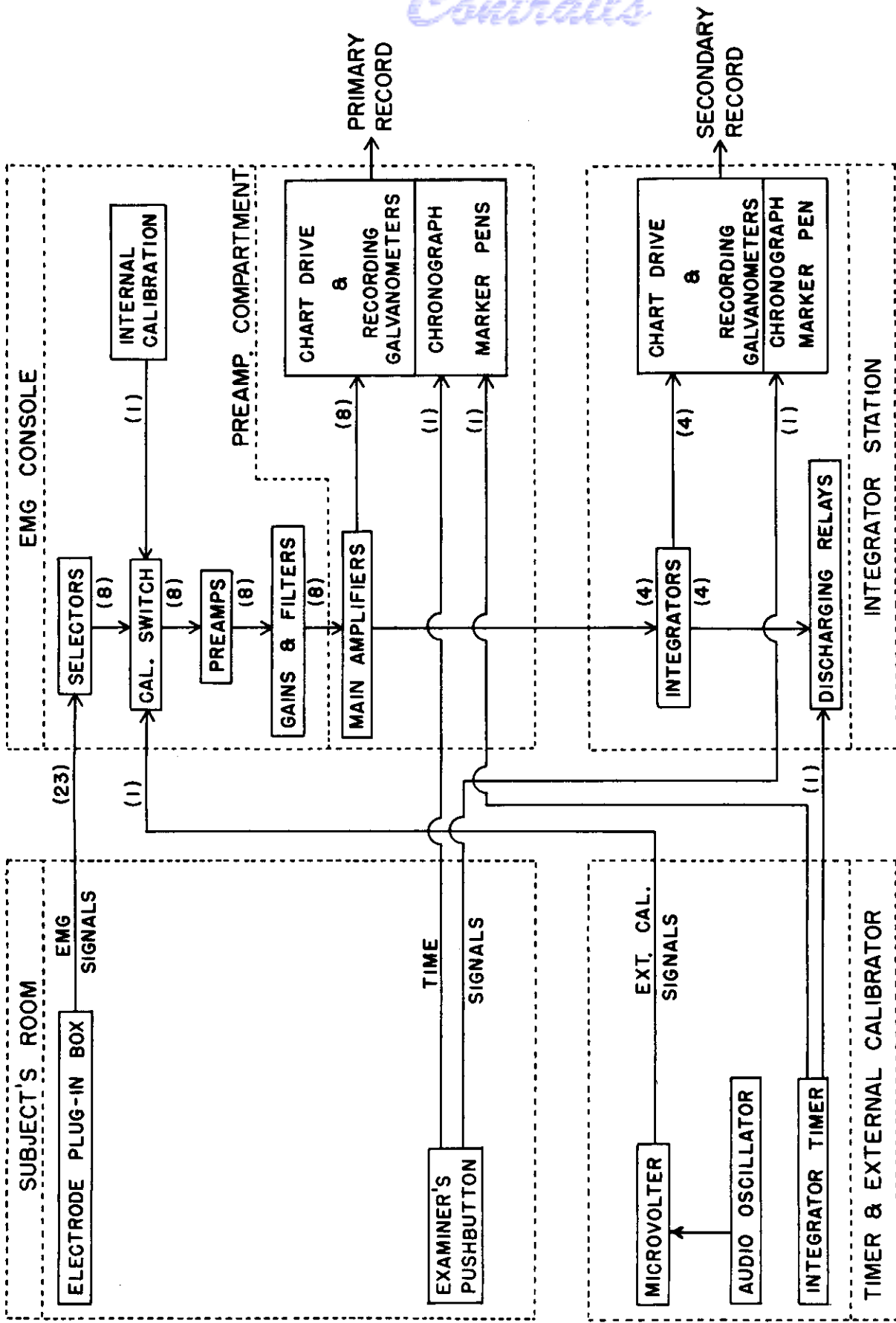


FIGURE 22. BLOCK DIAGRAM OF INSTRUMENTATION (TEST SUITE NO. 1)

*Continued*

The output from the system takes the form of a Primary Record which is the original EMG recorded by the EMG console, and the Secondary Record which represents the output of the integrators (the integrated form of four out of eight available channels of EMG primary recordings). Most of the important data analysis of a given experiment is carried out with the secondary record because it presents the data in a much more convenient form. However, the taking of a primary record of good quality is far from being superfluous even though very little actual analysis of this record is performed. Probably the most important use of the primary record is for the careful monitoring of those channels which are also presented in the secondary record. In this way, artifacts which cannot be recognized in the integrated output are spotted and measurements are not made on the secondary record at these times; and also, changes which are seen in the integrated record and are difficult to interpret can be checked up on the primary record for a more careful examination. In addition to this function, much information can be seen on the primary record which is very useful. Simple scoring procedures can be performed on the original EMG to give a rapid but rough assessment of the changes therein.

Although the instruments shown in this block diagram give the appearance of a rather complicated setup, they really represent only the skeleton upon which to build a very flexible system of electrophysiological recording. The instruments shown here would be suitable only for recording from a subject during an interview or some simple test procedure. All timing cues would have to be put in by the examiner's timing switch as no provision for simultaneous voice recording is shown.

A fairly complete list of accessories which have been used in conjunction with the above basic instrumentation in this laboratory during the past few years will be included here, but no details will be given.

Accessories for Use with EMG:

- a. For feeding special signals into the EMG preamps
  - (1) Throat microphones
  - (2) Crystal tremor pickups
- b. For voice recording and intercommunication

- (1) Directional and non-directional microphones
  - (2) Audio amplifiers
  - (3) Disc or tape recorders
- c. For stimulus-response studies
- (1) Headphones and loudspeakers
  - (2) Auditory stimulus amplifier
  - (3) White noise generator
  - (4) Special stimulus timers and relays
  - (5) Synchronizing timers
  - (6) Hardy-Wolff thermal stimulator
  - (7) Tone-Shock conditioning stimulator
- d. For measuring D-C signals
- (1) Thermistor and Wheatstone bridge for skin temperature
  - (2) D-C amplifiers for GSR, skin temperature, etc.
- e. Other accessories
- (1) Pneumographs
  - (2) Continuous blood pressure recorder
  - (3) Apparatus required in the performance of special tasks
  - (4) Electrical instruments of various types: ohmmeters for electrode resistance, vacuum-tube voltmeters for monitoring auditory stimuli, CRO for synchronization problems

We now proceed to a block-by-block description of the different parts of the equipment, giving qualitative explanations of the functions of each part and the various controls that are available to the operator, but not attempting to go into any degree of electronic detail. For each block the main description applies to the set-up in Test Suite No. 1 and an extra paragraph is included where necessary to cover the equivalent devices in Test

*Continued*

Suite No. 2. These are for the most part differences between the Edin and Offner electroencephalographs.

1. The electrode plug-in box. This unit is located on or near the subject's bed or chair and provides a means of connecting the various surface electrodes on the subject or subjects to the electromyograph. Certain types of accessory pickup devices can also be connected to the EMG through this box (for example, crystal finger tremor pickups, throat microphones, shock-current pickups, photo-electric pickups, etc.). In all, there are twenty-three connections available, i.e., twenty-two channels of information and one ground. This ground is a very important one because all large metal objects<sup>\*</sup> such as beds, metal stands, chairs, etc. should be grounded through this box in preference to other grounds, such as radiators. It should be mentioned that the ground at the input of the most sensitive recording device (which, of course, is the EMG) should be the reference ground for the whole system. Although there are twenty-two connections for electrodes and other pickups, no more than sixteen of these are ever in use at the same time. This is because they are always selected in pairs and fed to the eight channels of the recorder. The electrode plug-in box is connected by means of a long shielded cable to the preamplifier part of the main EMG console.

2. The selector switches. On each of the eight panels in the pre-amplifier compartment of the console are two selector switches. To each of these switches come all twenty-three of the connections in the electrode plug-in box. The system is arranged for balanced or push-pull recording, so that in each channel the two switches are connected to the two vacuum-tubes, forming the first stage of the preamplifier, and any one of the twenty-three possible sources of electrical activity may be selected by each switch. In practice, of course, no operating amplifier should be connected to a position where there is no electrode plugged in. This would cause an "open circuit" at the amplifier input and would probably send very large 60 c.p.s. signals

---

\* But only those metal objects likely to come in contact with the subject. Other metal objects should be grounded through the usual means (pipes or conduits).

*Controls*

through the amplifier. Also, it is not wise to set one of the switches to the "ground" or "G" position - at high gains this, too, produces 60 c.p.s. artifact for reasons given in the Preamplifier section below.

Thus, by means of the two selector switches associated with each channel, we pick out pairs of electrodes on the subject which give us the information we desire to record. If it is the type of information which has polarity (i.e., an electrical sense) such as in the EKG, one can make the instrument record the information right side up or upside down according to which way the selector switches are set. On the Offner Type D EEG, the selector switches are on a panel completely separated from the preamplifier unit.

3. The calibrator switch. The EMG signals picked up from the electrodes by the selector switches do not go direct to the preamplifier input but get there via the calibrator switch (sometimes called the function switch). On the Edin EMG, the calibrator switch has four positions marked "External Cal", "Internal Cal", "Subject", and "Balance". The two positions of this switch which are most commonly used by the operator are: "External Cal" in which a sine-wave signal of known frequency and amplitude from an outside source is fed through to the preamplifiers; and "Subject" in which the EMG signals are fed through from the selector switches to the preamplifier. The other two positions feed D-C signals for the purpose of D-C calibration and checking of the "rejection ratio". More details about calibration will be given in a special section below.

In the case of the Offner Type D EEG, the various functions of the calibrator switch are incorporated into a larger switch which is also used for selecting the amplitude of the desired calibration voltage. In this case, the change from internal to external calibrators is performed by a toggle switch located to the left of the main calibrator switch which was formerly used for the purpose of measuring electrode resistance.

4. The preamplifiers. In the Edin EMG, there is one individual preamplifier chassis for each channel. These chassis contain only four triode vacuum-tubes (two stages of amplification), some coupling condensers and the necessary resistors to complete the circuits. There are no power supplies included in the individual chassis. All eight preamplifiers derive

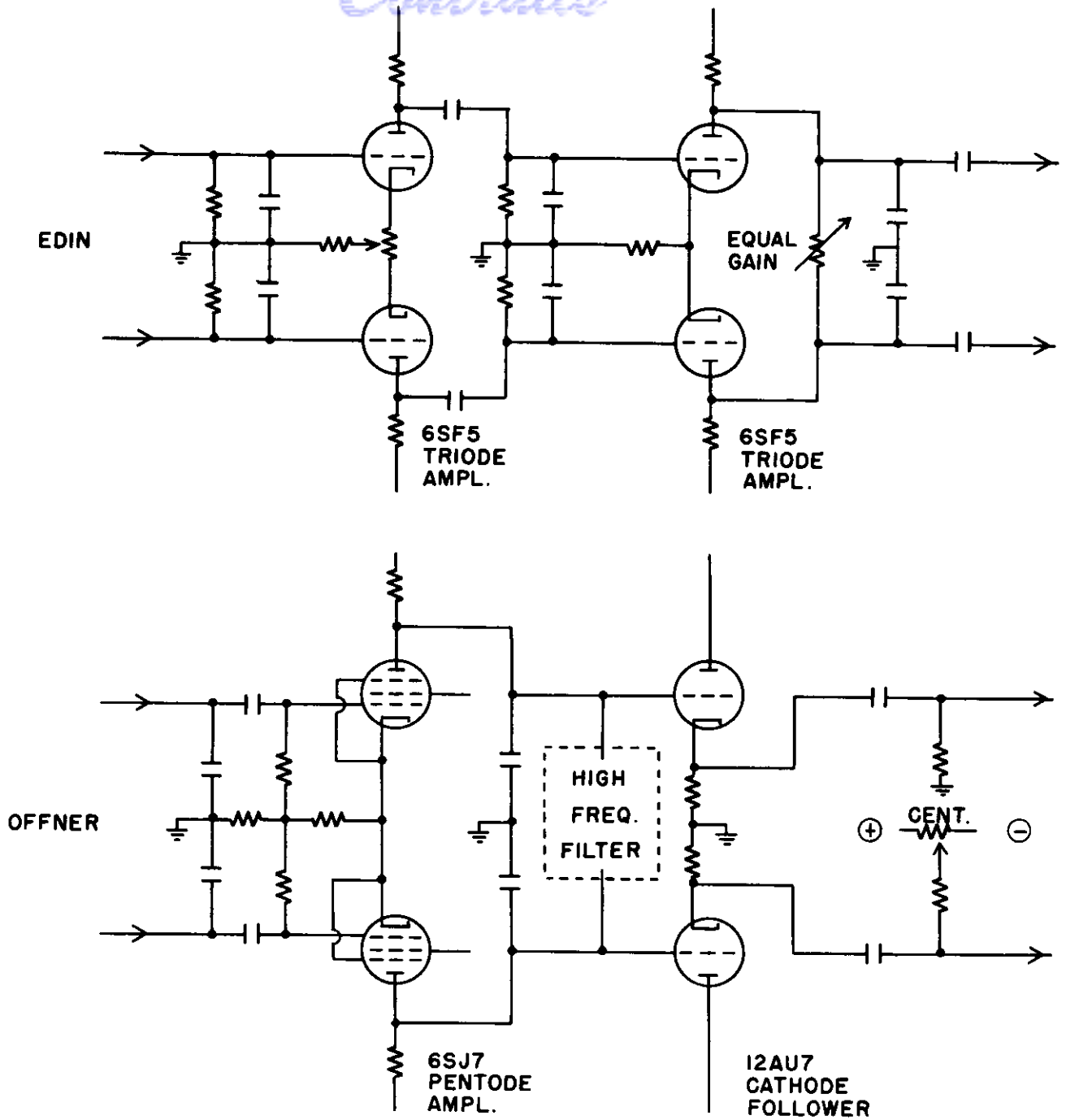


FIGURE 23. COMPARISON OF PREAMPLIFIER CIRCUITS

*Continued*

their high tension power from a single power supply called the B supply. The first four preamplifiers and the second four preamplifiers obtain their low tension power from two separate six-volt power supplies called the A supplies. All of these separate power supplies are A-C operated and voltage-regulated, and there are no batteries involved at all. Note that no alternating-currents are brought into the preamplifier chasses or even into the preamplifier compartment, as their presence in the vicinity of the extremely minute signal voltages would in all probability lead to increased 60 c.p.s. artifact (see Figure 23).

These preamplifiers must be treated with a good deal of respect because the tubes used in them are carefully selected for low noise and low microphonics, and the circuits are carefully adjusted to minimize the stray 60 c.p.s. interference getting into the chassis itself. All eight of the chasses are fixed inside a special compartment which is rubber shock mounted from the rest of the console to prevent as much as possible any vibration of the preamplifier tubes. Thus, the preamplifiers are both electrically and mechanically isolated from the rest of the circuit and from outside sources of electrical noise and mechanical vibration. However, if the whole amplifier unit is vibrated or knocked by the operator or a bystander, one can expect some or all of the channels to show artifacts which we call microphonics. If one or more channels contain tubes which have not been very carefully selected against this kind of defect, those particular channels will show greater artifacts than the others.

Each preamplifier chassis has a single adjustment available to the operator, i.e., the equalizing gain control. This control allows one to adjust the amplification of each preamplifier so that they are all equal and all conform to some fixed standard of sensitivity. The preamplifiers have a voltage gain of from 100 to 200, depending upon this adjustment.

We have seen that each pair of electrodes is connected via the selector switches and calibrator switch to the input tubes of a preamplifier. This means that two active sources of electrical activity are always fed to each preamplifier and the preamplifier actually "sees" the electrical difference between the two sources of activity (bipolar recording). The inputs of each preamplifier are also connected to the ground through large resistors, and if the subject is grounded by an independent electrode (which is common



practice), the system has the additional advantage of being able to discriminate against certain interfering signals, such as 60-cycle pickup from lamps, etc., which may be superimposed on the desired electrical activity. This function of the input circuit is known as "in-phase signal rejection", and a minimum rejection ratio of one thousand to one should be provided by a good preamplifier. Five thousand or ten thousand to one would be preferable. The meaning of the term rejection ratio is the ratio between an undesired in-phase signal and a desired signal which give equal recorded outputs. As an example, where the rejection ratio is one thousand to one, an in-phase 60 c.p.s. signal of ten thousand microvolts amplitude should give the same recorded output as a calibration or EMG signal of ten microvolts. Methods of checking this rejection ratio for any given EMG will be discussed in Part III.

Note that, if for some reason one of the preamplifier inputs is grounded instead of being connected to a proper electrode, the rejection ratio will be reduced almost to unity, with complete loss of the amplifier's ability to discriminate against in-phase interference signals.

In the Offner instrument, all eight preamplifiers are built into a single unit. Here again no power supplies are included and no A-C currents are brought into the unit. Other differences in the circuit are: one stage of voltage amplification (pentode) instead of two stages (triode) is used; the gain is around 500 instead of 200; there is no equalizing gain control; a cathode-follower output is used to give low-impedance coupling to the main amplifier (which is a special type of D-C amplifier); a centering control is provided for each channel.

5. Gain controls and filter controls. In the Edin instrument, the gain and filter controls are permanently wired into a preamplifier compartment but are quite separate electrically from the preamplifier units which are also located in this compartment (as shown in the block diagram of Figure 22). The main gain controls are also known as sensitivity controls and the number markings around the dial represent the number of microvolts per inch of galvanometer deflection which should be obtainable for each position of the switch. The dial marking actually represents the number of microvolts per

*Controls*

five millimeters of deflection when used in ordinary clinical EEG work, but since this instrument was built specially for our laboratory and has five times the gain of a standard EEG, the numbers now represent the number of microvolts per inch (i.e., 25 millimeters) of deflection. Note that the actual function of this control in the circuit is not to change the gain of the amplifier at all but to attenuate the signal as it passes from the pre-amplifier to the main amplifier of the unit. Thus, when the switch is set for maximum gain, actually there is no attenuation at all, but full signal is passed from the preamplifier to the main amplifier. For all other settings of reduced gain or sensitivity, there is some degree of attenuation of the signal.

This sensitivity control simply consists of two switches (one for each half of the balanced push-pull circuit) ganged together mechanically and wired with very accurate, stable, fixed, non-inductive resistors. Thus, it should be flat in frequency response from one end to the other of the range of frequencies which we deal with, and should not modify or distort the signal at all as it passes through the control. It merely makes the voltage smaller. One of the advantages of putting the sensitivity control in this position in the circuit is that all the noise and other artifactual signals at the output of the preamplifier are attenuated in the same degree as the true signal so that the signal-to-noise ratio of the preamplifier may be preserved throughout the rest of the circuit. Another reason is that fairly large signals (up to 50 millivolts pk-pk) may be fed into the pre-amplifier without saturating it but, as they are amplified and passed on to the main amplifier, they would overdrive it if no attenuation were introduced at this point.

Although the electrical operation of the gain control switches is identical in the Edin and Offner instruments, there are differences in their location in the circuit and in the ratio of the fixed resistances used for stepping down the gain. In the Offner EEG (Type D), the main gain control is wired in permanently at the input to the main amplifier and the gain change from one step to another is about 5 db (i.e., each step has a gain of about 56% of the next higher step). This means that it takes four steps downwards to reduce the gain to exactly one-tenth. In the Edin instrument,

it takes only three steps downwards to reduce the gain to one-tenth, the ratios of sensitivities being 1, 2, 5, 10, 20, 50, etc. There is much to be said in favor of both systems.

In the Offner instrument, each channel does not have its own stepped gain control. All of the gain controls for the eight channels are ganged together in a single control. This system is useful only where all channels are being used to record very similar information (as in the EEG), but for flexible physiological recordings this is a serious disadvantage. In order to get different gains in different channels it is necessary to use the individual controls which were originally intended as equalizing controls. These, of course, are not stepped but continuously variable controls and it is almost impossible to make resetttings with any degree of exactness. We propose to replace the ganged eight-channel control with eight individual stepped controls.

In the low and high frequency filter controls, we have a means of suppressing those components of the signal which are undesirable in the best recording of the information. The low frequency filter prevents to a greater or less degree the large, slow waves and slow changes of base-line from getting through, whereas the high frequencies of the muscle-potential wave are allowed to pass through undistorted. This makes for a much cleaner looking EMG record and one which is very much easier to read. Similarly, the high-frequency filter suppresses to a greater or less degree the highest frequency components by short-circuiting them instead of passing them on to the main amplifier. In EEG records (in which any muscle-potential merely represents an interfering signal), the reading of the alpha or low frequency EEG components is much easier to accomplish if the high frequency muscle-potential spikes are filtered out during the recording.

In the Offner instrument, the filters are located in a different place mechanically than they are in the Edin unit. The high frequency filter is actually wired into the last stage of the preamplifier unit so that the high frequencies are modified before the signal passes from the preamplifier to the main amplifier. The low frequency filter is located at the input to the main amplifier. Here too, the problem of individual channel adjustments

comes in. It is very desirable to be able to set different filter arrangements in different channels, especially where other measures are to be recorded simultaneously with the EMG. In the Offner Type D EEG the filter controls are ganged (as in the gain controls) and operate all eight channels together. The disadvantage in the research setting is obvious.

Figures 24 and 25 attempt to show how the low and high frequency filters work, the difference between these filters in the Edin and Offner instruments, and approximate data as to the critical cut-off frequencies of the filters.

6. The main amplifiers. In the lower part of the EMG console there are eight main amplifiers. Each one is built on a separate chassis, complete with its own power supply. The voltage gain of these units is about 30,000. The output (power amplifying) stage, consisting of push-pull 6V6's, used as cathode followers, can supply enough current to drive a galvanometer with an impedance of about 1,500 ohms. The maximum peak-to-peak output voltage would be 40 to 50 volts, but this is limited to about 32 volts (i.e., plus or minus 16 volts from the base-line) by a pair of 2D21 thyratrons which serve to protect the galvanometer from excessive voltage swings. There are no controls available on the front panel for these amplifiers. They operate at fixed gain.

These are straight condenser-coupled amplifiers working push-pull from beginning to end. They are completely A-C operated and there are special adjustments for balancing out the stray 60 c.p.s. pickup in the first stage. Special negative feed-back circuits are provided in order to help balance out differences in tubes and other components. Since the amount of negative feed-back determines the final over-all gain of the unit, changing of these feed-back resistors is a simple way to adjust the gains, should it be necessary.

The wiring of the EMG console is so arranged that the power output of each amplifier is fed to one of the galvanometers in the chart drive and also fed to a separate output plug which may be used to drive other accessory equipment, such as integrators.

All of the above applies to the Edin Main Amplifier; the situation is very different in the case of the Offner Main Amplifier. As in the case of

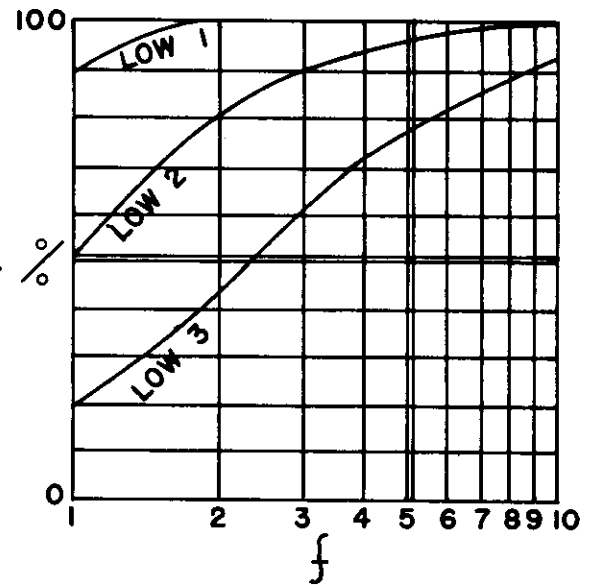
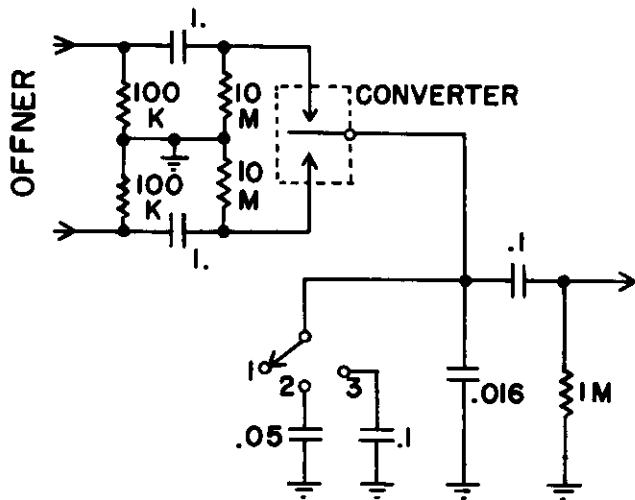
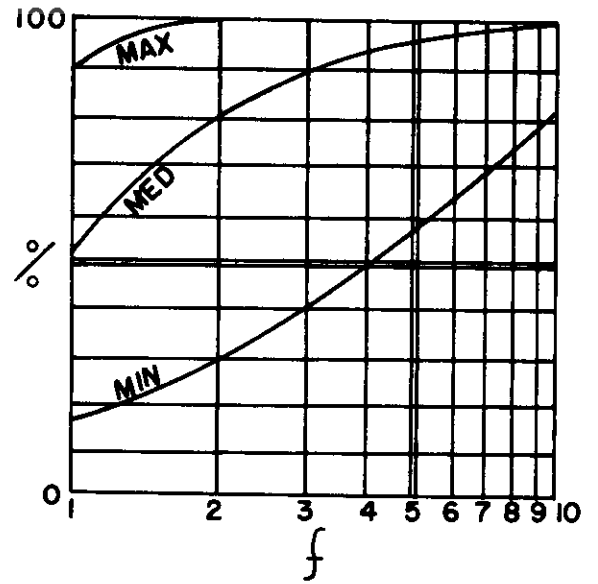
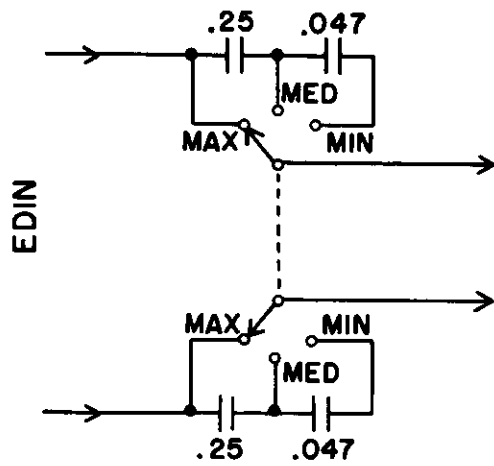


FIGURE 24. CIRCUITS AND DATA: LOW-FREQUENCY FILTERS

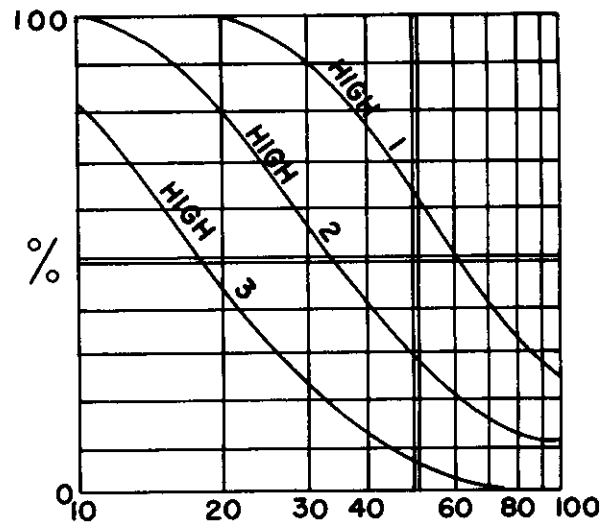
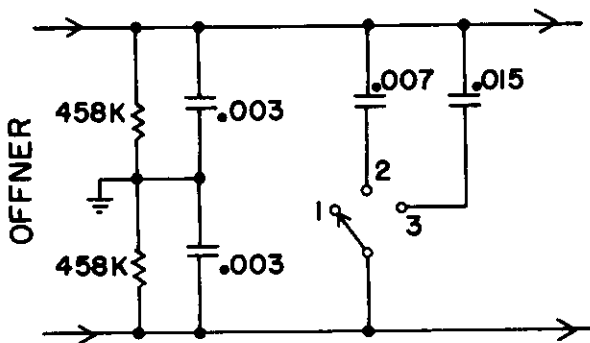
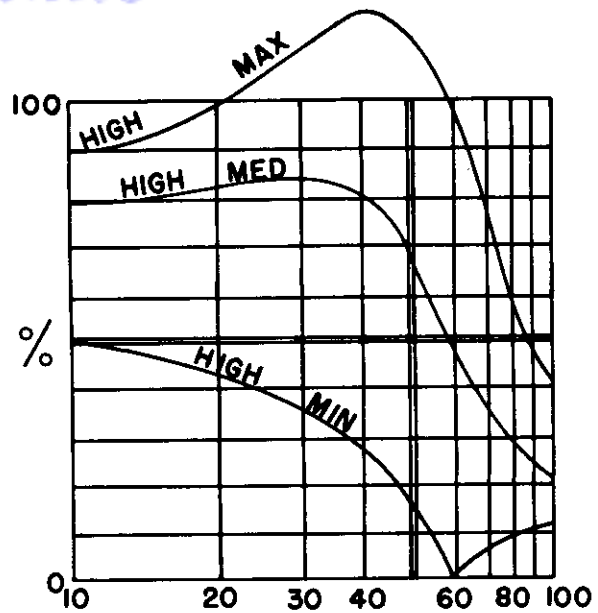
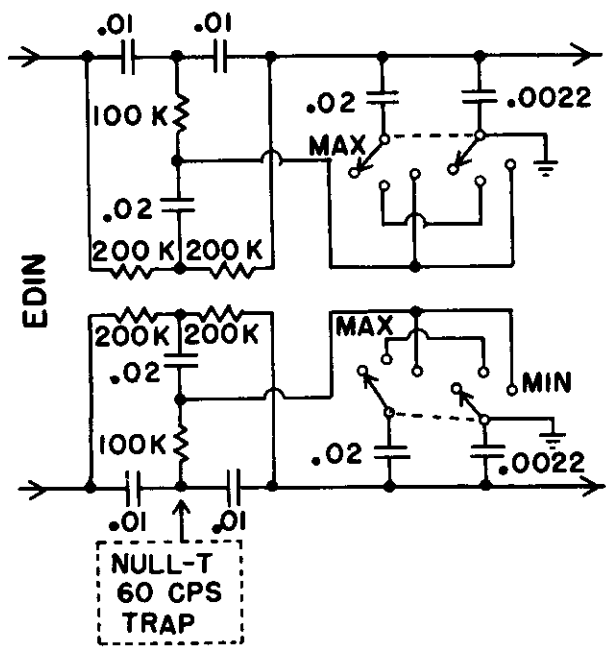


FIGURE 25. CIRCUITS AND DATA: HIGH FREQUENCY FILTERS

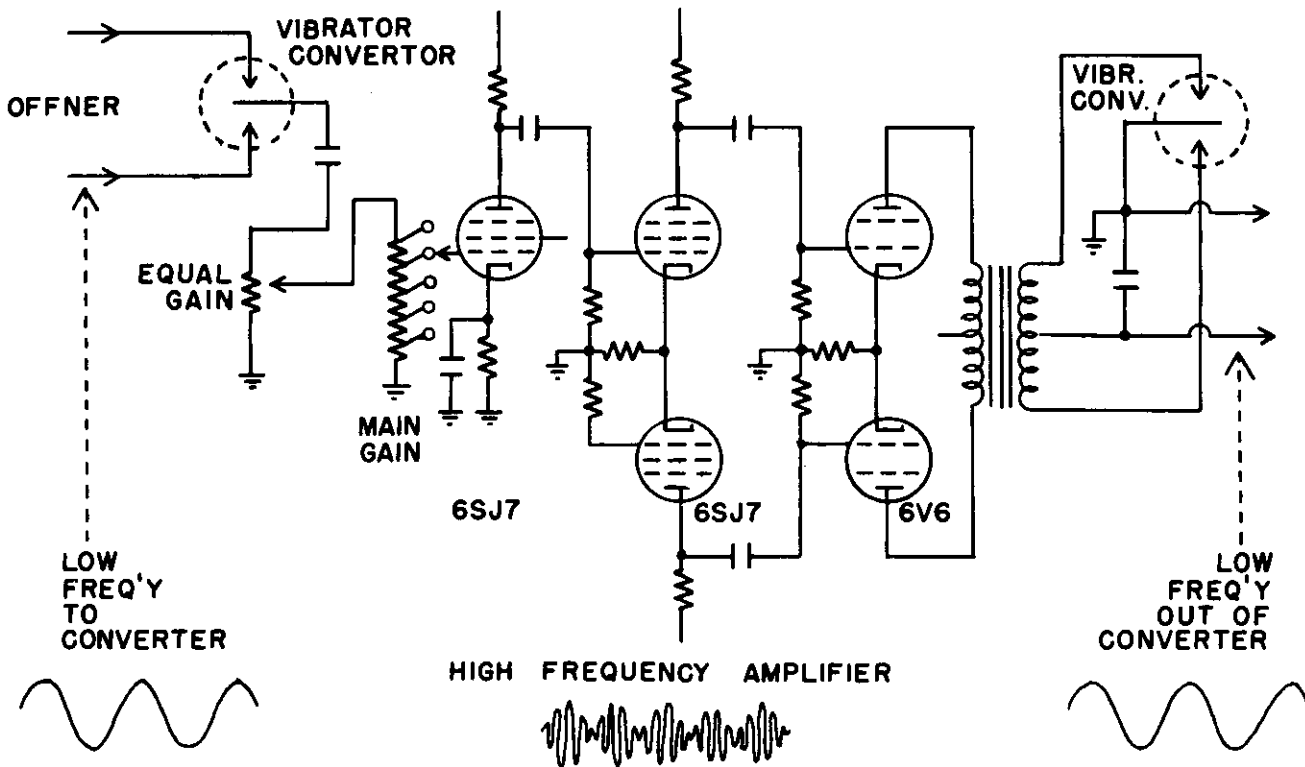
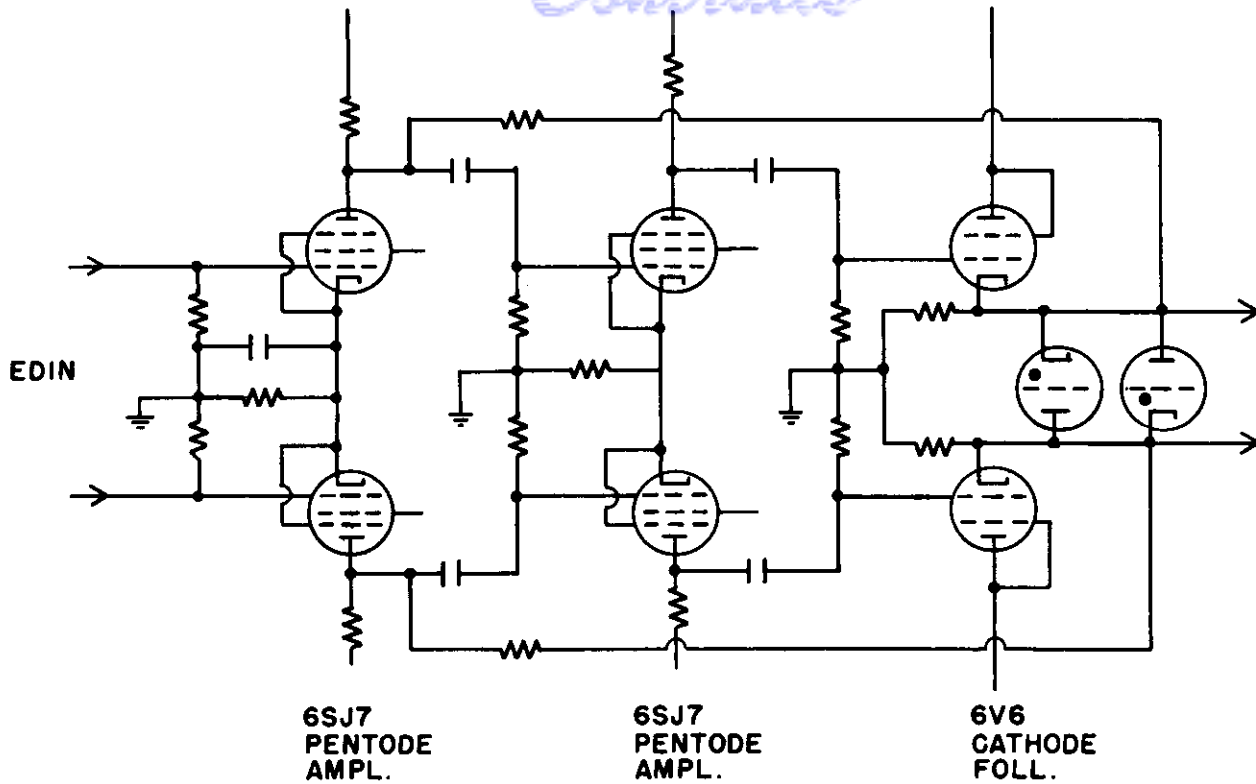
*Controls*

the Offner preamplifier, all eight channels of the main amplifier are built into a single chassis. This unit is not self-contained because it lacks a power supply, there being a separate power supply unit in another part of the console which feeds power to the preamplifier and main amplifier. The Offner Main Amplifier is actually a D-C amplifier and may be used as such by disconnecting the cable from the preamplifier and inserting the appropriate D-C signal. The over-all voltage gain of this D-C amplifier is about one thousand and the output has been designed specially to work into Offner's own galvanometer (the Dynograph) which has an extremely low impedance of 7.5 ohms. The maximum peak-to-peak voltage delivered to this galvanometer would be about six volts (i.e., plus or minus three volts from the base line). Since there are no other galvanometers on the market of comparable characteristics, this amplifier cannot be used with any other recorder.

The Offner D-C amplifier works on the chopper principle. In this type of circuit, the input signal is converted into a square wave of fixed frequency by means of a vibrating switch. The square wave, whose amplitude varies according to the input D-C or low frequency A-C signal, is then amplified in a perfectly standard A-C amplifier. The output from this amplifier is coupled by means of a standard audio-transformer (such as one used in an audio amplifier) to a second vibrating switch working in synchronism with the first one such that the square waves are reconverted back into the original D-C or low-frequency A-C signal. The reconverted signal is a much amplified version of the original input signal and has sufficient power to drive the recording galvanometer.

Naturally, the frequency of vibration of this chopper-type converter must be considerably higher than the highest frequency in the signal which it is desired to reproduce, otherwise certain details of the incoming waveform will be lost. In the case of the Offner D-C amplifier, the vibrator frequency is of the order of 200 c.p.s. Figure 26 shows the electronic line-up of the main amplifiers of the two instruments for comparison. A diagrammatic explanation of the chopper principle is also included.

# Contrails



**FIGURE 26. COMPARISON OF MAIN AMPLIFIERS**



7. The integrators.\* There are four separate integrator units, each complete with its own power supply. These were built by the Edin Company to our specifications but have been somewhat modified since. They are designed to work from the output of almost any standard EEG, even including the Offner Type D which has an extremely low output voltage. By means of a flexible cable arrangement, any four of the eight Edin power amplifiers may be connected to the four integrators, and for each experimental set-up, the experimenter selects the three or four most promising muscle potential channels for integration. At the present time, the integrators are wired up only for automatic operation, although with alterations they could be used for manual operation as well. By automatic operation is meant the charging and discharging of the integrators at a predetermined rate and the recording of the outputs on a galvanometer chart drive, whereas, by manual operation we mean that the charging and discharging of the integrators is under the operator's control, and the integrated outputs must be read from meters.

Figure 27 shows in a very diagrammatic way the operation of the integrator circuit. Each integrator has a panel associated with it on which are located the controls for that channel. The "Gain" switches are left in position 4 or 5 throughout a test as no gain changes are made at the integrator station at all. Where the deflections of the integrator recorder are too low or too high (below two millimeters or above 40 millimeters), there is an indication for a gain change, and the integrator operator should call for such gain changes to be made at the EMG console because in most cases the deflections will be found too low or too high on the EMG recorder also. The setting of the "Integrating Factor" switch will be determined by the rate of automatic integration. At ten integrations per second, position 4 or 5 should be used; at two integrations per second, position 3 or 4 should be used. The "Continuous-Automatic" switch should be left in the "auto" position all the time. The "Centering" control is used after gain equalization has been made to set the galvanometer pens to 15 millimeters below the geometrical centers. This equalization of gains of the four integrators is made by means of "Equalization" controls on the individual

---

\* For a more up-to-date and complete story on integrators, see the Integrator Manual referred to at the bottom of page 41.

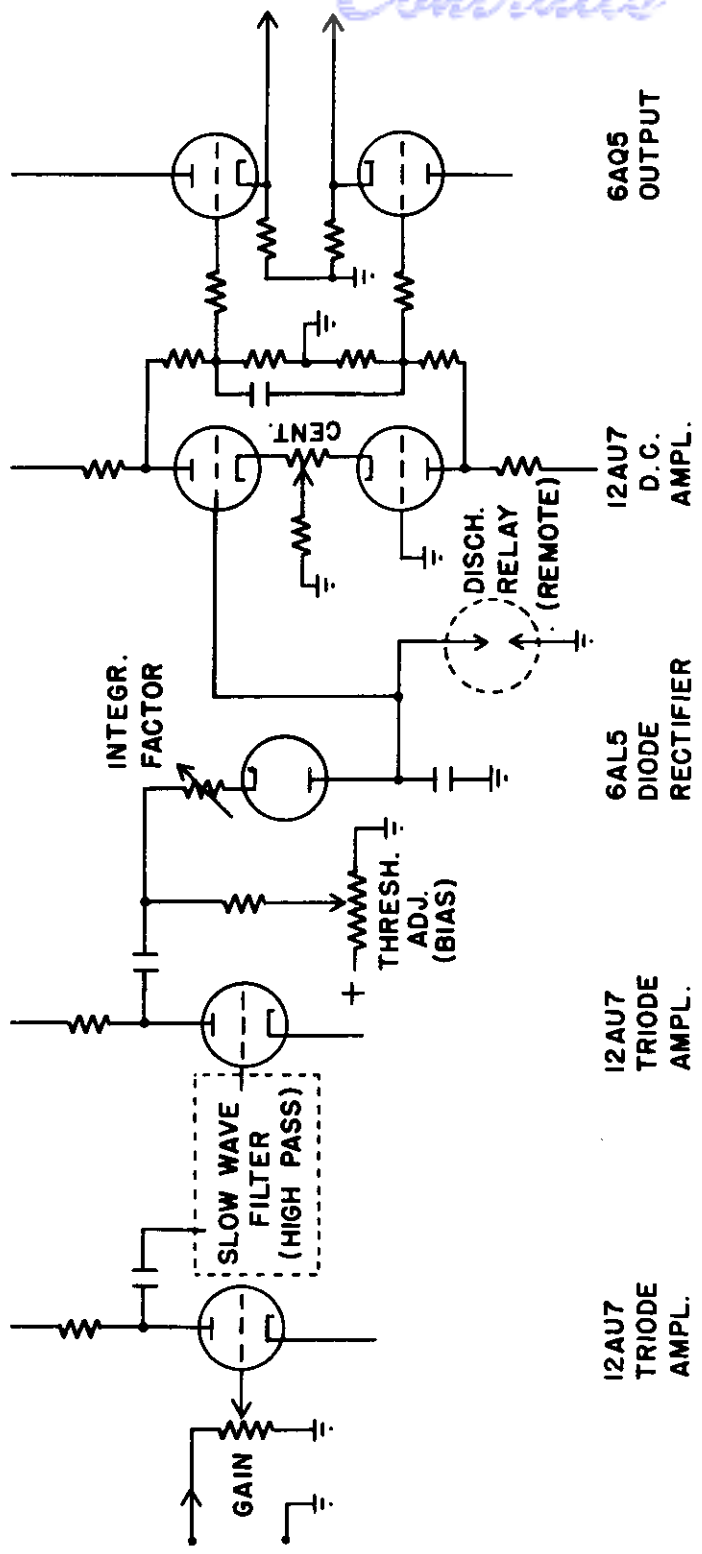


FIGURE 27. FUNCTIONAL DIAGRAM OF INTEGRATOR

chassis and not on the control panels. Located on each chassis near the input plug is a switch which provides a high gain position and a low gain position for the whole integrator. These switches are all left in the low gain position when the integrators are used with the Edin EMG. When used with the Offner EEG, the high gain position is used. Each integrator chassis is also provided with a "Threshold" voltage control which is used to adjust the deflection of the integrator galvanometer to one-half-millimeter when there is no signal being passed from the EMG to the integrator. This setting will, in general, have to be changed every time the integrating rate is changed, and the purpose of the adjustment is to assure that optimum linearity of integrator response to low signals is obtained.

8. Galvanometers and chart drives. In the first Test Suite, the main amplifiers are used to drive eight recording galvanometers (Edin Type 8003, impedance 1350 ohms, deflection sensitivity 1.0 volt per millimeter). The galvanometers are provided with individual switches so that they may be used individually or in groups. In channels 2, 4, 6, and 8 there are also switches which are used to disconnect the galvanometers from their respective main amplifiers and connect them to extra plugs mounted on the side of the console. These plugs may be connected to other types of recording amplifiers (for example, D-C amplifiers) as long as these can supply enough power to drive the Edin galvanometers. Two extra chronograph pens have been added at the lower margin of the paper for the marking of time signals of various kinds. One of these is used exclusively for marking integration periods and the other is connected to the examiner's signal button or to any other timing device in use. A purely mechanical tambour-type of recording pen has also been added to this chart drive for the purpose of recording respiration waves from a pneumograph fastened around the subject's chest or abdomen.

The four channels of integration are used to drive four recording galvanometers (Edin Type 8002, impedance 1350 ohms, deflection sensitivity 0.4 volt per millimeter). These are mounted in their own chart drive so that different speeds may be used for the primary and secondary records if necessary. The spacing of the galvanometers at the present time is double that of the EMG galvanometers (for ease of reading integrator outputs, very

# Contrails

wide deflections are used), but these will be closer spaced when two extra galvanometers are added to make it a six-channel integrator. It is not necessary to add extra timing signals to show the integration periods on this record, so that only one extra chronograph pen has been added and this records the examiner's signals and other time signals as required.

Since the output of the integrators is in the form of roughly triangular waves riding along a fixed D-C baseline, the most efficient use of the galvanometer deflections is obtained when they are offset by a fixed amount. A 15-millimeter negative offset is used at the present time; this gives available 40 millimeters of reliable and linear galvanometer deflection. (With closer spacing of galvanometers, to get eight integrator outputs on one chart, one has to use an offset of 11 or 12 millimeters and a maximum deflection of 25 or 30 millimeters. Calibration ratio between EMG and integrator is then kept at 1 to 1). We do not attempt to maintain linearity of the system above 40 millimeters. In general, the integrator is calibrated at the same time as the EMG in such a way as to obtain on the integrator galvanometer double the deflection obtained on the EMG galvanometer for a given channel and a given signal.

Mechanically, the EMG and the integrator chart drives are equivalent, having chains of gears giving a choice of nine paper speeds. The range of speeds is from .25 millimeters per second to 100 millimeters per second.

In the second Test Suite, the integrator chart drive is in every way the same as that in the first Test Suite, but the chart drive of the Offner EEG is somewhat different. In this case, the eight recording galvanometers are of the Offner dynograph type (low voltage, high current, impedance 7.5 ohms, deflection sensitivity 0.2 volt per millimeter). There are no galvanometer switches on this unit, all eight galvanometers being turned on and off simultaneously by a switch on the main amplifier panel. Six paper speeds are available in this chart drive ranging from 5 millimeters per second to 250 millimeters per second.

9. Internal and external calibrators. Some mention has already been made of the calibrator panel at the extreme right hand end of the preamplifier unit. The calibrator switch described above is the lowest of the three

# Contrails

switches on this panel. The internal calibrator shown in the block diagram is also located on this panel and this consists simply of a very stable battery, a voltage-dividing network, and a push-button switch for connecting the required D-C calibration voltage to the grids of all preamplifiers. The setting of the middle switch shows the magnitude in microvolts of this D-C voltage. A calibration signal is seen each time the push switch is either pressed or released (a positive-going transient on pressure and a negative-going transient on release).

This method of calibration is rough at best because the amplifiers do not respond to the D-C square wave but merely "see" transients corresponding to the fast rise at the beginning of the square wave and a fast fall at the end of the square wave. The shape of the calibration signal actually recorded will depend upon the settings of the low and high frequency filters, the transient response of the preamplifiers and main amplifiers, and the transient response of the galvanometers. In general, the duration of this calibration signal will depend upon the setting of the low frequency filter, and the sharpness of the peak of the signal will depend upon the setting of the high frequency filter. The response time, the mechanical and electrical damping, and the amount of friction loading the galvanometer will determine the shape of the calibration signal with the high frequency filters out of the circuit. We do not use this internal calibrator except to study the shape of the calibration signal when we wish to check up on the mechanical condition of the galvanometers.

In calibration we prefer to deal with steady state signals rather than transients. For this purpose, the position on the calibrator switch marked "External Cal" connects all eight grids of the preamplifiers to a special plug on the side of the console which leads, by means of a cable, to an external calibrator assembly.

Either a square-wave generator or a sine-wave generator of good quality may be used as the primary source of an external calibrator. However, since we wish to meter this calibrator voltage before passing it to the EMC console, and since meters are calibrated to read root-mean-square (RMS) voltage, the sinusoidal signal is the more appropriate one. In this case, a Hewlett-Packard Type 202-D audio-oscillator is used to drive a General

# Contrails

Radio Type 546-C microvolter. With the meter on the microvolter reading 2.2 volts, the dial settings give the number of RMS microvolts output. Since peak-to-peak measurements are always made on the recorded output from the galvanometers, the calibration voltage should actually be quoted in peak-to-peak microvolts. Thus, to deliver 100 microvolts peak-to-peak, one has to set the dials for 35.4 microvolts (the peak-to-peak measurement of a sine-wave is 2.828 times the RMS measurement).

The input resistance of the preamplifiers being greater than 100,000 ohms, no correction to the output voltage of the microvolter need be made. With this system, accurately metered calibration voltages as high as one volt and as low as one microvolt may be delivered to the EMG. Of course, when such minute signals are fed to the EMG from an outside source, the possibility of picking up 60 c.p.s. interference is very great. This is avoided, or at least minimized, by using shielded cables and by carefully avoiding the formation of "ground loops". Some discussion of this problem of ground loops will be included in Part III.

With the audio-oscillator as a source of signal, of course, any frequency may be selected for the calibration. This makes it convenient for running frequency response curves occasionally, but it is also convenient in selecting the appropriate frequency for carrying out calibration in any given application of the instrument. We have adopted the practice of using a frequency as close to the middle of the spectrum as possible for the physiological variable we are recording. For example, in EEG recordings we use frequencies of 10 or 20 c.p.s., depending upon which band we are primarily interested in; for EMG recordings we use 45 c.p.s. as being more representative of the frequency spectrum of the EMG. The only reason for doing this is that the over-all frequency response of the recording system is rarely flat from one end of the band to the other, so that in general a middle-of-the-spectrum frequency should give a more representative calibration than any other frequency, provided that there is not a resonance point at that particular frequency.

10. The integrator timer and discharging relay.\* The integrator timer

---

\*For more up-to-date information see the Integrator manual referred to at the bottom of page 41.



is an electronic pulsing unit which puts out ten pulses per second or two pulses per second, reliably synchronized to the 60-cycle line frequency. The pulses are used to drive a telephone-type relay (the Discharging Relay) with at least five sets of normally open contact springs. Four of these sets of contacts are used to short-circuit the outputs of the four integrators, and the fifth contact is used to control the marking pen on the main EMG console. The arrival of a timing pulse from this integrator timer marks the end of one integrating interval and the beginning of another one. The timing pulse closes the contacts on the telephone relay and these discharge all of the integrating condensers simultaneously. The reopening of the contacts allows the integrators to start feeding energy into the integrating condensers again (see Figure 28).

The circuit for this stable integrator timer has not yet been published, but a manuscript is in preparation. Very briefly, the principle of operation is as follows. The 60 c.p.s. sinusoidal line voltage is converted by means of an NE-51 neon bulb into synchronizing pulses. These are fed to the grid of a 2D21 thyratron which operates as a relaxation oscillator with a free running frequency of about nine cycles per second. The 60 c.p.s. synchronizing pulses cause this oscillator to speed up to exactly 10 c.p.s. (the nearest subharmonic of 60) and it locks in at this frequency in a very stable manner. Ten c.p.s. synchronizing pulses derived from this oscillator stage are fed to another 2D21 thyratron also operating as a relaxation oscillator, this one with a free running frequency of about 1.8 c.p.s. The synchronizing pulses in this case cause the oscillator to speed up and lock in at 2 c.p.s. Thus, the first thyratron fires on every sixth pulse from the line frequency and the second thyratron fires on every fifth pulse from the first thyratron.

Output pulses from these relaxation oscillators are fed to the grids of two cathode followers. These are the two halves of a 12AU7 double triode and they merely act as buffer stages to prevent undue loading of the relaxation oscillators. By means of a frequency selector switch either the two-per-second or the ten-per-second pulses from the 12AU7 cathodes may be used to fire a 2D21 thyratron relay stage which operates the telephone-type relay described above.



The discharging relay is mounted along with any other relays, which may be used for various purposes, in a special sound-proof box in order to make the operation of the instruments as silent as possible.

The importance of frequency stability in the operation of the discharging relays cannot be overemphasized. It will be appreciated that any variation in this frequency will cause variations in the interval between discharging pulses, and this in turn will be reflected as variation in the amplitude of the integrand corresponding to each integrating interval. It will be noted that the accuracy of all the time relationships in this circuit depend upon the accuracy of the line frequency. The choice of the power-line frequency as the primary synchronizing signal is based upon the fact that this frequency is maintained constant to within much better than 1%, which is, of course, perfectly adequate in most biological experiments. The ability of the relaxation oscillators to lock into their respective synchronizing signals in a dependable fashion results from the choice of the inherently stable cathode-output saw-tooth generators. In order to further enhance this stability, the relaxation oscillators are run from a regulated D-C voltage supply, and also, their outputs are fed through the buffer amplifier, the 12AU7 stage, to prevent loading effects in the frequency determining circuits.

#### F. DISADVANTAGES OF SOME COMMERCIAL EEG'S FOR EMG USE

In the preceding section, references have been made to inconveniences which one encounters in trying to use an instrument designed for clinical electroencephalography as a research polygraph. Actually, we have had experience with seven or eight different commercial polygraphs and have accumulated a list of disadvantages which are met with in one or another of them. We propose to present this list here so that the newcomer in the field will be prepared in advance. This list is not intended as a general criticism of the available instruments; for the most part, they were designed as clinical EEG's and we use them quite differently.

In the preamplifiers:

1. The use of dry batteries for a B supply introduces a battery replacement problem.

# Contrails

2. Use of wet batteries for the A supply introduces recharging and battery maintenance problems.

In the gain and filter controls:

1. When gain controls for all channels are ganged in a single control, one is forced to use the equalizing controls as individual gain controls.
2. When the filter controls for all channels are ganged in a single control it is impossible to have ideal filter settings for several different physiological variables.
3. Poor quality filter switches have been seen in certain machines, necessitating frequent replacement.
4. The use of 60-cycle wave traps in the filter circuits cannot be allowed in EMG work because 60 cycles per second lies in the middle of the EMG frequency band. These wave traps are usually cut out when the high frequency filter switch is in its highest position.

In the main amplifiers:

1. Not sufficient gain - a common finding.
2. The use of a vibrator type D-C amplifier compromises the high frequency response of the main amplifier.

In the chart drives and recording pens:

1. In crystal operated pens the deflection sensitivity falls off at summer temperatures and one can maintain it only by the use of forced air cooling.
2. In crystal operated pens there is a tendency for the crystals to shake loose from their moorings with large transients (which are more numerous in research than in clinical EEG work).
3. Some pens with high inertia and stiff suspension have poor high frequency response.
4. Some pens draw too heavy a line to give good EMG resolution.

# Contrails

5. Some pens cannot be adjusted for alignment in the longitudinal direction.
6. Some chart drives lack a good range of paper speeds.
7. The standard EEG speed is 30 millimeters per second, whereas we prefer 25 millimeters per second.
8. Some ink feed systems are purely gravity fed, which causes too heavy inking when the pots are full.
9. Some inkpots are too small for a one-hour recording.
10. In some recorders there are no individual switches for each pen.
11. In some multi-channel recorders the pens cannot be set close enough together to get eight channels on the chart.
12. The special papers required for use with non-inking styli are very expensive.

In general:

1. The various controls are badly located in certain machines - they may be altered inadvertently by brushing against them with clothing, etc. Centering controls and equalizing gain controls are the worst offenders in this respect.
2. In some machines, in the interests of saving space, the components, particularly of the preamplifiers, have been crowded, with the result that servicing is extremely inconvenient and in some cases it is difficult to remove the preamplifiers without damaging some of the component parts.

## G. SPECIFICATIONS FOR A RESEARCH EMG

With experiences such as those outlined above in mind, it is possible to write a set of specifications for an instrument to be used mainly as an electromyograph, but which should also be capable of recording EEG's and EKG's, for example. We first laid down such a set of specs in 1949, and

# Contrails

these, with slight modifications and abbreviations, will be repeated here. As yet, no instrument has been produced which meets all of these requirements, but we believe that the special high-gain low-noise model built for us by the Edin Company comes fairly close. The special feature of high-gain and low-noise was dictated by the need to record from muscular areas at rest, in which muscle spikes as small as one or two microvolts are commonly seen.

We have already noted in our introductory remarks that very good work may be done with any standard clinical EEG instrument. We do not, therefore, wish to discourage the newcomer to the field by saying that he should aim immediately at instrumentation which will satisfy these specifications. We include them only for the sake of completeness.

## Specifications:

1. Power supply.
  - a. All A-C operated, no batteries.
  - b. Self-contained line-voltage and D-C voltage regulators to allow operation from 100 to 125 volts (RMS) line voltage.
2. Recorder.
  - a. To accommodate 12-inch width paper, self folding. With provision for narrower papers down to five inches.
  - b. Speeds from 1 to 100 millimeters per second (especially important are 25 and 50 millimeters per second). Gear changing by direct manual control.
  - c. Accommodation for paper packs 12 in. by 12 in. by 3 in.
  - d. Galvanometers 1 to 1-1/4 in. on centers.
  - e. Pens of radius not less than four inches.
  - f. Inked line not greater than 1/4 millimeter width. (No glass-tipped pens).
  - g. Galvanometer coils and pivots to be protected from ink spillage.
  - h. Galvanometer impedance not less than 500 ohms.

# Contrails

- i. Pen deflection absolutely linear to plus or minus 15 millimeters. Maximum usable deflection plus or minus 25 millimeters.
  - j. Galvanometer response not less than 70% at 60 cycles-per-second. Not greater than 5% rise at resonance. Phase response linear to 60 cycles-per-second. Gross phase distortion cannot be tolerated in the range of 30 to 60 cycles-per-second.
  - k. Ink-wells large enough for three to four hours of continuous running, arranged for capillary rather than gravity feed.
  - l. Paper ruled preferably as follows: 5mm spacing in time dimension and every fifth line heavy (1/5 seconds at 25mm/sec.); 5mm spacing also desirable. Self-folding packs of about 25cm page lengths are ideal.
3. Preamplifiers.
- a. Input impedance not less than 750 K grid-to-grid.
  - b. Rejection ratio to in-phase signals at input not less than 5,000:1.
  - c. Highest quality components only. Preferably no electrolytic condensers.
  - d. Replacement of selected components and/or tubes to be made as easy as possible so that specifications on noise and sensitivity may be maintained throughout the life of the instrument.
4. Control panel.
- a. Each channel to have a "gain" control attenuator giving sensitivities in microvolts per millimeter as follows: 0.5, 1, 2.5, 5, 10, 25, 50, 100, 250, 500 and infinity (with the low frequency filter in minimum position). In addition to this, a ten-to-one emergency attenuator should be included.

# Contrails

- b. Equalizing gain controls to give at least five-to-one adjustment and to have no effect on pen damping.
  - c. Selector switches for electrode connections to have 23 positions, 22 signals plus ground. No circuit combination switch is necessary.
  - d. Low frequency filters to give 90% response at the pen at the following frequencies: maximum 0.5 cycles-per-second, medium 2.5 cycles-per-second, minimum 12.5 cycles-per-second.
  - e. High frequency filters to give 90% response at the pen at the following frequencies: maximum, amplifier wide open, preferably to 1,000 cycles-per-second for CRO use, medium 60 cycles-per-second, minimum 35 cycles-per-second, (with or without a special 60 cycles-per-second filter).
  - f. Built in ohmmeter panel not essential.
  - g. Calibration switch to include: 1) A-C calibration (external), 2) D-C calibration (internal), 3) Operate.
  - h. Calibration voltages (internal) of 2, 5, 10, 20, 50, 100, 200, 500 and 1,000 microvolts to be provided.
  - i. Calibration push-switch to operate without production of microphonics (vibration).
5. Main amplifiers.
- a. Output jack for connection to integrators, etc., to be provided.
  - b. Output circuit to include thyatron or other gas-tube limiter for pen protection (preferably limit to be adjustable).
  - c. No detectable 60 cycles-per-second output from sources referable to the instrument itself (with high frequency filter at medium and 100 K input impedance). This means that 60 cycles-per-second output must be considerably below the noise level specified in the next paragraph.

- Contracts*
- d. Noise output (with high frequency filter at maximum and low frequency filter at minimum and 100 K input impedance) not greater than one microvolt peak-to-peak (approximately 0.4 microvolts RMS).
  - e. Microphonics to be kept as low as possible.
  - f. Gain stability of warmed-up amplifiers (30 minutes) to be such that gain will remain constant within plus or minus 5% over a four-hour period with line voltage variation of 105 to 120 volts RMS.

#### H. LABORATORY DESIGN AND LAYOUT

Much has been written on the subject of choosing an ideal laboratory location and the facilities which are desirable in such a unit, so that we propose here to mention very briefly the particular aspects of laboratory location, design, and layout which apply specifically to this type of experimental setup. The requirements are pretty much the same whether one wishes to use this equipment to study a subject during a simple psychiatric interview or whether one wishes to observe a subject during stimulation of one or more of the sensory modalities. Basically, these requirements are: privacy, quiet, and low electrical interference.

1. Privacy. There are two aspects to consider. One is that during the test procedure the subject should feel that he or she is absolutely alone with the interviewer, examiner, or observer. The other is that the subject should not have to appear in public corridors after being made ready for an elaborate test procedure. In spite of the generally serious atmosphere of a hospital or research department, nothing looks sillier than to see a subject walking down the corridor with his hair disarranged, a large black spot on his forehead, a white coat or towel draped around the shoulders, and a large number of wires leading from head, shoulders, arms, and legs, being supported by an accompanying technician. This situation can very easily develop if it is necessary to make a subject ready in one room and do a procedure in another

room, or if the subject decides that he has to go to the washroom after all the leads are attached!

One of our laboratories consists of a suite of two rooms with a single entrance from the corridor. One enters the suite directly into the control room or instrument room and then proceeds via a connecting door to the subject's room or test room. Once the communicating door is closed, the subject is alone with the examiner, and the operators of the various instruments remain in the control room. There is also a one-way vision window between the two rooms so that the operators may observe the procedure in the test room but the subject very rarely notices the presence of this window. The preparation of the subject for the test procedure is carried on in the test room itself. The disadvantages of this setup are fairly obvious: since the subject has to enter the suite through the instrument room he gets an unnecessarily close view of the impressive instrumentation (which can lead to increased apprehension); also the air in the test room becomes rather heavily laden with the vapors of the various solvents used in applying the electrodes.

The other laboratory consists of two completely separate rooms, each with its door to the corridor and with no inter-communicating door between the rooms, although there is an observation window. Here again it is necessary to apply the electrodes right in the test room, with the same disadvantages as mentioned above, but the main disadvantage here is that there is a door from the corridor into the test room where the most privacy is desired. In spite of elaborate signs posted outside the door during the progress of tests, strangers or workmen not infrequently knock on the door or actually try to open it.

Obviously, neither of these setups is ideal for the purpose. We believe that the most convenient arrangement would consist of three inter-communicating rooms: the preparation room, the testing room, and the control room. The preparation room and the control room should communicate with the corridor. The centrally placed testing room should not be accessible from the corridor but should have communicating doors with both the preparation room and the control room. The preparation room should be fitted with running water and a compressed air line, and there should be a one-way vision window between the



control room and the testing room. This arrangement should make it unnecessary for the subject to see all the equipment that is essential in carrying out this type of procedure.

2. Quiet. This is the second essential feature of a laboratory for psychological studies. While it is not practical to go to the extreme in building a quiet room (for example, the very elaborate construction used in the "anechoic" or echo-less chambers at Harvard University), it is possible to provide a fair amount of soundproofing at not too great an expense.

The worst types of noise disturbance are the following: traffic noise, corridor noise, ceiling noise, and plumbing noise. Traffic noise, of course, enters mainly through windows or outside walls and is best controlled by choosing a room without an outside wall or window, or by sealing up with acoustic materials any existing windows. Corridor noise is reduced by the fact that the testing room should have no communicating door with the corridor and the wall separating the corridor from the testing room should be acoustically treated in some manner. Ceiling noise consists mainly of overhead foot traffic and movement of furniture, etc., and again, can only be minimized by means of a good acoustic treatment in the ceiling of the test room. Plumbing noise is conducted along pipes (water, steam, air, etc.) which are connected to pumping machinery and compressors, and is very persistent and difficult to handle. Choosing a site for the testing room with a minimum of visible piping and with no plumbing stacks in the adjacent partitions is the best approach to this problem but not always easy to manage.

The "room within a room" type of construction offers a fairly good compromise both from the point of view of sound deadening qualities and of expense. Here, the general idea is to prevent any mechanical vibration which reaches the outer wall of a room from penetrating to the inner walls. In order to achieve this effect, the room must have double walls on all four sides, including the ceiling. There must be an air gap of an inch or two at least between the inner and outer walls, and there must be no solid objects whatsoever bridging this gap. In other words, the inner room must be completely self-supporting and preferably built on a soft base such as Ten-Test or other insulating board. Hair felt or shredded paper insulation

may be suspended in the space between the walls for additional acoustic insulation and any pipes which pass through the space above the false ceiling should be well wrapped with insulating material, although noise originating in such pipes is well-nigh impossible to eliminate.

Doors, observation windows and portholes for wiring and lighting are built into the inner wall of the room to match those of the outer wall but no wood or metal is allowed to bridge the gap. In order to seal off the doors and windows sheet rubber can be used to bridge from inner to outer jambs. Of course, all doors and windows are double, there being a set in the inner wall and a second set in the outer wall. A soft wallboard should be used to finish the interior of the test room.

3. Low electrical interference. This is the third requisite for reliable electromyographic recordings. This is best guaranteed by arranging for all or most of the following details:

a. Private branch electrical power line (i.e., not to be shared with any other lab or department and especially not to be shared with any electric motors).

b. Test room to be located at least 50 feet from any transformer vault, elevator motor room, circulating or booster pumps, air compressors, or other electrical loads over 1/2-horsepower, and from X-Ray or Diathermy departments, and from kitchens employing electric stoves and toasters.

c. Test room should have copper screening tacked to the inside wall, ceiling and floor. This should be soldered at the joints and should not be shorted to ground at any random point but connected to ground via an accessible grounding strap.

Doors should also have copper screen contacting the room screen around all edges. Windows may be screened with coarse mesh (one inch or two inches) heavy copper screen.

d. Conduits, empty or wired may be run around the walls of the inner room but must not be allowed to touch the screening at outlet boxes. The grounding strap for such conduits should also be accessible.

# Contrails

The construction described above for acoustic insulation of the inner room is ideally suited to electrical insulation and shielding, too. The screening is put on just before the final wallboard and the self-supporting inner room insures that no random grounding occurs. Laying the floor so that no grounds occur, is simply a matter of careful workmanship and layer-on-layer construction (note: no watery cleaning solutions should be allowed on this floor after construction).

Nothing has been said about heating and ventilating the test room. Duct systems are best because they offer the possibility of changing air, which would otherwise become very stagnant in this sealed off, windowless space. Again, the metal ducts must not be allowed to touch the screening around the room and a canvas or rubber sleeve should be provided at the registers. Duct noise can be reduced by acoustic ductlining and/or acoustic duct baffles.

## I. COSTS

The following list of approximate prices (1952) will enable those unfamiliar with the field to form some idea of how much money it takes to get started.

INSTRUMENT	PRICE RANGE
2-channel EEG	\$1200.00 to \$1600.00
4-channel EEG	\$2200.00 to \$2800.00
8-channel EEG	\$3000.00 to \$4000.00
1-channel Integrator	\$ 350.00 to \$ 400.00
4-channel Integrator	\$1000.00 to \$1200.00
Integrator Timer and Relays (4-channels)	\$ 300.00 to \$ 350.00
Multi-Speed Chart Drive with 4 Galvanometers	\$1200.00 to \$1400.00
Audio-Oscillator	\$ 300.00 to \$ 400.00
Microvolter	\$ 120.00 to \$ 150.00

# Contrails

If modifications to the standard EEG are ordered to bring it more in line with the recommended specifications for EMG work, one should expect a surcharge of 20% to 40%.

If one has access to a four-channel or eight-channel EEG, then one can add the four-channel integrator system and have a very complete EMG setup. The four-channel integrating system plus the four-channel extra chart-drive plus the calibrating system amount to about \$3000.00.

An eight-channel EEG with extra gain and low-noise input circuits designed to meet as many of the EMG specifications as possible would cost \$5000.00 to \$6000.00. If the complete four-channel integrating system is added to this, the total expenditure will come to between \$8000.00 and \$9000.00.

If one wishes to set up a very simple EMG and integrator system with only a single channel of recording, it can be done for as little as \$2300.00. For this purpose, one could order a two-channel EEG, a one-channel integrator, an integrator timer, and an audio-oscillator and microvolter. In this case, no extra chart-drive is included, the idea being to record the original EMG on one channel and the output of the automatic integrator on the second channel.

The cost of paper for the recorders is by no means insignificant. Owing to the necessity for using paper speeds of at least 2.5 cm/sec for most recordings (in order to obtain readable records) and to the rather lengthy test sessions, anything from \$1.00 to \$2.00 worth of chart paper may be used at each test.

The Allan Memorial Institute integrator system is now manufactured by Biophysical Electronics Inc., 400 Northern Boulevard, Great Neck, Long Island, New York.

OPERATION - PRACTICAL POINTS IN THE USE  
OF THESE INSTRUMENTS

## A. APPLICATION AND CARE OF ELECTRODES

We have already gone into some detail in the matter of electrode construction, different means of attachment of electrodes, the problem of skin resistance and how to prepare the skin in order to reduce this resistance to a minimum. By keeping the facts presented in those sections in mind, the experimenter should be able to apply a good set of electrodes after a little practice. It cannot be emphasized too much that the success or failure of an experiment may depend upon the matter of electrode application. Even after several years of experience with surface electrodes we, in this laboratory, are still improving our methods. Hardly a month goes by but what some member of the research team suggests a technical improvement which, after testing and proving its value, is incorporated into our standard technique.

In general, the order of procedure in applying an electrode would be as follows: locating the appropriate anatomical landmarks and marking the precise point where the electrode is to be attached, cleansing the skin at this point, massaging electrode jelly into the skin, wiping off any excess jelly, applying the electrode attachment device, inserting the jelly-soaked electrode into the attachment device and fixing the lead wire at some point fairly close to the electrode to prevent stress in the wire. Usually the two electrode positions corresponding to a lead will be marked at the same time and prepared concurrently, and it is not a bad idea to have the electrode lead wires twisted together and taped as a pair, since the two electrodes are usually fairly close together anyway. After a pair of electrodes has been applied, the next step is to measure the resistance of the pair by means of an ohmmeter.

# Contrails

1. Measurement of electrode resistance. The measurement of electrode resistance is so much more important in surface EMG work compared with EEG work that we definitely recommend the practice of measuring each electrode pair as it is attached. For this purpose, it is much better to have a completely separate ohmmeter rather than use an ohmmeter which may be built into the EEG control panel. Of course, there is no absolute guarantee that a pair of electrodes with a satisfactorily low resistance will give artifact-free recording, but a low resistance is a good general indication that electrical contact has been made with the skin. The range of resistances to be expected with different types of electrodes is shown in Figure 18. Gross departures from these normal ranges should be investigated.

Too high a resistance usually means that the skin under one electrode has not been properly cleaned or that the jelly has not been massaged into the skin well enough. This may be remedied by adding a little electrode jelly and by massaging and abrading the skin under the electrode with the end of an applicator stick. The high resistance may also be due to too loose an attachment so that the electrode is not pressing hard enough against the skin. However, in spite of carefully checking these points or even replacing the electrode completely, one may still get a very high resistance. If this should be the case, don't abandon the recording; one often gets a very good record from a high resistance lead, but don't be misled by this; it is very worthwhile to aim for low resistances.

Note that when a pair of electrodes reads a high resistance only one electrode may be at fault. To check this, measure the resistance of each of the electrodes combined with some other electrode which is known to be of low resistance (the ground electrode, for example). By this means, the offending electrode may be identified and remedial measures concentrated on this one.

Remember that high electrode resistance does not affect the fidelity of the recording to any great extent, it merely makes the electrode more susceptible to 60-cycle pickup and in some locations to EKG artifact. It is probably also true that a lead made up of one normal and one very high resistance electrode is worse from this point of view than a lead made up of

two medium high resistance electrodes. In other words, we believe that balanced resistances in electrodes may be a desirable feature, although hardly one worth striving for in all cases.

Too low a resistance, on the other hand, probably will affect the fidelity of recording because this usually means that there is a conducting bridge of jelly or saline across the skin surface between the electrodes. This acts as a short circuit to EMG potentials before they ever reach the amplifier and consequently they will be reduced in amplitude and distorted in shape. It is a mistake to attempt to put sponge electrodes too close together because the jelly seeps out and covers a wider area than is intended.

2. The ohmmeter. An ohmmeter of the simplest type may be used (that is, a battery, a series resistance, and a meter), but the current delivered to the subject while measuring resistance should not be over 100 microamps. The common one milliamp meter movement used in ohmmeters is not recommended because such ohmmeters deliver a current high enough to be felt by the subject as minute electric shocks or seen as white or blue flashes of light when temporal or forehead electrodes are tested. These, of course, are not very harmful effects or even disturbing, but best subject cooperation when measuring electrode resistance can be achieved by avoiding any sensation whatsoever. It can be very embarrassing to say to the subject: "This is just for testing the electrodes, you won't feel anything", and then have the subject jump or wince when you apply the ohmmeter. As for the ohmmeter scale, if the center scale resistance is 10,000 ohms, then good coverage from 1,000 to 100,000 ohms is available on a single scale and no scale switching need be provided.

For the benefit of those who prefer to use a home-made saline jelly, we give the formula below for the jelly used in our laboratory. Some of the commercially available EKG and EEG jellies are very satisfactory but others are too granular or too liquid. We have found that this mixture suits our purposes best. As well as applying the jelly with the fingers it is convenient to use a hypodermic syringe with a blunted No. 18 needle to get jelly into the less accessible places and in particular to inject the jelly through the access hole in the middle of a collodion electrode. The most

important single factor in the matter of jellies is to keep your stock fresh. Most jellies become thicker and granular after a few months or after an even shorter time if the jelly is not kept in an airtight jar. Even an unopened tube of jelly may deteriorate in this respect after a few months.

#### Formula for Electrode Jelly:

Boric Acid	42.0
Distilled Water	720.0
Sodium Chloride	300.0
(not all will dissolve)	
Glycerin	210.0
Tragacanth	40.0
Hydrochloric Acid 10%	15.0

3. Electrode maintenance. A new set of electrodes which has never been exposed to a saline solution may be expected to last indefinitely if stored dry in a clean box, but once the electrodes have been used a process of deterioration sets in which is very difficult to halt even though every effort is made to keep the electrodes clean. After every use the electrodes should be washed thoroughly in hot water or hot detergent solution, and then rinsed in clear running water in order to remove as much as possible all traces of ionized electrolyte. The electrodes may then be allowed to dry in between uses. In this way, failure of electrodes due to corrosion of the wire is reduced to a minimum so that the main problem of electrode maintenance then becomes one of repairing the mechanical breakages.

A very light grade of plastic insulated wire (e.g., Belden No. 8014) is recommended for making up lead wires because of its great flexibility and light weight. This flexibility gradually deteriorates and the wire becomes quite brittle as the strands become corroded at the electrode end of the lead, so that eventually the wire may be expected to break and this will necessitate stripping back to the fresh wire and replacing the connection to the electrode. In the same way, at the other end of the lead wire where a soldered connection is usually made to a banana plug or a phone tip, the flexibility is lost at the point where the strands are soldered together, and



this is another common point for mechanical failure. Naturally, the operation of the lead is not compromised by the failure of a few of the strands of wire, but there comes a point when the lead is not worth the trouble of attaching to a subject because of the danger of breaking the last few strands. In order to avoid this situation, we use what we call the "jerk test". In other words, we adopt the attitude that if a lead is not in good enough condition to withstand a fairly strong jerk at both ends of the wire, then it is probably not good enough to use on a subject. This "jerk test" cannot be applied to a dry cellulose sponge because of the danger of cutting through it with the wire loop.

Even with careful washing of electrodes corrosion does occur between uses. Therefore, the electrode end of the lead should be inspected carefully before every use. A slight amount of darkening of the wire and verdigris present does not mean that the electrode cannot be used, but when the discoloration of the wire becomes very marked it can be expected that electrical conductivity is impaired to some extent and it would be better to renew the electrode connection. Sponge electrodes and collodion electrodes have been found to last up to a year in occasional service, and for shorter periods under more constant use. As to mechanical repairs (resoldering, etc.), one can expect to do these rather frequently, perhaps daily, especially if the strenuous jerk test is applied after each use of the electrodes.

We have found it a good plan to make some member of the research team responsible for the upkeep of electrodes. These responsibilities usually involve the following things: keeping a supply of new electrodes always on hand, inspection and testing of electrodes after the completion of a session, inspection and testing of electrodes before applying them to a subject, maintaining an adequate stock of fresh jelly, saline, detergent, ether, acetone, alcohol, syringes and blunt needles, lastonet, elastoplast, adhesive tape, gauze swabs, absorbent cotton, applicator sticks, and materials for making electrodes.

## B. CONNECTING THE SUBJECT TO EMG

After suitable electrode placements have been chosen, and the electrodes applied, the subject is made as comfortable as possible in the sitting or lying posture and all wires connected to the subject are then plugged into the electrode plug-in box. No wires are ever left hanging from a patient as they may accidentally touch each other, or a nearby ground, or, worst of all, a live wire. The operator of the EMG then selects for each of the available channels the two leads representing the particular muscle placement which he wishes to record on each channel. The proper filter settings to use for electromyographic recording will usually be the poorest low-frequency response and the best high-frequency response that the particular machine will give. (Edin settings: Low, "Min.", High, "Med.". Offner settings: High, "1", Low, "3"). Starting with the gain selector switches at the lowest sensitivity, the gains for each channel should be turned up slowly until EMG potentials begin to come through on the recorder.

At this point, one is usually faced with the appearance of gross artifact of one kind or another, or, in any event, before going on to the taking of clean and useful records, there are several important questions which must be faced. These are: "What shall we do about grounding the subject?"; "How shall we recognize artifact and what shall we do about it?"; "What about calibration and the accuracy of the instrument?"; and "How shall we measure the record?". We shall proceed to discuss each of these problems separately.

## C. GROUNDING PROBLEMS

The electromyograph itself should, of course, be grounded. One ground wire should be sufficient for this duty since all metal parts of the electromyograph are connected together internally by means of the manufacturer's cabling. He will also have provided a special binding-post for a ground wire and this should be used because it is usually placed in the best position in the circuit electrically, whether or not it happens to be convenient

# Contrails

mechanically. It is not necessary to use a very heavy wire for this main ground connection because heavy currents are not involved, but it should be a sound wire and preferably a stranded one. It should be connected to the metal part of the nearest electrical conduit system, if there is such a thing nearby, or if the electric wiring is not carried in conduits, then the nearest cold water pipe should be used as the official grounding connection.

All accessory electrical equipment situated close to the operating console of the EMG should be grounded to the EMG ground binding-post. Similarly, electrical accessories which might be located close to the subject should be grounded, not via the ground connection on the electrode plug-in box, but by a separate wire back to the main ground binding-post mentioned above.

The subject should be grounded by means of an electrode connected to the special ground terminal on the electrode plug-in box. And any large metal objects which are likely to come in contact with the subject (for example, a metal bed, metal chair, or other metal equipment) should also be grounded to this special ground terminal, and one should be very careful to note that none of these metal objects are in contact with one another or are in contact with any other ground.

Some of the readers will no doubt have heard that it is possible to make recordings of this general kind without grounding the subject, and in fact, some manufacturers may recommend that no ground be used unless necessary. It is true that in favorable conditions and where excessively high sensitivity is not necessary, the ungrounded subject may pick up very little interference. However, we think that, as a general rule, and especially where one does not want to limit the use of the highest available sensitivities, the grounded subject is by far the best method. A word of warning about the grounding of subjects should, of course, be inserted here. A subject with a well connected ground electrode is in exactly the same position as the man standing in a bathtub full of water! It should, therefore, not be possible for the subject to touch any electrical equipment whatsoever while he is connected to the EMG. This warning applies to electric heaters,

# Contrails

electric heating pads, goose-neck lamps, radios, wall switches or wall plugs, etc. It may be necessary, of course, in the carrying out of an experiment, to connect other electrical apparatus to the subject, but this must be done with due regard for the fact that the subject is grounded. A particular warning should be mentioned here about certain electroshock machines, some of which merely meter out the regular line voltage through a suitable controlling mechanism. In these, the phasing of the plug that goes into the wall socket may be important when it is desirable to administer an electric shock to a subject who is already grounded.

As for the choice of a grounding electrode, the main criterion is that the resulting electrode resistance should be as low as possible, and preferably lower than any of the other electrodes connected to the subject. For this reason, it is usually necessary to use one of the larger types of electrode such as an EKG plate-electrode or a sponge-type electrode. As to location of this ground electrode, this will depend upon the kind of investigation under way. Some more will be said on this subject under the discussion of artifacts below, but in general, the ground electrode may be placed fairly close to the general grouping of electrodes in use. Common locations are: the center of the forehead, the mid-line of the neck, the elbow and the wrist.

In the following section on 60-cycle artifact, further grounding problems are discussed.

## D. ARTIFACTS IN THE PRIMARY RECORD

1. "60-cycle" artifact. It is not at all surprising that 60-cycle artifact should be one of the commonest problems in surface electromyography. Into every room in a modern building go several wires carrying 115 volts of 60-cycle-per-second line voltage. Some of these wires are unshielded (i.e., they do not pass through conduits of any kind); some of them are carried only in the B-X type of conduit, and only a few of the wires actually go through solid steel conduits. Sometimes we are forced to use the electromyograph at its maximum sensitivity and, of course, we always set the filters to give the

# Contrails

maximum sensitivity to 60 cycles-per-second, because that frequency happens to be at about the middle of the frequency spectrum of the electromyogram. Remembering that the 115-volt line carries a peak-to-peak voltage of about 300 volts, it is not unusual for peak-to-peak voltages of 2, 5, 10 or even 20 microvolts of 60-cycle interferences to appear at the grids of the input tubes. One should, therefore, expect to see 60-cycle signals quite frequently and should be prepared to handle them when they appear. Incidentally, 60-cycle artifact is best recognized at higher than normal speeds (50 mm/sec, for example) and this speed change should be used when there is any doubt in distinguishing 60 from small high-frequency EMG's.

There are two important ways in which 60-cycle artifact may reach the grids of the input tubes. These are indistinguishable in appearance and, therefore, the diagnosis of the source of the trouble cannot be made by looking at the record, but it is important to realize that there are two separate and distinct types. "Inductive 60" is an electromotive force induced in the grid circuit of the amplifier by virtue of the fact that 60-cycles-per-second magnetic lines of force thread through the loop made up of the two wires leading from the grids of the amplifier to the patient. "Capacitive 60" results from the spanning of 60-cycles-per-second electric lines of force from a nearby electrical appliance to the subject (i.e., the electric appliance represents one plate of a condenser, the subject represents the other plate of the same condenser, and the air between represents the dielectric; the subject, of course, is connected to the EMG).

Inductive 60 is worst in locations near rotating machinery (e.g., elevator motors), transformers, main switches and fuse boxes, and electrical appliances which carry heavy currents, for example, stoves, heaters, toasters, etc. It is the current, in this case, which generates the offending magnetic fields, and not the voltage. These magnetic fields are very powerful and are not at all affected by enclosing the subject in a metal screening, unless that screening happens to be of iron (which is a poor metal from a conduction point of view, copper being the usual one used). Solid steel conduit is the only means of minimizing such fields. From the EMG operator's point of view, once a site has been chosen and nothing more can be done about nearby wiring, all

# Contrails

that can be done is to minimize the pickup of remaining magnetic fields. This is done simply by making sure that the area of the loop represented by the lead wires on the subject is as small as possible, and this is best done by either twisting each pair of wires leading to an electrode placement or by taping the wires together up to within a few inches of their attachment to the subject. Note that grounding the subject and minimizing electrode resistance do not have any effect on this particular type of 60-cycle pickup.

Capacitive 60 results from too large stray capacitance from the subject to nearby 60-cycle lines. In this case, the current carried by nearby electrical devices is of no consequence. It is the mere fact that such devices are connected to the line and, therefore, carry 115 volts of 60-cycles-per-second energy, feeding it by capacitive coupling to the subject. If there are too many such devices around the subject or if they are too close to the subject, they are almost sure to result in 60-cycle pickup regardless of countermeasures. Grounding of the subject is the first step towards reducing this source of 60. This provides a conductive path to ground in parallel with the subject's own distributed capacitance and bleeds away a certain proportion of the 60-cycles-per-second current which would otherwise go to the amplifier grids. The second important means of dealing with this type of 60 is shielding or screening. Here, any metallic sheathing which comes between the subject and the source of the 60-cycle voltage will reduce or eliminate the interference, provided that the shielding is grounded. Then the lines of force which normally would terminate on the subject terminate instead on the screening and the resultant 60-cycles-per-second currents are bled away to ground immediately rather than through the subject. The screening may take the form of a screened compartment in which the subject is located, or screening built into the walls of the room, or screened cables carrying the current from the wall plugs to any electrical devices near the subject, or screened compartments more or less completely enclosing such electrical devices. Grounding of all metallic objects near the subject also helps because every line of force that lands on these objects will then be eliminated as a source of interference. Occasionally the trouble can be cleared merely by reversing the A-C plug of some nearby electrical apparatus! This, of course,

# Contrails

redistributes the pattern of the electric lines of force so that a smaller number of them terminate on the subject.

Capacitive 60 may also be generated in the wires leading to the subject as well as in the subject himself. All of the means discussed in the paragraph above apply here too, but in addition to these, the problem of electrode resistance comes up. The impedance (or electrical resistance) to ground of each individual lead wire will in general be the sum of the resistance of that particular electrode plus the resistance of the ground electrode, since the resistance to ground inside the amplifier is usually very high compared to these other values. It is a general rule in all electrical work that the amount of capacitive interference picked up on a line is in direct proportion to the impedance of that line. Thus, the higher the impedance or resistance of a given electrode, the more 60 will be picked up by that particular electrode. It is for this reason that we emphasize throughout this work the attainment of lowest possible electrode resistances and ground resistances.

A third type of 60-cycle artifact should be discussed which has nothing to do with the connection to the subject and which might be called "instrumentation 60". This will be whatever 60-cycles-per-second output is inherent in the EMG itself, plus additional amounts of 60 arising from the connection to the EMG of other accessories, such as calibration devices, timers, etc. In those EMG machines which do not use any batteries, the changing of a tube in the preamplifier or some other such simple operation may introduce fairly large amounts of 60-cycle signal. In such machines, there is usually a control whereby this residual amount of 60 may be balanced out or at least minimized.

As for other types of "instrumentation 60", the main point to keep in mind here is to avoid duplicating ground connections between various machines. Wherever there are two paths to ground from an instrument, a so-called ground loop is formed. At first sight one might think that two grounds are better than one because of the lower net resistance between the device and ground, but this is a fallacy. Ground wires may at times carry significantly large currents with a resulting voltage drop along the wire. This voltage drop, to be sure, may be minute (one millivolt or less) but if a second ground wire is connected in parallel with the first one, it will share the current in



# Contrails

proportion to the conductances of the two wires and the small voltage drop will appear in the second wire as well as the first one. If this second wire happens to be part of the grid circuit of an amplifier, for example, then a considerable interfering signal may be introduced along with the desired signal.

This situation most commonly occurs in setups where shielded input cables and shielded output cables are used to connect various pieces of electrical equipment together. The tendency is to supply an independent ground to every piece of equipment, forgetting that the pieces of equipment are themselves tied together by means of the screens in the shielded cable. Thus, several ground loops may be introduced quite inadvertently. It should be realized that in most cases the shielding around a coaxial cable is intended to act only as an electrostatic shield, and for this purpose it performs its function just as well if it is grounded at only one end as if it is grounded at both ends. However, where the shield is also expected to act as a conductor, it must be connected to the instruments at both ends of the cable.

2. "EKG" artifact. The heart is probably the most powerful muscle in the body. It is not surprising, therefore, that it should generate very large muscle potentials. And the electrocardiographic complex which is the summation of these muscle potentials is always stronger because of the fact that many muscle bundles in the cardiac muscle contract synchronously. This powerful electrical complex is carried by the volume-conductor action of the body to the furthest extremities. Here again the general principles of spacing of electrodes, and proximity of electrodes to the heart itself, etc., apply so that, as in clinical electrocardiography, if electrodes are placed at widely separated points on the body, one gets fairly large electrocardiographic potentials of the common limb-lead variety. If an electrode is placed immediately over the heart itself, even larger potentials are picked up, so that the chest leads in electrocardiography usually give larger complexes than the limb leads.

By ordinary electrocardiographic standards, if two leads are placed on the same arm and a recording made from them, very little or no electrical



## Contrails

complex is picked up as compared with the magnitude customarily seen in electrocardiography. This is because, although the whole arm may carry a fairly large potential with respect to the other parts of the body, nearby points on the same arm generally rise and fall together electrically and the net voltage between the two neighbouring points is very small indeed. However, it is not nearly small enough from the electromyographer's point of view because recording from two leads on the same arm is precisely the situation in surface electromyography. One may be recording from two nearby electrodes over an arm muscle which is in a fairly quiescent state and may be giving out potentials of the order of 10 to 20 microvolts. At the same time, the EKG complex picked up between these two electrodes may be as high as 30 or 50 microvolts, and, therefore, represents a considerable nuisance from the point of view of reading the electromyogram.

It is difficult to lay down any hard and fast rule for the minimization of these artifactual EKG's. Experience would indicate, however, that keeping electrode resistances low, keeping electrode resistances equal in a given pair, keeping ground resistance low, and proper selection of a site for the ground electrode are all important factors. In general, locating the ground plate nearby the two active electrodes seems to help in the reduction of the EKG as compared with a more distant placement of the ground electrode. Bearing in mind that muscle potentials in general have a vectorial quality, the proper selection of the axial placement of the muscle electrodes, with respect to the arm, may give an optimal ratio of EMG to EKG. This axial arrangement of electrodes is extremely important in the region of the shoulder because in this area the EKG field strength is much stronger than on the arm and, in fact, it is almost impossible to take an EMG without any sign of the EKG present.

The clinical axis of the heart, too, is a factor in the production of this type of artifact. The normal heart with its slight degree of left axis deviation places the heart vector broadside to the left arm socket and pointing almost directly away from the right arm socket. This tends to make EKG artifact much worse on the left arm than on the right and, similarly, it is much worse on the left shoulder than on the right shoulder. The trunk, in general, presents a very difficult problem from the point of view of the electromyographer.

# Contrails

In almost all locations, the EKG potentials are so great as to make the detailed study of EMG's very difficult or impossible. Even using all the devices of choosing our axes carefully, keeping electrodes closely spaced, and choosing the site of the ground electrode very carefully we have been unsuccessful in getting absolutely clear records of trunk muscles.

3. "EEG" artifact. Although the ordinary electroencephalogram is best picked up from those parts of the head where the structures of the brain come closest to the surface, it should be realized that the EEG is transmitted to practically all parts of the head and can be picked up under certain circumstances from various parts of the face and from points fairly low on the neck. One should, therefore, be prepared to see a considerable amount of EEG coming through on those electromyograph channels which are recording potentials from facial, scalp, or neck muscles. The settings of the filters used for muscle recordings do tend to minimize the low frequency EEG (i.e., the alpha band) but do nothing to remove the higher frequency component of the EEG (i.e., the beta band). There is very little that can be done to improve this situation except to use the greatest care in selection of sites for the muscle electrodes. Of course, it is quite easy to distinguish visually between the alpha type of EEG artifact and muscle potentials, and even in the lower section of the beta band (i.e., frequencies from 14 to about 20 cycles-per-second), EEG artifact is not too difficult to distinguish from muscle potentials. The higher frequencies of the beta band, 20 to 30 cycles-per-second or even higher, are very difficult, indeed, to distinguish from muscle potentials and, in fact, Dr. H. H. Jasper, of the Montreal Neurological Institute, declares that in certain cases it is impossible to say whether the wave is an EEG or a muscle potential. Even where visual distinction between the artifact and the EMG is possible, it may cause considerable confusion when it comes to the actual measurement of the muscle potentials. There is definitely a need for further instrumentation research to be done on this particular problem.

4. "Eye-blink" artifact. The monophasic slow wave which accompanies the blinking of the eyes is a very familiar artifact to the electroencephalographer. It is seen most prominently in the pre-frontal, frontal, and

# Contrails

central leads and becomes smaller as one progresses towards the occiput. It is pretty well recognized that the eye-blink artifact is due to the retino-corneal potential and not just muscle potentials occurring in the muscles around the eyes. This retino-corneal potential is a more or less steady D-C voltage between the front and the back of each eyeball. This D-C potential causes no trouble in recordings even close to the eyes as long as the eyeballs remain in a fixed position, but any amount of roving or shifting of the gaze will produce transients and large slow waves in EEG or EMG recording from neighbouring areas due to the vectorial shift of this D-C potential. When the eyes are closed or blinked, the eyeballs roll in the upward direction, and it is this rolling of the eyeball which produces the eye-blink artifact.

Of course, if muscle potentials are being taken from a situation fairly close to the eye itself, then one would expect to see some muscle potential associated with the blinking of eyes as well as the so-called eye-blink artifact. The eye-blink artifact has an almost purely vertical axis on the forehead, so that purely horizontal muscle placements on the forehead should pick up very little eye-blink artifact.

5. "Pulsation" artifact. Occasionally one will see small, blunt artifacts appearing with and synchronous with the heart rate in electrode attachments to the neck, cheek, or arm. The complete absence of any spiky component gives the clue that this is not ordinary EKG artifact, and if one takes the trouble to record a true EKG at the same time, one will see that the little blunt artifacts occur after the QRS complex in each heart beat. The exact nature of this artifact is not explained at the present time but it is probable that it is a specialized form of movement artifact because it is practically never seen except in instances where the electrodes can be seen to pulsate with each pulsation of a nearby artery.

6. "GSR" artifact. The galvanic skin response or psychogalvanic reflex, as it is sometimes known, is a well known physiological response which can be picked up in many areas of the body, particularly those areas where sweating occurs. Briefly, it is a fairly rapid transient change with a slow recovery of the skin resistance and surface potential of the skin.

# Contrails

However, even with filters set to eliminate frequencies from D-C up to about 10 or 12 cycles-per-second, a distorted version of this response is sometimes seen. It is nearly always seen as a response to some sharp stimulus, but may occur spontaneously, too. The sharp onset of the response may actually block the EMG amplifiers, but the amplifiers usually recover within a fraction of a second; then the long, slow, swinging tail of the response is seen. It is not at all difficult to see the muscle potentials that you are recording superimposed on this slow wave, but it may be quite difficult to measure them because there is no steady base line to refer them to.

Other physiological artifacts occur as a result of swallowing, nervous tics and habit spasms, oculomotor tremor, and various forms of nystagmus, etc. The muscular spasm type simply produces showers or bursts of muscle potentials and the nystagmus type of artifact, which, of course, is due to the roving vector of the retino-corneal potential, may appear in the form of slow rhythmic waves of various frequencies.

7. "Electromechanical" artifact. Gross movement on the part of the subject, or any part of the subject, is usually accompanied by a relatively slow base line swing and, of course, superimposed on this there will usually be a burst of very large muscle potential. The slow wave component of this artifact is probably due to a transient upset in the field pattern of the D-C potentials of the skin which probably accompanies all muscular contractions. It may also be due, in part at least, to physical movement of the electrodes at their point of attachment. Sliding of the electrode over the surface of the skin, streaming of the electrode jelly, and slight distortion of the skin itself may all be factors in the production of this artifact. Finally, blocking or partial blocking or saturation of the amplifier itself may contribute a slow wave of this type. A rhythmic kind of movement artifact is often noted when one or more leads are allowed to swing or vibrate. Here, a slow wave, more or less synchronous with the swinging movement of the lead wire, may be observed, and it again is probably due to the slight movement of the electrode over the surface of the skin.

8. "Open circuit" artifact. This may be recognized as a particularly vicious deflection of the pen out to the limits imposed by saturation of the

amplifier or some other limiting device, and is usually followed by a fairly rapid recovery within a half second or so. The commonest cause of open circuit artifact is a loose electrode, i.e., one which makes and breaks contact with the skin with slight movements on the part of the subject. This is usually the result of improper application of the electrode jelly or improper fixation of the electrode attachment. Other causes for this same artifact are: corrosion of the electrode wire just at the point where the electrode is soldered to the wire, or corrosion or mechanical wear on the lead wire at the point where it is soldered to the pin which connects it to the electrode plug-in box.

## E. ARTIFACTS IN THE SECONDARY RECORD

Most of the artifacts which appear in the primary record (EMG) will, of course, cause erroneous readings in the secondary record (Integrated EMG) but most of these are impossible to detect in the secondary record without reference to the original EMG. This is the main reason why it is important to record the EMG and provide accurate timing marks on both records which enable the interpreter to correlate the two in the time dimension. It is necessary before scoring the secondary record for the experimenter to scan the primary record very carefully, marking all movement artifacts, EKG artifacts, and other interruptions to smooth recording. These markings are then transferred to the secondary record very carefully, channel by channel, so that the scorer will know which parts of the automatic integrator recording cannot be scored.

There is one special circumstance of an artifact in the primary record which does not interfere too greatly with the measurement of muscle potentials in the primary record, and that is the GSR type of artifact. The muscle spikes often come through very clearly even though the base line is swinging quite wildly due to the GSR phenomenon. However, when it comes to the secondary record, there is an entirely different picture. Even though special low frequency filters have been included to minimize the effect of swinging base lines, nonetheless, with very large slow waves the integrator

# Contrails

may actually integrate some of the area under the slow wave as well as that under the individual muscle potentials. It is therefore important to monitor very carefully those portions of the primary record which have large slow waves in them.

If the integrator has been properly calibrated and adjusted, there will be a small integrator output even when no signal is appearing on the primary record. This "zero signal" output is the result of the bias or threshold adjustment of the integrator and the amplitude should be as close to 0.5 mm as possible. The purpose of the adjustment is to compensate for the rather flat, non-linear portion of the diode rectifier curve (the signals, of course, are rectified by means of a diode before being integrated by the integrating condenser).

It should be possible to record from zero signal to full amplitude and back to zero signal again with the integrator recorder and have very little departure from a straight baseline. If the integrator galvanometer is not matched carefully to the integrator power amplifier some irregularity in the baseline will be observed. The actual controlling factor is the value of a condenser from grid to grid of the final integrator stage which has an electrical damping effect upon the galvanometer. If this condenser is not large enough the baseline will be seen to dip downwards during large amplitude deflections, and if the condenser is too large, then the galvanometer will not quite swing back to zero before the next deflection commences.

If the secondary record is run off at very high speed, then considerable detail in the shape of the individual integrator deflections can be observed. The fact that these curves [which represent the instantaneous charging action of each integrator condenser] are not perfectly triangular in shape is, of course, no accident. The actual shape of the charging curve will depend upon the type of signal being sent to the integrator. If, towards the beginning of an integrating period, a large burst of muscle potentials arrives, then the charge will rapidly increase. If there is then a relatively quiet period until the end of that integrating period, the charge curve will remain flat until that particular condenser is discharged. If the signal arrives at a fairly constant amplitude, then the integrating condenser will



# Contrails

charge at a constant rate and the wave will have a roughly triangular shape. In the case of calibration, where a sinusoidal signal of about 45 c.p.s. is used, each positive half cycle of the sign wave causes a burst of current to flow into the integrating condenser, and the resulting wave form will have a staircase appearance. None of these effects are artifactual, but truly represent the signal arriving at the integrator.

Since the integrator condensers are discharged at regular intervals, there will be a certain amount of "dead-time" during which the relays are closed. Whatever signal arrives at the integrator during the dead-time period will be short-circuited to ground. When the condensers are being discharged twice per second or at slower rates, this dead-time effect is not at all serious, being of the order of 5% or less, but at the integrating rate of ten per second the loss of information resulting from the dead-time period may be as high as 20% since the relays are closed for approximately .02 second. This effect explains a very interesting artifact which is seen during calibration only, while running the integrator at ten integrations per second. With a calibration frequency of 45 c.p.s. and a dead-time loss of 20% it can be seen that either four positive half waves or three positive half waves will arrive at the integrator during an integration period, depending upon the phasing of the calibration signal. And since the calibration signal is not synchronized with the integrator frequency, this phasing will be quite random and will vary with time. As a result, the amplitude output of the integrator will vary by as much as 30% from moment to moment. This gives the effect of a "beat frequency" or modulation of the output signal. This effect, of course, is not seen in the case of EMG's because of the much more random nature of the wave; however, the dead-time effect is still present and represents an actual loss of information.

## F. EQUALIZATION, CALIBRATION, AND OTHER DAILY ADJUSTMENTS

If all the sensitivity controls of the EMG are set to the same value, all the equalization controls are set to maximum, and a calibration signal is recorded, it will be noted that each channel has a different amplitude

# Controls

output. Now, if the gains are to be equalized, the controls of all channels but one will have to be turned down until all the channels with larger gain have been reduced to the level of the channel with the lowest gain. If a signal is then fed into all channels, it should appear identical at the outputs. This, however, would still not be very convenient from the point of view of measuring the record at a later date, since each millimeter of deflection would represent some odd number of microvolts.

A more useful procedure is to feed in, either from an external calibrator or from the internal calibrator provided with the instrument, a signal of known amplitude in microvolts and set all channels by means of the equalization controls to give equal outputs. Of course, the largest setting of gain sensitivity possible should be used in order not to have the equalization controls set too low. Our own procedure is to set all the sensitivity controls to the fourth position down from the highest sensitivity (this ensures that the random noise output is minimal and therefore will not interfere with the calibration procedure). We then feed in from an external calibrator a 50-microvolt peak-to-peak sinusoidal signal at 45 c.p.s. All equalization controls are then adjusted to give outputs on all channels of ten millimeters exactly. This gives a deflection sensitivity of five microvolts per millimeter all across the board. This calibration procedure is carried out after at least 30 minutes of warm-up time, immediately before the beginning of a test procedure, with all filters set for the optimal conditions for EMG recording, and with the chart drive running at the standard operation speed of 2.5 centimeters per second. If some of the channels are to be used for EEG recording, we use different filter settings and a frequency of about 20 c.p.s. for calibration.

The calibration of the integrator recorder is best carried out at the same time as the calibration of the EMG. The integrator factor settings will depend upon the rate of integration, the higher settings being used for the higher rates. The centering adjustment is made such that the galvanometers are deflected exactly 15 millimeters below dead center (the dead center is the point which divides the writing arc of the galvanometer pen symmetrically). Equalization gain controls are then adjusted to give deflections of exactly



20 millimeters when the deflections on the primary record are ten millimeters. The threshold or bias adjustments are then made to give deflections of 1/2 millimeter, with the signal from the EMG cut off. Since there is some interlock between the threshold adjustment and the equalizing gain adjustment, the deflections at full signal should be checked again.

Other adjustments which might have to be made daily are: alignment of all galvanometer pens on both chart drives in the time dimension and stopwatch checks or cathode ray synchronization checks of the rate of the integrator timer.

#### G. GETTING A FIRST-CLASS RECORDING

Once the equipment has been properly equalized and calibrated, and the test procedure is underway, the EMG and integrator operators must do their best to produce clean, well-labeled and complete records which are easy to interpret and measure. This requires the highest degree of alertness and coordination on the part of the operators, for all eight channels of continuously recorded data must be constantly scrutinized so that appropriate gain changes may be made as the levels of EMG amplitude change and so that the appearance of artifacts may be observed early enough to do something about them before a whole test record is spoiled (it is not desirable to stop a recording in the middle in order to deal with an artifact problem, but sometimes this is preferable to the complete loss of some important information in the latter half of a record). At the same time, the operators must observe in a general way what is going on in the test room itself so that any special remarks which might be of use in later interpretation can be written on the record as the events happen.

It cannot be overemphasized that adequate labeling of every record is of the utmost importance. At the beginning of the record there should appear the name of the subject, the date and any other pertinent information which applies to the particular test, and notes telling what each channel is recording. All gain changes made during the recording should be marked at

# Contrails

the time they are made. Whatever calibrations are made at the end of the recording should be very clearly marked and there should be additional notes describing any non-standard procedure or situation which occurred.

For best coordination of the operators and the examiner in the test room, all members of the team should be equipped with clearly written instruction sheets and time schedules. By using such aids it is often possible for the operator to anticipate sudden changes in amplitude of the muscle potential recordings so that gain changes may be introduced at opportune moments when they will not spoil the recording and, incidentally, saving many a galvanometer pen from breakage in cases where the commencement of a task would introduce suddenly very large muscle potentials.

Specimen calibrations need not be included at the beginning of a record because these are always made to a set specification, but it is very important that they be included at the end of every record. A rather liberal sampling of the various gains used during the recording and various microvolt levels of calibration signal should be included here simply for completeness so that where there is any doubt about the measurement of a particular portion of the record full information is available as to the calibration. Also, although every effort is made to keep the gain of these systems stable, the presence of the calibrations at the end of the record gives an additional opportunity to check that no change in the gain or sensitivity has occurred during the recording.

As soon as possible after the completion of the record, the operator and the examiner should get together to go over the primary recording and write down as much information as possible while the actual test is still fresh in the minds of both individuals. The examiner will have, in most cases, put through a number of special signals onto the recording to indicate special features of the test procedure which will be covered in his handwritten notations, and these should be transferred to the actual primary record as completely as possible. And, again, wherever these notations apply to gross movement on the part of the subject or any other event which might produce artifactual signals in the record, the information should be transferred over to the secondary record so that the integrated muscle potentials may be interpreted accordingly.

## H. MEASUREMENT OF THE RECORDS

The amount of information obtained in a continuous multi-channel recording during a test procedure or interview is very great indeed. So much data can be extracted from such a record that any attempt to extract all of the available information is bound to fail through the accumulation of too much detail. The problem of sorting statistically such a massive body of data then becomes almost impractical. In most cases, in order to reduce the number of individual measurements to be made, some system of sampling will have to be used and the sampling method of choice will depend entirely on the design of the experiment. In some cases random samples of the recording will be selected for measurement, in others each sample will be time-related to specific events in the test procedure, and in cases where the test procedure is not rigidly controlled the sampling will be determined by the course of events taking place during the procedure (for example, the subject matter of an interview may determine at which points samples will be measured).

The first step then is to mark off carefully in the time dimension those parts of the recording which are to be studied for amplitude and amplitude changes. In order to do this properly, timing marks signaled by the examiner during the test should give the required timing cues, but between such signal marks one must use the known paper speed in order to mark off appropriate time intervals. It should be noted here that the paper speeds given by the manufacturer of the chart drive are nominal only and any one instrument may have a slightly different paper speed than that indicated. For example, one of our chart drives runs four per cent higher in speed than it should and another one runs one-half per cent lower than indicated. For any particular machine it is fairly important to know what the error is, since over a 20- or 30-second period such error can represent several millimeters of record length. An easy way to determine the true paper speed is to make a recording from two electrodes which are not connected to a subject and will therefore pick up quite a large amount of 60 c.p.s. artifact. By setting the instrument to a fairly low gain and a rather high speed (at least 50 millimeters per second), a very good representation of the 60-cycle wave can be recorded.

# Contrails

In most good power systems the frequency is maintained constant to within about  $\pm 0.25\%$ . It is therefore a fairly safe procedure to use this power line frequency as a means of measuring out accurate time intervals.

In measuring the amplitude of either EMG signals or integrator outputs, one cannot assume that the instruments are absolutely linear. In other words, if the recorded amplitude of a signal suddenly doubles, it does not necessarily mean that the original signal in microvolts actually doubled. Most of these instruments are fairly linear, but there are special circumstances where the linearity is impaired. Some recording systems which have a lot of friction tend to respond rather sluggishly to very small signals (for example, those below one millimeter in amplitude). This represents a loss of amplitude out of proportion to the smallness of the signal and would show up as a non-linear portion of the curve giving microvolt input versus recorded amplitude output. Again, other instruments might respond very well to minute signals, but their sensitivity might fall off at the larger amplitudes. In fact, some instruments are built especially to have reduced sensitivity to very large signals in order that such large signals will not damage the ink-writing system. This again shows up as a non-linear portion or plateauing of the curve of microvolt input versus recorded amplitude output. In our research EMG, the response to varying amplitudes is almost perfectly linear to plus or minus 15 millimeters of deflection. Beyond this there is a very slight departure from linearity, but this is more due to the curvature of the ink-writing arc than anything else. At deflections of about 20 millimeters an internal protective device fires and the galvanometer refuses to respond to higher amplitudes. This, of course, represents a very sharp break in the amplitude response curve, but there is very little departure from linearity up to the point where this break occurs. In the case of the integrators the worst problem of non-linearity occurs at the very low amplitudes because of the fact that diode rectification is used in the integrator circuit, and diodes are inherently non-linear devices. The later circuits are arranged to reduce this non-linearity to a minimum, but it is still present. At the highest deflections, the integrator is apt to reproduce any non-linearity that exists in the EMG which feeds it simply because the signal is handed on from the one instrument to the other.

# Contrails

If these sources of non-linearity are recognized in developing a measurement technique, then the accuracy of the measurements need not suffer appreciably. For this reason, the particular form of the amplitude response curve (that is, output deflections plotted as ordinates against input signal values) should be known for each instrument used in this kind of work. In general, the curve will have approximately the same form in all channels of a multi-channel instrument but, where very accurate work is to be done, it is better to know the curve for each channel.

Where a relatively small number of amplitude measurements are to be made on a record, an ordinary millimeter scale may be used and these measurements may be converted into microvolts of signal by reference to the curves described above. However, if very large numbers of measurements are to be made, then the process of conversion from millimeters to microvolts may be avoided by constructing special transparent scales which are marked off in actual microvolts corresponding to the calibrations and gains used. In order to prevent confusion in making the measurements it is better to have a special scale made up for every setting of the main gain control so that wherever the scorer comes upon a gain change marked on the record, he simply picks up another scale corresponding to this new gain setting and continues reading off his deflections directly in microvolts. For any one record, of course, the scales used in scoring it should be checked against the calibrations at the end of the record to see whether the gain of the instrument remained constant throughout the test. It is assumed that the instrument starts off at the beginning of every test properly equalized and calibrated.

We have adopted the practice of drawing two vertical lines on our transparent scales corresponding to a time period of one second or two seconds at the paper speeds used in our work. If the horizontal lines on this scale extend from the one vertical line to the other, then the scale may be laid down over the record and used to estimate the average amplitude of the signal over the one or two second period. The same scale, of course, may be used to measure the peak amplitude of a given burst of muscle potential or to measure the highest spike in each fifth of a second (a technique used by R. C. Davis to good effect, and also used by this group in our early work). The two

# Contrails

vertical time lines are also convenient where it is desirable to measure or estimate the frequency of a given signal. This feature is particularly useful in the EEG field.

In the case of measurements on the secondary or integrator record, much the same technique is used, except that since the integrator deflections occur at regular time intervals the measurement of these deflections proceeds very rapidly. Usually the peak of each deflection is recorded and no attempt is made to get any more information from the record. Since the repetition rate of the integrator is variable, the actual number of deflections per second or per minute may be selected to fit the given experiment. In the special circumstance where the average integrator deflection over a very long period of time, such as two, five, or ten minutes is desired, the measurement of each deflection and calculation of a mean can be avoided by the following technique. A common planimeter is run from point to point along the peak deflections (i.e., along the envelope) and returned to the starting point along the baseline, giving an area which when divided by the length of the baseline gives the average height of the integrator deflections for that period. Planimeter measurement of the original EMG wave could also be done but, owing to the very complex form of the wave and the difficulty of deciding exactly where the envelope of the wave is, the accuracy of the technique is doubtful.

The reader will note that the scales used in scoring the integrator deflections are marked directly in microvolts (i.e., peak-to-peak microvolts in a sinusoidal calibration signal). Now, since the integrator measures the area between the waveform and the baseline, and not the peak amplitude, the unit of integrated output would actually be the volt-second, or microvolt-second. We do not attempt to analyze the EMG in terms of this rather cumbersome unit (which has little meaning physiologically), but assume that there is a constant relationship between the peak amplitude and the mean amplitude. The mean amplitude is, of course, proportional to the area in any given time period. Our assumption holds true for sinewaves but, of course, it is only roughly true for the muscle-potential wave. The imperfect correlation between peak and mean amplitudes of the EMG wave would not appear to introduce any serious error into findings based on integrated EMG measurements.



I. ROUTINE EQUIPMENT CHECKS

It need hardly be said that with equipment as elaborate as that used in this type of work the number of ways in which breakdown may occur are almost without limit. In order to avoid equipment failure at inopportune moments, and especially during actual tests, it is a wise plan to make routine checks of all instruments in order to try to anticipate trouble before it becomes serious. A program has already been outlined for maintenance of electrodes. A similar program should be set up for the maintenance and ordering of spares for the instruments.

At least three months' supply of recording paper and recording ink should be kept on hand at all times plus a liberal supply of ink remover, if any such exists for the kind of ink used. As for spare parts, this will depend greatly on the type of instruments used, but in general, the kind of parts which require replacement most often are: pens, calibration batteries, bias cells, other batteries (depending upon the particular manufacturer), specially selected vacuum tubes for the input stages of the preamplifier, vacuum tubes for the input stages of the main amplifier, output tubes, electrolytic condensers, wire-wound resistors, toggle switches, filter switches, rotary switches.

A useful logbook of the condition of a recording instrument may be kept by taking special records at approximately monthly intervals to show the following things: noise at maximum gain, microphonics at normal operating gain, a calibration at maximum gain to show the actual amplification, transient response to the D-C internal calibration at low gain, and transient response of the galvanometers in the open circuit condition by means of a deflection made by hand. By keeping this type of record on hand, gradually increasing noise or microphonics in a channel can be observed in time to replace a set of input tubes or make some other adjustment which will prevent the trouble from developing to the serious point. Similarly, a channel in which the overall maximum gain is gradually falling off can be watched and something done to improve the gain before it falls too low. The transient responses to the internal D-C calibration can be used to check the condition of all the filter settings and, in this way, a failing filter switch or

# Contrails

dirty contacts may be spotted early. Similarly, the open circuit response of the galvanometer to a hand deflection will show the resonant frequency of the galvanometer and its natural damping. An overdamped response to this deflection would indicate a shorted turn or some excess mechanical friction in the system and is a sign that the galvanometer needs replacement or repair.

At less frequent intervals, complete calibrations of the instrument should be performed. This will include overall frequency response curves for each channel and for each setting of the filter switches. It will also include linearity curves (recording of signals from zero to maximum deflection) for every channel and all the commonly used gain positions. In addition to checking the inherent linearity of the instrument, this last test also affords one the opportunity of checking the ratios of gain between the different positions on the gain control.

Along with the frequency response and linearity checks, a check of the rejection ratio should also be carried out for each channel of the instrument. This may be done in the following manner: a calibration signal of the usual frequency but much greater intensity, say 50 millivolts, should be connected between the ground terminal and one of the regular terminals on the electrode plug-in box. All the selector switches, that is both switches on each channel, should then be turned to that particular electrode terminal. This means that exactly the same signal goes to each grid of each amplifier. If the recorded output should then be equal to the recorded output from a 50-microvolt signal applied from the external calibrator in the usual way, then the rejection ratio is exactly one thousand. For higher rejection ratios the deflections will be smaller with this in-phase connection, and for lower rejection ratios the deflections will be higher than that for the standard 50 microvolt signal. When this rejection ratio falls below a thousand, help should be sought from the manufacturer or some qualified person to readjust the instrument for optimum rejection ratios.



*Contrails*  
REFERENCES

1. Davis, R. C. The muscular tension reflex and two of its modifying conditions. Indiana Univer. Publ. Sci. Ser., 1935, No. 3. (P. 9: Amplitude vs. frequency measurements in EMG).
2. Davis, R. C. Set and muscular tension. Indiana Univer. Publ. Sci. Ser., 1940, No. 10. (P. 12: Method of measuring peak amplitude per 0.2 seconds).
3. Lindsley, D. B. Handbook of experimental psychology (S. S. Stevens, Ed.). New York: Wiley, 1951. (P. 480: Surface leads preferred in emotional studies).
4. Malmo, R. B., & Shagass, C. Psychosomatic medicine, 1949, 11, Pp. 9-24. (P. 23, col. 2, para. 2: Previous neglect of striate motor function in studies of emotion).
5. Malmo, R. B., Shagass, C., & Davis, J. F. J. clin. exp. Psychopath., 1951, 12, Pp. 45-66. (P. 51, Fig. 1 and text: Validating experiments).
6. Beranek, L. J. acoust. Soc. Amer., 1946, 18, 140. (Description of anechoic room or free-field sound room).
7. Clarke, J. G. Differentiating and integrating circuits. Electronics, 1944, November, P. 138. (Basic circuits and equations for integration by electrical means).
8. Davis, J. F. Integrator-counter for muscle spike-potentials. M. Eng. Thesis, McGill Univer., Montreal, 1949. (Design procedure for manually operated integrator).
9. Davis, R. C. Integrator and accessory apparatus for recording action potentials. Amer. J. Psychol., 1948, 41, 100. (Balanced push-pull integrator circuit).
10. Freeman & Hoffman. Electrical integrator for action currents. Rev. Sci. Inst., 1940, 11, 283. (Integrator with minimum time duration of 15 seconds).

11. Hill, J. D. N., & Parr, G. Electroencephalography: a Symposium. London, Mcdonald, 1950. (P. 22: Chapter II by Walter, G., & Parr, G; Recording equipment and technique).
12. Jacobson, E. Integrating voltmeter for nerve and muscle potentials. Rev. Sci. Inst., 1940, 11, 415. (Use of ballistic galvanometer to measure condenser charge).
13. Martin, W. S., & Morton, H. S. Clinical studies with the EGG. A. M. A. Arch. Surg., 1952, 65, 382-396. (P. 384: Technique and electrode construction).
14. Offner, F. Push-pull resistance-coupled amplifiers. Rev. Sci. Inst., 1937, 8, 20. (Early description of the balanced differential amplifier).
15. Stevens, S. S. Rectilinear rectification applied to voltage and integration. Electronics, 1942, January, P. 40. (P. 41: Rectifying system of good linearity described).