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UNIPOLAR ELECTROCARDIOGRAPHIC LEADS

EFFECTS PRODUCED BY ELIMINATING THE RESISTORS BETWEEN THE LIMB ELECTRODES AND THE CENTRAL TERMINAL*

J. MARION BRYANT, M.D., FRANKLIN D. JOHNSTON, M.D., AND FRANK N. WILSON, M.D.
ANN ARBOR, MICH.

INTRODUCTION

IN 1934, Wilson, Johnston, Macleod, and Barker[1] described a method of obtaining electrocardiograms that represent the potential variations of a single electrode. In this method an exploring electrode is paired with a central terminal connected to electrodes on the right arm, left arm, and left leg through three equal noninductive resistances. It was recommended that these resistances be made large in comparison with the largest body-resistance in any of the three standard limb leads, and it was pointed out that they could be considered adequately large when the deflections in these leads were not significantly altered by connecting the central terminal to the limb electrodes. In the earliest experiments resistors of 25,000 ohms were employed, but these were later replaced by resistors of 5,000 ohms in order to reduce distortion of the tracings due to stray 60 cycle current.

In 1942, Goldberger[2] introduced a modification of this method in which the resistors between the central terminal and the limb electrodes are eliminated. In a series of cases he compared the deflections of the precordial and the unipolar

From the Department of Internal Medicine, University of Michigan Medical School.
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limb leads taken with a central terminal connected directly to these electrodes with those of the same leads taken in accordance with the original technique, and was not able to detect any significant difference between them. It may be mentioned incidentally that soon after unipolar precordial leads began to be used regularly in this laboratory, Dr. F. D. Johnston took a considerable number of tracings in the manner afterward advocated by Goldberger. Cursory examination of these records did not disclose any striking difference between them and those taken with resistors. At that time, however, it seemed advisable to adopt a single standard technique for taking precordial electrocardiograms, and it was felt that the use of resistors should not be given up until an exhaustive investigation had shown that they were unnecessary.

Goldberger's method has now come into widespread use, and it seemed desirable to have more exact information bearing upon the question as to whether the insertion of resistors in the arms of the central terminal serves any useful purpose. The potential variations of the precordium are large in comparison with those of the extremities and it is not to be expected that the presence or size of such resistors will have very conspicuous effects upon the amplitude or form of the larger deflections of the precordial electrocardiogram. Taking precordial tracings by both of the methods in question and comparing them did not, therefore, seem to us to be a particularly advantageous way of securing the data required. For this reason, as well as others, we adopted a different plan.

METHOD AND OBSERVATIONS

In a series of 500 consecutive routine electrocardiographic examinations, the electrode on the left arm was paired with a central terminal connected to electrodes on the right arm and left leg through equal resistances of 5,000 ohms. As soon as this lead had been taken, the electrodes on the right arm and left leg were connected together by means of a short length of copper wire with a clip on each end, and a second record was made. This technique made it possible to take the two records to be compared in quick succession and thus eliminate variations in "contact" or "skin" resistance, such as are likely to take place with the lapse of time. The records were taken by the electrocardiographic technicians in the course of their regular work and any conclusions based upon them are, therefore, applicable to routine clinical electrocardiograms.

In each of the 1,000 tracings the deflection produced by throwing 1.0 millivolt into the circuit and the amplitudes of the P,Q,R,S, and T deflections were measured to the nearest two-tenths of a millimeter. After appropriate corrections for errors in standardization had been made, the corresponding deflections of each pair of records were compared with the following results:

P Wave.—In twenty-nine instances (5.8 per cent) there was a conspicuous difference in the auricular complex between the records taken by the two different methods. In some instances the P wave was isoelectric in one tracing and upright or inverted in the other; in other instances this deflection was upright in one tracing and inverted in its fellow (Fig. 1, Tracings *1,2,3,9*, and *17*).

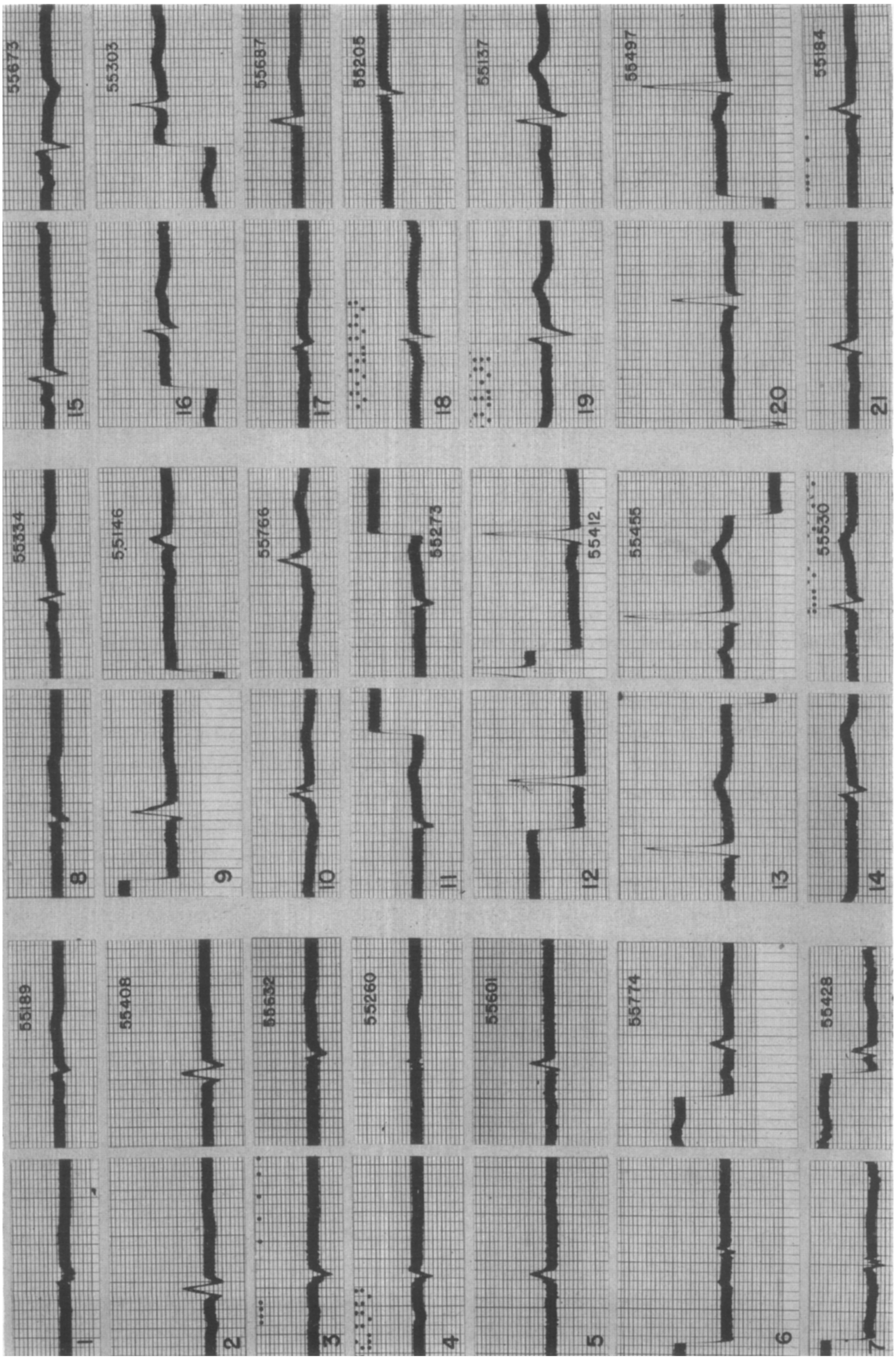

Fig. 1.—Leads from the left arm taken with a central terminal connected to electrodes on the right arm and left leg through resistances of 5,000 ohms. The first tracing of each pair was taken before, the second after, these electrodes were connected together by means of a short length of copper wire.

Q Wave.—This deflection was absent in one record and present in the other in eight instances (1.6 per cent). Tracings 3 through 6 of Fig. 1 show the most striking differences encountered.

R Wave.—A difference of 2 to 7 mm. in the height of the R deflection occurred in fifty cases (10 per cent). See Tracings 6 through 20 of Fig. 1.

S Wave.—This deflection was present in one tracing and absent in the other in five instances (1 per cent). See Tracings 16 and 17 of Fig. 1. In twenty-eight additional cases (5.6 per cent), it was at least twice as large in one record of the pair as in the other.

T Wave.—This component was upright in one tracing and inverted in the other or isoelectric in one tracing and not in the other in twelve cases (2.4 per cent). See Tracings 3, 4, 6, 20, and 21 of Fig. 1. In thirty-two additional cases (6.4 per cent), it was at least twice as large in one record as in the other.

DISCUSSION

These observations indicate that under conditions such as obtain in the taking of routine clinical records, a central terminal connected to the limb electrodes through large resistances may be expected to yield results significantly different from those obtained with a central terminal connected directly to these electrodes in about one case out of ten. Why should the elimination of the resistors in the arms of the central terminal have striking effects in some cases and not in others? Are the results of eliminating these resistors predictable? Is it possible to estimate the maximal change in the potential of the central terminal that this procedure can produce? We shall not undertake here to offer complete and final answers to these questions, but it seems desirable to call attention to some of the factors that have an important bearing upon them.

Connecting electrodes on the extremities to a central terminal completes circuits previously open and establishes currents which did not exist before. These currents are necessarily accompanied by a voltage drop across each of the circuit elements through which they flow. Among these circuit elements are the resistances in the arms of the central terminal, the resistances at the surfaces of the electrodes, the resistances of the areas of skin beneath the electrodes, and the resistances of the internal tissues of the extremities and of the trunk. If the electrodes are small in comparison with the magnitudes of the currents set up, the current densities over their surfaces will be large and the voltage drops at these surfaces and across the underlying skin may be significantly affected by polarization.[3]

It is evident, therefore, that the potentials of the limb electrodes before and their potentials after they are connected to the central terminal must always differ in some degree, and under some circumstances, may differ greatly and in an unpredictable manner. It is also clearly desirable that leads in which the central terminal serves as the reference electrode shall not be less trustworthy than the standard limb leads; that is to say, that the results which they yield shall not be dependent upon the personal equation of the person who uses them or upon purely extrinsic circumstances which he cannot take account of or modify.

Of the circuit elements mentioned, the resistances in the arms of the central terminal, at the surfaces of the electrodes, and in the skin are either completely or to a large extent under our control. Making the first as large as is practicable will reduce the currents set up by connecting the limb electrodes to the central terminal to their lowest possible values and thus greatly diminish the likelihood of significant polarization and the magnitude of the alterations in the potential differences inside the body and at its surface produced by this procedure. The limb electrodes should be relatively large also, for the densities of the currents through their surfaces and the underlying skin, and consequently the "contact" and skin resistances and the magnitude of any polarization that may occur, will vary inversely with their size. The skin resistances can be diminished by proper preparation of the skin, and the lower these resistances, the smaller the chance that they will be grossly unequal or constitute large fractions of the total resistances in the circuits of which they are a part.

The simple equations which express the potentials, V_R, V_L, and V_F, of the apices of Einthoven's triangle in terms of the deflections in the standard limb leads were originally based upon the conclusion that the sum of the potentials of these apices is zero for all positions of the electrical axis of the heart. This conclusion may or may not be valid. In either case, these equations give the potentials of the right arm, left arm, and left leg with respect to their mean as the reference level. Take for example the equation for the potential of the left leg in terms of the deflections in Leads II and III. We have

$$(1) \quad \frac{II + III}{3} = \frac{2V_F - V_R - V_L}{3} = V_F - \left(\frac{V_F + V_R + V_L}{3}\right)$$

The last expression is obtained from the second by first adding and then subtracting V_F.

What exactly do the expressions V_R, V_L, and V_F in these equations represent? That clearly depends upon what the deflections in the limb leads represent. It was shown long ago[4,5] that when the standard limb leads are properly taken one at a time in the usual way, the deflections recorded represent the potential differences between the limb electrodes that would have existed if they had not been attached to the terminals of the electrocardiograph. The principle upon which this surprising conclusion depends is one that was discovered by Helmholtz[6] as long ago as 1853. We conclude, therefore, that the symbols in question represent the potentials of the limb electrodes before they have been brought into contact with any conductor other than the body.

It is then clearly possible to compute the potentials of the limb electrodes with respect to their mean when the deflections in the limb leads are known. The values so obtained may be considered the potentials of these electrodes with respect to an "ideal" central terminal joined to them by infinite resistances. It is also possible, by a procedure analagous to that devised by Einthoven, Bergansius, and Bijtel[4] for another purpose, to construct a central terminal which will have the same potential as an "ideal" terminal of this kind. They showed that by employing three string galvanometers it is possible to take the three limb leads simultaneously and still obtain accurately standardized records, provided that the resistances in the three circuits are equalized and the sensitivities of the three galvanometers are properly standardized.

We can in the same way adjust the value of the resistances in the three arms of the central terminal in such a way as to make the total resistances in the circuits which include the body equal. The procedure required is the same as that employed by Einthoven and his associates[4] and the example discussed by them is equally suitable for the present purpose. Fig. 2 is reproduced from their paper. The measured body resistances in Leads I, II, and III are given as a, $a + p$, and $a + p + q$, respectively. It is required to determine x, the resistance that must be attached to the right arm electrode, and the resistance y that must be attached to the left arm electrode in order to equalize the resistances in the three limb leads. If we represent the resistances associated with the contacts on the right arm, left arm, and left leg by R_r, R_l, and R_f, respectively, the equalized resistances in three leads will be represented by the following equation:

$$(2) \quad R_r + R_l = a + x + y = R_r + R_f = a + p + x = R_l + R_f = a + p + q + y$$

Solving for x and y, we get x equals $p + q$ and y equals p.

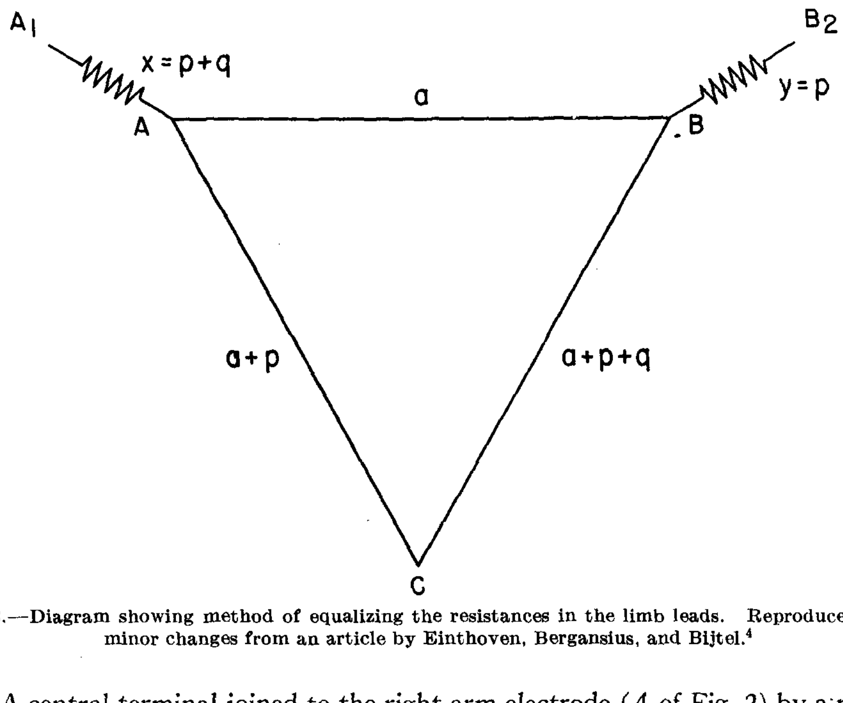

Fig. 2.—Diagram showing method of equalizing the resistances in the limb leads. Reproduced with minor changes from an article by Einthoven, Bergansius, and Bijtel.[4]

A central terminal joined to the right arm electrode (A of Fig. 2) by a resistance R plus x, to the left arm electrode (B) by a resistance R plus y, and to the left leg electrode (C) by a resistance R, will be separated from the points labeled A_1, B_2, and C in Fig. 2 by equal resistances of R ohms. The total resistances in the circuits of which these equal resistances are corresponding elements are equal. Each of the three potential differences between the central terminal and the points A_1, B_2, and C is proportional to, and represents the same fraction of, the total drop in voltage, or electromotive force, in the circuit to which it belongs. The relations which these statements express are not dependent upon the magnitude of the equal resistances of R ohms. If these resistances are increased step by step, the fraction of the total drop in voltage in each of the circuits corresponding to the potential differences specified will become larger and larger. The limits approached by these potential differences as the value of R becomes infinite are clearly the potentials of the limb electrodes (with respect to their mean) before they were connected to the central terminal. It is easily shown, however, that under the circumstances postulated, the potential of the central terminal is not altered by changing the size of the equal resistors between it and the points A_1, B_2, and C. The sum of the voltage drops across these equal resistors is zero and their relative magnitudes are constant. For very large values of the resistors we have, therefore,

$$(3)\quad (V_R - V_T) + (V_L - V_T) + (V_F - V_T) = 0 \qquad V_T = \frac{V_R + V_L + V_F}{3}$$

For any other value of the resistors, we have

$$(4)\quad K(V_R - V_T) + K(V_L - V_T) + K(V_F - V_T) = 0 \qquad V_T = \frac{V_R + V_L + V_F}{3}$$

where K is a fraction equal to R divided by the total resistance in each of the circuits of which the three resistors of R ohms are corresponding elements.

The various circuit elements involved in problems of the kind under consideration are shown diagrammatically in Fig. 3. In this figure E_1, E_2, and E_3

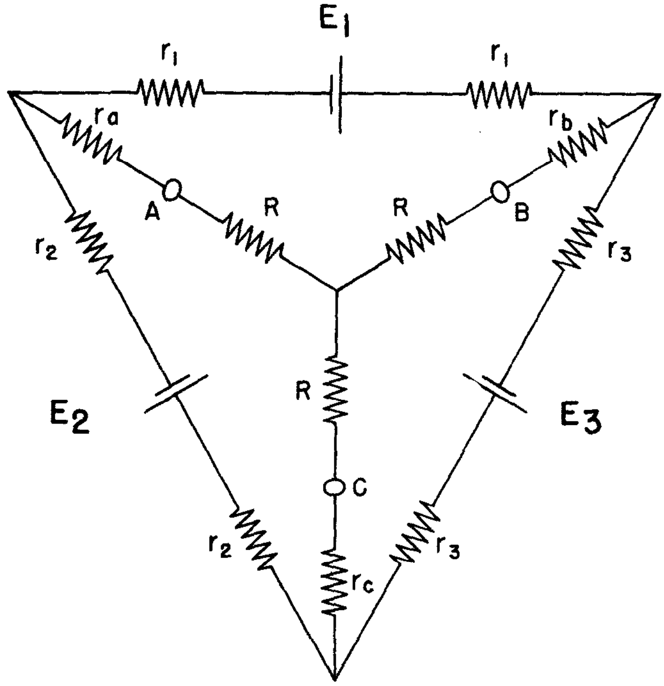

Fig. 3.—Diagram showing the circuit elements of the circuits established by connection of the limb electrodes to a central terminal. See text.

represent the open circuit voltages in the three limb leads, and the small circles (A, B, and C) are the limb electrodes. The body resistances are divided into two fractions. The resistances, across which there is a flow of current only when the limb electrodes are connected one to another by an external conductor, are indicated by the symbols r_a, r_b, and r_c. The other body resistances are labeled r_1, r_2, and r_3. The letter R refers to the equal resistances in the arms of the central terminal. The resistances, r_1, r_2, and r_3, of the tissues of the trunk and those parts of the extremities adjacent to the trunk, through which there is a flow of current before the limb electrodes are joined to any external conductor, are presumably small and approximately equal. On the other hand, the "contact" and skin resistances, which constitute the greater part of r_a, r_b, and r_c, are probably relatively large and frequently unequal.[3]

The following conclusions require no further explanation. When the differences in magnitude between the resistances in the limb leads are small in comparison with R, the potential of the central terminal is the mean of the open circuit potentials of the limb electrodes. When the resistances R are large in comparison with the resistances in the limb leads, the deflections of the leads from the central terminal to the limb electrodes represent the open circuit potentials of these electrodes with respect to their mean. When the resistances R are not large and one of the resistances r_a, r_b, and r_c is much smaller than the other two, the potential of the central terminal will fluctuate in unison with that of the corresponding limb electrode unless the potential variations of this electrode happen to be small in comparison to those of its fellows. When R is not large in comparison with the resistances in the limb leads and r_a, r_b, and r_c are equal, the voltage drops across the resistances R will represent only a fraction of the open circuit potentials of the limb electrodes.

When the value of R is zero, all of the limb electrodes are at the same potential. If the resistances in the limb leads are equal, this potential will be the mean of the open circuit potentials of these electrodes. If r_a, r_b, and r_c are unequal, the potential of the short-circuited limb electrodes will reflect the potential fluctuations of the limb electrode corresponding to the smallest of these resistances. If a central terminal directly connected to the limb electrodes is paired with an exploring electrode, and this electrode is placed on one of the extremities distal to the electrode which is connected to the central terminal, the record obtained will represent the fluctuations of the voltage drop across the skin under the latter. This voltage drop will be proportional to the open circuit potential of the extremity only in case the resistances in the limb leads are precisely equal.

When the resistances R are so large in comparison with the resistances in the limb leads that the voltage drops in the arms of the central terminal are approximately equal to the open circuit potentials of the limb electrodes with respect to their mean, the augmented unipolar limb leads introduced by Goldberger will yield deflections of the same form as, but 50 per cent larger than, the deflections of the corresponding unaugmented leads. This is obviously not the case when R is small, for then the unaugmented leads will record only a small and the augmented leads a large fraction of the open circuit potential variations of the limb electrodes. When R is zero, the unaugmented leads record nothing. When augmented unipolar leads are taken with a central terminal connected directly to two limb electrodes (R zero), the results are likely to be greatly influenced by the relative magnitude of the two skin resistances involved. The potential of the central terminal, under these circumstances, will not be the mean of the open circuit potentials of the limbs to which it is attached unless these skin resistances are equal.

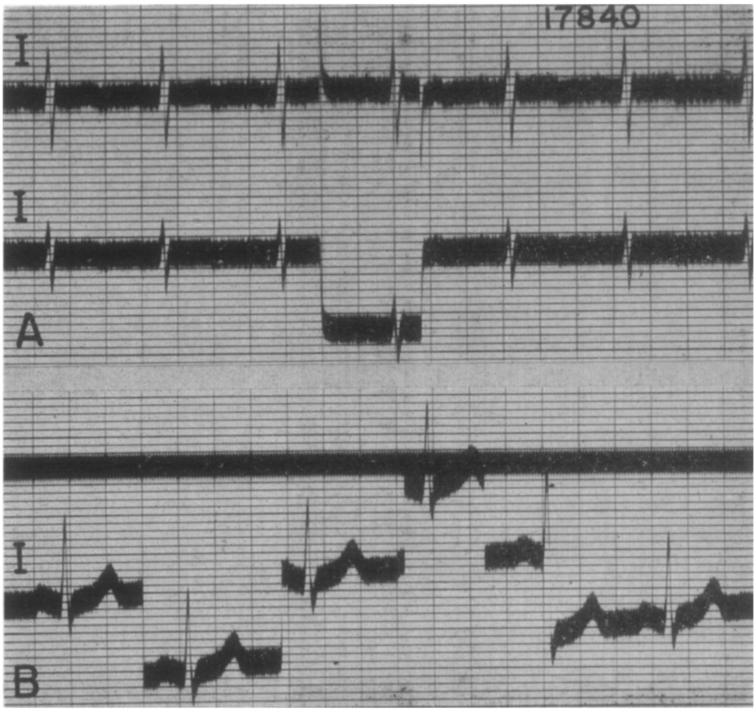

Fig. 4.—*A*, Lead II taken simultaneously with two string galvanometers from a single pair of needle electrodes in the subject's right arm and left leg. The upper record was taken without and the lower record with a single-stage direct current vacuum tube amplifier in the circuit.

B, Record taken with the galvanometer, having the vacuum tube in the circuit, after the other galvanometer had been disconnected from the electrodes.

It may be worth while to give an illustration of the effect on the form of the electrocardiogram produced by polarization in a circuit of relatively low resistance. The tracings shown in Fig. 4 were obtained in the following way. Small steel needles thrust through the skin of the two arms were substituted for the usual limb electrodes and two records of Lead I were taken simultaneously with two coupled string galvanometers. The same electrodes were connected to both galvanometers; to *one* in the usual way and to the other through a single-stage direct current amplifier.[1] The external resistance in the first circuit was then the relatively low resistance of the galvanometer string (about 2,000 ohms), whereas that in the second circuit was the extremely high input resistance of a vacuum tube. When 1.0 millivolt was thrown into the two circuits, they behaved very differently; the high-resistance circuit yielded a sustained deflection of approximately 1.0 cm. (Fig. 4,*A*). The low-resistance circuit, however, displayed a sharp upward deflection of short duration when the test voltage was thrown in and a similar downward deflection when it was thrown out. On the other hand, the deflections of the two electrocardiographic tracings are identical in form, although different in size. After this record had been taken, the low-resistance circuit was broken and it will be noted that the effect upon the tracing obtained with the high-resistance circuit was profound (Fig. 4,*B*).

We have no evidence bearing on the question as to whether polarization does or does not commonly occur in the low-resistance circuits established when the central terminal is connected directly to the limb electrodes. Nor do we know whether the effects produced by short-circuiting the right arm and left leg electrodes, which are illustrated in Fig. 1, were due chiefly to polarization or chiefly to inequalities of the skin resistances involved. It should be noted that when the standard limb leads are taken with a low-resistance electrocardiograph, the presence of polarization can be easily recognized by the effect which it has upon the deflection produced when a standardizing voltage is thrown into the circuit (Fig. 4). On the other hand, polarization resulting from the flow of current set up by connecting the central terminal to the limb electrodes cannot be easily detected. Polarization arising in this way will distort the tracings obtained through its effect upon the potential of the central terminal; it will not distort the deflection produced by throwing a test voltage into the galvanometer circuit while taking a lead from the central terminal to some other point. It seems essential, therefore, that the resistances in arms of the central terminal be large. Einthoven and Bijtel,[3] who made an exhaustive study of the resistance, electrostatic capacity, and polarization capacity of the skin and their effects upon records taken with the string galvanometer, expressed the opinion that when the external resistance in the galvanometer circuit was 10,000 ohms or more the tracings obtained would not be significantly distorted, provided that the skin resistance had been reduced by the use of 20 per cent sodium chloride solution. At that time the electrodes commonly used were of the immersion type.

CONCLUSIONS

The potential of a central terminal connected to the limb electrodes through resistors of 5,000 ohms and the potential of a central terminal connected directly to these electrodes without intervening resistors may be expected to differ significantly in about one case out of ten.

The resistances in the arms of the central terminal should be large in comparison with the body resistances in the limb leads.

When the resistances in the arms of the central terminal are eliminated, its potential is determined by the relative magnitudes of the resistances of the areas of skin underlying the electrodes to which it is attached and possibly, to some extent, by the effects of polarization.

APPENDIX

A. The Currents in the Arms of the Central Terminal.—

Let i_1, i_2, and i_3 represent the counterclockwise currents in the three loops of the network shown in Fig. 3, containing the resistances r_1, r_2, and r_3, respectively. By Kirchhoff's voltage law we have then the three equations:

$$r_1 i_1 + R_b(i_1 - i_3) + R_a(i_1 - i_2) = E_1$$
$$r_2 i_2 + R_a(i_2 - i_1) + R_c(i_2 - i_3) = -E_2$$
$$r_3 i_3 + R_c(i_3 - i_2) + R_b(i_3 - i_1) = E_3$$

The symbols R_a, R_b, and R_c are here used to represent $(r_a + R)$, $(r_b + R)$, and $(r_c + R)$, respectively. These three equations can be solved for i_1, i_2, and i_3. The expressions for i_a, i_b, and i_c, the currents flowing toward the central terminal through its three branches, may then be computed by means of the relations; i_a equals i_2 minus i_1; i_b equals i_1 minus i_3; and i_c equals i_3 minus i_2.

In this way we obtain

$$i_c = \frac{[r_1 r_3 + (r_1 + r_2 + r_3)R_b]E_2 + [r_1 r_2 + (r_1 + r_2 + r_3)R_a]E_3}{r_1 r_2 r_3 + r_1 r_2(R_b + R_c) + r_1 r_3(R_a + R_c) + r_2 r_3(R_a + R_b)\ (r_1 + r_2 + r_3)(R_a R_b + R_a R_c + R_b R_c)}$$

For i_a and i_b, the denominator is the same and the numerators are, respectively:

$$-[r_2 r_3 + (r_1 + r_2 + r_3)R_c]E_1 - [r_1 r_3 + (r_1 + r_2 + r_3)R_b]E_2 \text{ and}$$
$$[r_2 r_3 + (r_1 + r_2 + r_3)R_c]E_1 - [r_1 r_2 + (r_1 + r_2 + r_3)R_a]E_3.$$

When the resistances r_2 and r_3 are equal to r_1, the expression toward the central terminal from the leg electrode is

$$i_c = \frac{(r_1 + 3R_b)E_2 + (r_1 + 3R_a)E_3}{(r_1)^2 + 2r_1(R_a + R_b + R_c) + 3(R_a R_b + R_a R_c + R_b R_c)}$$

and when, in addition, the resistances R_a and R_b are equal to R_c, we have $i_c = \dfrac{E_2 + E_3}{r_1 + 3R_c}$

B. The Potential of the Central Terminal.—

When the resistances R_a, R_b, and R_c are equal, the potential of the central terminal is the mean of the potentials of the three extremity electrodes:

$$V_T = (1/3)(V_R + V_L + V_F)$$

When these resistances are unequal, the potential of the central terminal V_T' may be obtained as follows:

We have the equations:

$$(1/R_a)(V_R - V_T') = i_a$$
$$(1/R_b)(V_L - V_T') = i_b$$
$$(1/R_c)(V_F - V_T') = i_c$$

By Kirchhoff's current law the sum of the currents i_a, i_b, and i_c is zero. Consequently,

$$V_T' = \frac{R_b R_c V_R + R_a R_c V_L + R_a R_b R_F}{R_a R_b + R_a R_c + R_b R_c}$$

and

$$V_T' - V_T = \frac{R_b R_c V_R + R_a R_c V_L + R_a R_b V_F}{R_a R_b + R_a R_c + R_b R_c} - \frac{V_R + V_L + V_F}{3}$$

or

$$V_T' - V_T = \frac{R_b R_c(V_R - V_T) + R_a R_c(V_L - V_T) + R_a R_b(V_F - V_T)}{R_a R_b + R_a R_c + R_b R_c}$$

This last equation gives the difference in potential between the central terminal when the resistances are unequal and the central terminal when the resistances are equal in terms of the unequal resistances and the open circuit potentials of the limb electrodes with respect to their mean potential.

When R_b and R_c are equal, but R_a has a different value, we have

$$V_T' - V_T = \frac{R_b(V_R - V_T) + R_a(V_L - V_T) + R_a(V_F - V_T)}{2R_a + R_b}$$

and since $(V_R - V_T) = -(V_L - V_T) - (V_F - V_T)$, this gives

$$V_T' - V_T = \frac{(R_b - R_a)\ (V_R - V_T)}{2R_a + R_b}$$

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