Computer Search for Electrocardiographic Lead Directions to Optimize Diagnostic Differentiation

A Novel Concept in Electrocardiographic Lead Design

By CHARLES D. BATCHLOR, M.S., ALAN S. BERSON, M.S., I. ALZONA NAVAL, M.D., and HUBERT V. PIPBERGER, M.D.

SUMMARY

A computer was programmed to search for electrocardiographic lead directions, yielding optimal separations between records obtained from 500 normal subjects and 422 patients believed to have either left ventricular hypertrophy (LVH) or right ventricular hypertrophy (RVH). The majority of the patients with RVH (86%) exhibited chronic pulmonary disease with severe pulmonary insufficiency where development of chronic cor pulmonale was assumed. Autopsy confirmation of RVH or LVH was obtained in 38 cases. The diagnoses in the remainder were based on history and physical findings.

Resolved leads derived from a corrected orthogonal system were tested for discrimination of the three groups. The number of false-positive and false-negative classifications was kept approximately equal. To simplify record analysis, the number of QRS measurements necessary for interpretation was limited to a single one.

The optimal lead direction to separate normal records from those obtained in patients with LVH had an azimuth angle of 306° and an elevation angle of −58°. The lead for separation of cases of RVH was almost identical with horizontal lead X. Comparison between results obtained with optimized leads and 12-lead records showed approximately equal performance for LVH when sensitivity and specificity were kept the same. These results were based on up to eight measurements from 12 leads as compared to one measurement in a single lead.

The diagnostic performance of optimized leads exceeded that of the 12-lead electrocardiogram when a set of the most commonly used criteria for LVH and RVH recognition was used.

A simple analog device for obtaining optimal leads was designed which can be attached to conventional single-channel electrocardiographs.

The feasibility of directional lead optimization by orthogonal lead resolution could be demonstrated with concomitant simplification of record analysis and greater ease in record taking.

Additional Indexing Words:
Resolved orthogonal leads ECG lead resolver Ventricular hypertrophy
ECG classification ECG lead direction Computer optimization

DIGITAL COMPUTERS have been used successfully for some years for processing and analyzing both orthogonal¹ and conventional 12-lead electrocardiograms.² Since relatively extensive data handling facilities are required for this task, applications will probably be limited to larger medical centers in the foreseeable future. The question must arise,

From the Veterans Administration Research Center for Cardiovascular Data Processing, and the Department of Medicine, Georgetown University, School of Medicine, Washington, District of Columbia.

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therefore, whether new knowledge gained from computer analysis of large record samples, together with the relative ease of machine testing of a variety of different types of analyses, could not be used with advantage to enhance presently used techniques of ECG recording.

Since both computational facilities and a large taped ECG record library were available at this laboratory, a computer program was developed for determining ECG lead directions which would optimally separate diagnostic entities. The following constraints were set for this task: (1) Records should be easily obtainable from direct-writing electrocardiographs which are almost universally available. (2) Any required modifications of these electrocardiographs should be kept to a minimum. (3) Measurements from recorded ECG leads should be as simple as possible and kept within the limits of accuracy of visual resolution. (4) The separation of diagnostic record samples by the new leads should be based on an equal-error distribution, that is, the number of false-positive and false-negative classifications should be the same.

To test the feasibility of this new lead search and to demonstrate the usefulness of this new tool, 500 orthogonal ECG records from normal subjects and 422 records from patients with left or right ventricular hypertrophy were selected for the study. These diagnostic entities are the most difficult to separate both electrocardiographically and anatomically because the transition from normal to hypertrophied hearts is naturally a gradual one. A sizable overlap between these groups will, therefore, always persist.

In the past, electrocardiographic lead axes have been selected on the basis of anatomic or geometric considerations or on both. To base the choice of leads on optimal statistical separation of ECG findings represents, therefore, a substantial conceptual departure from past practice. If this approach proves feasible and economical, the total number of leads necessary could be decreased considerably since only one lead is required to separate two diagnostic entities, for example, left ventricular hypertrophy from normal, or right ventricular hypertrophy from high posterior infarction, and so forth. The technique of lead resolution of orthogonal leads was considered most practical for obtaining leads in any desired direction. Only minor modifications of a conventional single-channel electrocardiograph are required for selecting such special lead directions without the need of relocating electrodes on the patient.

Methods

Records used in the present study were taken from a magnetic tape library of corrected orthogonal ECG leads. The Frank lead system was used, with chest electrodes at the horizontal level of the junction between the fourth intercostal space and the sternum. Analog-to-digital data conversion and details of computer analysis of orthogonal electrocardiograms have previously been described in detail. A digital computer (Control Data Corporation 3200) was available for the study.

The sample of 500 normal records obtained from subjects without past or present evidence of cardiovascular disease has previously been described in detail. A second sample of 323 records was considered to be representative of patients with left ventricular hypertrophy.

Table 1

<table>
<thead>
<tr>
<th>Clinical and Pathological Diagnoses of Patients Whose Records Were Used for Determining Special LVH and RVH Leads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis</td>
</tr>
<tr>
<td>Left ventricular hypertrophy</td>
</tr>
<tr>
<td>Hypertensive cardiovascular disease</td>
</tr>
<tr>
<td>Arteriosclerotic heart disease</td>
</tr>
<tr>
<td>Aortic stenosis and/or insufficiency</td>
</tr>
<tr>
<td>Mitral insufficiency</td>
</tr>
<tr>
<td>Primary myocardial disease</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>LVH confirmed by autopsy</td>
</tr>
<tr>
<td>Right ventricular hypertrophy</td>
</tr>
<tr>
<td>Pulmonary emphysema and other chronic pulmonary diseases</td>
</tr>
<tr>
<td>Mitral stenosis</td>
</tr>
<tr>
<td>Ventricular septal defect</td>
</tr>
<tr>
<td>Atrial septal defect</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>RVH confirmed by autopsy</td>
</tr>
</tbody>
</table>
Table 2
QRS Criteria Used for Twelve-Lead Electrocardiograms for Comparison of Performance with the Special Leads

<table>
<thead>
<tr>
<th>QRS criteria for LVH</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum of S in lead V1 and R in V5 or V6 greater than 3.5 mv⁹</td>
<td></td>
</tr>
<tr>
<td>2. R in lead V5 or V6 greater than 2.5 mv⁹</td>
<td></td>
</tr>
<tr>
<td>3. R in lead I, II, III or aVF greater than 2.0 mv¹⁰</td>
<td></td>
</tr>
<tr>
<td>4. R in lead aV1 greater than 1.2 mv¹¹</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>QRS criteria for RVH</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. R/S ratio in lead V6 less than or equal to 1¹²</td>
<td></td>
</tr>
<tr>
<td>2. R/S ratio in lead V1 greater than or equal to 1¹²</td>
<td></td>
</tr>
</tbody>
</table>

(LVH). They were selected on the basis of the clinical diagnosis, made in the Medical Service of this hospital (table 1). A cardiac history of at least 1-year duration was made a prerequisite for inclusion in the LVH group. Cases in which more than one episode of congestive heart failure had occurred were excluded because in such cases biventricular hypertrophy was almost invariably found at autopsy. Of nearly 500 autopsied cases on file in this laboratory only 22 showed pure LVH. These were included in the study. All cases in which the 12-lead electrocardiogram suggested the presence of an old myocardial infarct, based on classification 1, 1 of the Minnesota Code⁵ were excluded. This was done in order to keep samples uniform, as far as this is possible on the basis of clinical findings. Separate studies to differentiate LVH and RVH from myocardial infarction will have to follow the present feasibility study. To test the effectiveness of the new lead for LVH recognition, an additional sample was selected randomly from patients followed in the Antihypertension Clinic of this hospital.

Records from 99 patients with right ventricular hypertrophy (RVH) were selected on the basis of similar criteria. Due to the limited availability of patients with congenital or rheumatic heart disease in Veteran Administration Hospitals, this material consisted primarily of patients with chronic cor pulmonale due to chronic pulmonary disease persisting for many years (table 1).

In the great majority of cases, conventional 12-lead electrocardiograms were available and were used for comparison with the new leads. The LVH and RVH criteria used for diagnoses are given in table 2. Patients with more than one episode of congestive heart failure and ECG findings of myocardial infarct were also excluded for the same reasons given for LVH. Autopsies were available in 16% of the cases confirming the clinical diagnosis of chronic cor pulmonale. In addition to the commonly used LVH criteria listed, an approximation of an equal-error classification was also obtained for conventional leads by equalizing false-positive and false-negative findings in the LVH sample and a group of 149 normals, selected according to criteria described previously. When one or more measurements exceeded the listed limits, the record was classified as LVH or RVH.

To obtain an initial estimate of optimal lead directions to separate the group samples under study, mean instantaneous vectors of time-normalized QRS complexes were computed for each group and plotted in vectorcardiographic (VCG) projection planes (fig. 1). These plots were also

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**Figure 1**

Vectorcardiographic plane projections of average QRS vector loops for three diagnostic categories. QRS durations were divided into eight equal parts, and an instantaneous vector was obtained for each eighth. Subsequently, a mean of these time-normalized vectors was computed for each group and plotted in the three planes. Rotations of the normal and RVH groups in the frontal plane are clockwise, whereas the LVH group forms a narrow figure eight. Rotations of all groups in the left sagittal and transverse planes are counterclockwise.
useful in selecting ECG measurements which might be most suitable and practical for record classification. The LVH group differed from normal most conspicuously by increased voltage in leftward posterior direction with a concomitant voltage decrease in anterior and rightward direction. The QRS complex showed a simultaneous increase in elevation. In order to derive maximum information to be contained in one simple scalar measurement, it was decided to test the Q/R ratio of a lead extending from the right anterior to the left posterior quadrant. It was hoped that this ratio would provide an indicator for both of the observed voltage changes.

The most conspicuous differences between normal and RVH records consisted in a QRS shift from left to right. The R/S ratio of a lead in an approximately left to right direction appeared most promising for separating these groups. Voltage ratios rather than single voltage measurements were also selected for RVH because they contained information of more than one ECG change. They can be measured easily and may even be estimated in most cases without appreciable loss of accuracy. The two lead directions for discriminating the normal from LVH and RVH were based exclusively on QRS criteria. As shown below ("Results"), T and S-T abnormalities were well represented for LVH in the RVH lead and vice versa, thus eliminating the need for additional leads.

Computation of test leads for diagnostic discrimination was accomplished as follows:

The ECG vector \( \mathbf{V} \) with orthogonal components \((X, Y, Z)\) is represented in a polar coordinate system by \(M, \theta, \phi\) where \(\theta\) is called the "azimuth angle," \(\phi\) the "elevation angle," and \(M\) the "vector magnitude." Azimuth is measured in the \(X, Z\) plane, clockwise from the \(+X\) axis; elevation is measured in the plane containing the vector and the \(Y\) axis; it is positive toward \(+Y\) and negative toward \(-Y\). The rectangular and polar coordinates are related by the expressions: \(X = M \cos \phi \cos \theta\); \(Y = M \sin \phi\); \(Z = -M \cos \phi \sin \theta\).

Defining \(u\) as a unit vector with arbitrary, fixed azimuth and elevation angles \((\theta, \phi)\), the projection \(\xi\) of \(\mathbf{V}\) upon the line directed along \(u\) is given by

\[ \xi = u \cdot \mathbf{V} \]

Since an ECG vector loop is approximated by the aggregate of vectors \(\mathbf{V}\) sampled at suitably chosen time intervals over the complex, a lead, in a selected \(\theta, \phi\) direction, is approximated by the corresponding set of projections \(\xi\). This computed lead simulates the output which might have been obtained directly by placing the properly chosen resistances in the voltage dividing networks used between the electrodes and the recorder. This principle was used in a computing scheme in which the initial estimates of the optimal lead azimuth and elevations were varied systematically over preselected zones, at equal angular intervals. For each lead direction (angle pair \(\theta, \phi\)), the measurements (R/S ratios, Q/R ratios, or T-wave amplitudes) were averaged separately over the groups being considered. These group means, with their corresponding variances and gross frequency distributions, were used to compare the relative discriminating effects of the leads.

The initial estimates of the threshold values, for equalizing positive and negative errors, were made by assuming the measurements to be normally distributed by groups; hence if \(\mu_1\) and \(\mu_2\) are the estimates of two group means, and \(\sigma_1^2\) and \(\sigma_2^2\) their respective variances, then the initial estimate of the required threshold, \(\varepsilon_0\), satisfies the relation:

\[ \frac{\varepsilon_0 - \mu_2}{\sigma_2} = \frac{\mu_1 - \varepsilon_0}{\sigma_1} \]

\[ \int F(X) dX = \int F(X) dX, \]

where the function \(F\) is the normal distribution function for a variable of zero mean and unit variance. Threshold values established by this
method generally required less adjustment than those selected by more arbitrary means.

Results

The normal and LVH groups were used to test 1,251 computed leads. Since the LVH group contained 323 ECG records, about half were used in the lead search and the remainder provided a means of checking the stability of the results. An initial set of 684 leads, spaced at 10° intervals of azimuth and elevation, was computed with their respective normal and LVH group-mean Q/R ratios and dispersions about these means. Lead directions which produced poor separation of the group-means or excessive overlapping of the distributions or both were discarded. A new set of 567 leads was computed at 1° intervals of azimuth and elevation, centered about the remaining ones. The final lead selected had an azimuth of 306° and an elevation of 58° (fig. 2). In this lead, 76% of the Q/R ratios of the LVH group were less than 0.5, and 78% of those of the normal group were greater than 0.5. There was no significant change in these percentages when the entire LVH group was used instead of the reduced sample upon which the lead direction was based.

The normal and RVH groups were used in a similar manner to determine the optimal lead direction for separation on the basis of R/S ratios. A smaller number (312) of leads was computed initially for this pair of groups, at 15° intervals of azimuth and elevation, and the final choice was made from 490 leads separated by 2° angles. With an azimuth of 2° and an elevation of 2°, this lead was nearly coincident with lead X of the orthogonal set. In this lead, 85% of the RVH group had R/S ratios of less than 2, and 87% of the normal group had ratios of greater than 2.

Fortuitous by-products of the lead choice were multipurpose capabilities of such leads. Analyses of T-wave vector-loop plots suggested that the RVH lead might be useful in discrimination of the normal from LVH. This was borne out by the computation of T-wave amplitudes in this lead for a subsample of the normal and LVH groups, resulting in a recognition rate of 74%.

Using the linear transformations defined by the azimuth and elevation angles, two modified Frank networks were built and incorporated in a direct-writing ECG machine ("Appendix"). Duplicates of the networks were also added to an ECG analog magnetic tape recording system, with the capability of recording the X, Y, and Z orthogonal leads simultaneously with either of the special diagnostic leads. Several such recordings were made and the data were digitized. The special lead voltages, over the QRS complexes, were compared with voltages computed from the X, Y, and Z leads at the same time points. The differences were well within tolerable limits, usually about the same amplitudes as the random and 60-cycle noise present in the data (fig. 3). It was not practical to digitize the direct-writer tracings with a degree of simultaneity comparable to that attained by the magnetic tape system, but a procedure was devised which allowed the matching of QRS complexes on magnetic tape output with those from the direct writer. Amplitude measurements taken at the Q, R, and S peaks of the direct-writer tracings were found to be in agreement with those computed from the magnetic tape records. A final check on the fidelity of the modified Frank networks was made by using a lead-resolver to produce an oscilloscope display of the special lead. This was compared with a simultaneous display of the modified Frank network output. The agreement of the different methods was excellent (fig. 4).

Figure 3
Solid line represents the QRS complex of the special lead recording with the modified Frank network. Broken line represents a digital plot of the same complex computed from the three orthogonal leads.
The direct writer, equipped with the modified Frank network designed for LVH recognition, was used to record the electrocardiograms of 94 patients from the Antihypertension Clinic referred to previously. A recognition rate of 81% was achieved in this independent control sample.

Comparisons between the performance of the special leads and the 12-lead ECG are given in table 3. When the widely used LVH and RVH criteria, listed in table 2, were used, LVH was recognized in 76% of the cases from the LVH lead as compared to 73% from the conventional leads. In the independent sample of hypertensives, recognition rates were 81 and 73%, respectively. Subsequently, an equal-error classification for the standard leads was obtained. When the limit of normal of S in V\textsubscript{1} plus R in V\textsubscript{5} or V\textsubscript{6} was lowered to 3.0 mv, the percentage of false-positive findings was 19 and that of false-negative findings was 21, that is, approximately equal.*

On applying this new limit of 3.0 mv to the initial sample of 323 LVH records, the recognition rate rose to 79% or 3% above that of the special lead. In the independent sample of hypertensives it reached the same level as the special lead, namely 81%.

Using the RVH criteria of table 2, only 46% of the 12-lead records were diagnosed as compared to 85% with the special RVH lead (table 3). An equal-error classification for the conventional leads was not obtained for RVH because the total number of cases was too small to lead to representative results.*

*At the more commonly used limit of 3.5 mv, the percentage of false-positive findings decreased to 11 and that of false-negative findings increased to 39.
**Discussion**

In the present study, leads for differentiation of only two diagnostic groups were described in order to demonstrate the feasibility of this approach. The same principles can be applied to any additional diagnostic entity. The lead selector switch described in the "Appendix" permits the recording of three orthogonal leads in addition to the special diagnostic leads. It is questionable, however, whether this choice needs to be retained once selective leads for most or all ECG abnormalities have been established. Preliminary estimates indicate that a total of six leads may suffice. In some instances, one lead may even be adequate for differentiation of two or three ECG abnormalities in a similar manner as the described RVH lead proved effective for recognition of LVH T-wave abnormalities. When applying the described leads for recognition of ventricular hypertrophy, it should be kept in mind that the samples on which their design was based were not necessarily representative of their total respective disease group populations. This is particularly important for the RVH lead which was based almost exclusively on records from patients with chronic cor pulmonale. In these patients, QRS complexes shift to the right without the substantial anterior displacement which is more characteristic of RVH cases due to congenital or rheumatic heart disease. An optimal RVH lead for the latter may differ considerably from the one described. The LVH lead, on the other hand, should prove to be more invariant because of the nature of the abnormality as well as the number and variety of cases in the sample used. Extensive tests of the sample size needed to achieve stable statistical boundaries suggested that a sample of 300 records would represent this abnormality adequately.³

As mentioned above, the direction of the optimal lead for RVH differentiation differed from that of orthogonal lead X by an angle of only 3°. Replacement of this special lead by lead X did not result in appreciable deterioration in the recognition rate. It was interesting to note that an R/S ratio of 2 in lead X was found as the limit for equal-error classification whereas a ratio of 1 is commonly used as the normal limit for lead V₆. Part of the discrepancy is due to the smaller normal ranges when corrected orthogonal leads are used.⁷ The increase in RVH recognition rate from 47% attained by conventional leads to 85% with the RVH lead is a clear indication of the advantage of the use of corrected leads with their valuable property of greater constancy of performance. It has to be remembered, however, that an equal-error classification was obtained for the special lead. Equalizing specificity and sensitivity of the 12-lead RVH criteria would certainly lead to a higher recognition rate, particularly in the age group under study where vertical or semivertical QRS axes are relatively rare in normals.

Table 3 which summarizes the results obtained from one RVH and two LVH groups shows that the special leads compare very favorably with those obtained from the standard 12-lead electrocardiogram. It appeared encouraging that this relatively simple tool equalled standard methods to a remarkable degree. It should be borne in mind that this comparison is between one measurement from a single lead and up to eight measurements of the standard 12 leads. Although it is self-evident that the information of the special leads is also contained in the orthogonal leads from which they are derived, it was not possible to obtain comparable results from X, Y, and Z leads without making three or more measurements. Time coherence of orthogonal leads, which was found previously to contribute significantly to diagnostic performance,⁶ may have contributed to the present results since this time coherence is preserved in resolved leads. Whereas the latter can be obtained with the generally available single-channel electrocardiographs, a three-channel device is needed for simultaneous recording of orthogonal leads.

In the present feasibility study, T-wave and ST-segment changes were not included in the tabulation of diagnostic recognition rates.
because such changes alone are often observed in cases unrelated to ventricular overload. They appeared, however, equally well-represented in the special and the conventional leads, and their interpretation needs to be included, of course, in clinical applications.

The attempt to equalize the number of false-positive and false-negative findings was made primarily for experimental reasons. In certain applications, that is, epidemiological investigations, it may be desirable to increase or decrease sensitivity and specificity of these leads. This can be accomplished by raising or lowering the limits of the differentiating measurements without modification of the leads. The effect of such shifts of normal limits was illustrated for one 12-lead LVH criterion when the range of normal was decreased from 3.5 mv to 3.0 mv and the percentage of false negatives decreased almost to half and that of false positives nearly doubled.

Application of the proposed leads is relatively simple since ordinary direct-writing electrocardiographs can be used for recording with only minor modifications. A patient cable for orthogonal leads, a set of resistors, a lead selector switch, and a battery-powered operational amplifier are the only additions required. These parts could be incorporated of course in the initial electrocardiograph design. The proposed leads can be obtained from any corrected orthogonal lead system with appropriate modification. Selection of ECG measurements required for interpretation of the new leads was purposely kept as simple as possible. Q/R and R/S ratios can be estimated in most instances and voltage measurements are needed only in borderline cases. Such simplification in record analysis would at the same time simplify the teaching of electrocardiography considerably.

The information content of orthogonal leads including the described resolver derivations is limited largely to the dipolar portion of the body surface information. Recent work by Taccardi, Horan and associates and Flowers and associates has shown that the QRS complex contains components which cannot be ascribed solely to a single dipole current generator equivalent. Factor analysis, first applied to this problem by Scher and associates, indicated contributions of multipolar origin. Selective leads to record nondipolar components have not yet become practical, however. Due to the relatively small magnitude by these components, it appears extremely difficult to recover this information. In a previous study from this laboratory, it was found that the third factor of a three-factor or threed-lead system contained practically no diagnostic information when tested in 296 abnormal cases. Whether such information can be recovered from higher order components may be questioned, therefore, and remains to be further investigated. The authors believe that at this time orthogonal lead systems probably represent the most practical and rational approach to clinical applications. The described leads are solely a further development of such applications where collected data are used to optimize leads without consideration of other factors which may be extraneous for the classification problem.

Acknowledgment

Data on patients followed in the Antihypertension Clinic were made available through the courtesy of Dr. Edward D. Freis.

![Figure 5](http://circ.ahajournals.org/)

Standard resistor network for the Frank lead system.
Modified Frank resistor network. The values of the weighting resistors for the X and Z contributions have been changed and the three outputs have been combined into a single output. The particular values shown will produce the LVH-lead.

Appendix

The Frank lead system (fig. 5) is designed for recording three orthogonal leads, either independently or simultaneously. The circuitry has been designed so that each of the three outputs X, Y, and Z represents the electrical field in the direction indicated with an amplitude approximately equal in strength to the others. For example, the X output produces a potential difference parallel to the X axis with an amplitude proportional to the dipole strength in the X direction. The shunt resistors in the X and Z outputs have been used to diminish these amplitudes by the factors 1.28 and 1.15, respectively, in order to reduce them to the same strength as the Y output. Thus the three outputs can be called "X, Y, and Z."

If it is desired to record a lead direction other than X, Y, or Z, an instrument such as a resolver can be used. The resolver converts the three Cartesian coordinates X, Y, and Z into spherical coordinates, M, θ, φ, indicating magnitude, azimuth, and elevation angles. Any lead direction can be obtained by selecting the angles θ and φ.

This method of instrumentation requires three preamplifiers for X, Y, and Z and an analog computing circuit for making the transformation. However, if one specific lead direction is being sought, the Frank resistor values can be modified to obtain this lead with the use of just one preamplifier.

As an example, consider the lead desired in differentiating between normal and LVH. In this case, the voltage desired is

\[ V = 0.312X - 0.848Y + 0.428Z \]  

(1)

The Frank network can be modified, as in figure 6, to obtain this voltage. The X, Y, and Z outputs have been merged together with the proper polarities, to form a single output and
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Figure 8

A commonly used single channel direct-writing electrocardiograph with the equipment required for recording specific lead directions. The smaller chassis attached to the right side of the electrocardiograph contains the added circuitry. The two switches on top are the on-off switch and the lead-selector switch. The small black plug-in units (5 shown in this photograph) contain the individual resistor networks required for each lead direction. The amplifier and batteries are just below the switch panel and are not in view.

The resistor values have been modified by appropriate factors. To mechanize equation 1, for instance, resistor values should be selected to obtain

\[ V = \frac{1}{1.28} (0.312) X - \frac{1}{0.848} (0.438) Z \]

since no shunt-loading resistors can be used independently for X and Z. If we normalize equation 2 by dividing by 0.848 we obtain

\[ \frac{V}{0.848} = 0.287 X - Y + 0.438 Z \]  (3)

Equation 3 implies that if the resistor values that contribute to the Y lead remain unchanged from the original Frank network, then each resistor which contributes to the X lead must be increased in value by the factor \( \frac{1}{0.287} \) and each resistor contributing to the Z lead must be increased in value by the factor \( \frac{1}{0.438} \).

Assuming that the preamplifier to be used has an input impedance sufficiently high to produce negligible loading, the next problem to be considered is the formation of this lead is the loading effect that the network has on each input because there is just one pair of leads to serve as the output. Thus, if all the leads that make up the Z voltage are active, voltage will be attenuated by a factor of 0.257 because of the shunting effect of all the other resistors. For an X input, the attenuation is 0.166, and for a Y input, the attenuation is 0.58. Therefore, the actual output will be

\[ V_1 = 0.166 X - 0.58 Y + 0.257 Z \]  (4)

If equation 4 is multiplied by \( \frac{0.848}{0.58} = 1.46 \), equation 2 is obtained. Thus, the output is correct so far as the lead direction is concerned but is too low in amplitude by a factor of 1.46. A modestly priced operational amplifier with differential input, powered by dry cells, can be successfully employed to provide this gain factor. Figure 7 is a block diagram of the complete addition to the direct-writing electrocardiograph. Because the required gain factor will be different for different lead directions, a switch can be used to change the gain of this operational amplifier, as needed, by changing the value of \( R_Y \).

The type of arrangement described above has been constructed to operate integrally with a standard electrocardiograph. Figure 8 is a photograph of the equipment. The smaller chassis attached to the side of the electrocardiograph contains the networks, switch, and operational amplifier for recording up to 10 different lead directions.

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