The Missing Waveform Information in the Orthogonal Electrocardiogram
(Frank Leads)

I. Where and How Can This Missing Waveform Information be Retrieved?

By F. Kornreich, M.D.

SUMMARY
The orthogonal electrocardiogram (Frank leads) is a reasonable compromise between the demands of practicability and diagnostic accuracy. The accuracy has been enhanced by the use of computerized multivariate statistical procedures. The work of the last two or three decades, however, has shown that these leads account for only part of the total available surface information. In this paper, the missing waveform information with respect to the Frank leads is quantitatively and systematically determined and a method of retrieval is worked out.

The essence of this method rests on the empirical evidence obtained by testing each of the 126 surface electrocardiograms for the XYZ content. The results are analyzed by a least squares, best fit procedure. The poorly fitted curves are considered as additional waveform sources. The number and the sites of the additional information are determined on a test group of 207 patients. The “total” surface waveform information is found to be represented by nine surface leads. This set of waveforms is then tested on a control group consisting of 205 patients. An average resynthesis coefficient of 96% is reached. No further resynthesis is looked for because of the estimated noise level.

Although the waveforms recorded at these sites represent the minimum number of unique building blocks capable of synthesizing any waveform on the body surface, they cannot predict the surface potential distribution at all surface points. This information is “total” as far as statistical procedures—performing discriminant analysis on time-functions—are concerned. This “total” waveform information consists of a set of electrocardiograms recorded in each individual at nine well-defined anatomic locations.

Additional Indexing Words:
Multivariate analysis Curve-fitting Multiple surface leads Waveform information
Resynthesis surface maps

THE RECORDING on the thoracic surface of the electrical activity of the heart remains one of the most useful tools in the diagnosis of heart conditions. The advent of powerful digital computers has enabled us to handle large numbers of ECG measurements and to submit them to complex statistical procedures. Early comparisons between the conventional 12 lead ECG and the corrected orthogonal lead systems (e.g., the Frank leads) have shown that these systems were almost interchangeable as far as the clinical information provided is concerned.1, 2, 3 Subsequently, large-scale studies based on sophisticated statistical procedures were conducted by Pipberger et al. using Frank’s XYZ leads.4, 5 Considerable improvement in diagnostic accuracy was reported in the Frank lead system when compared with either descriptive or semiquantitative methods of ECG waveform analysis.6, 7, 8 It must be realized, however, that even when multivariate analysis is performed, the true diagnosis may be missed by the use of XYZ leads exclusively in an unknown percentage of cases and false positive results also will be observed.9, 10

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Assuming that a high degree of accuracy is achieved with multivariate analysis techniques, this limitation can be ascribed to a paucity of information content of the recorded electrocardiograms. Both the standard 12 lead ECG and the orthogonal corrected XYZ leads rest on the dipolar concept. The considerable amount of research carried out during the last two or three decades has made us keenly aware of the shortcomings of the dipolar hypothesis with respect to the total available surface information.11, 12, 13

Several studies of the retrieval of this total surface information have been published. Among them, Horan et al.14 found eight principal factor waveforms accounting for the total waveform information, and Barr et al.15 determined 24 positions of measuring locations which allow the reconstitution of the total body QRS surface potential distribution. While the method reported in the first study permits the reduction of 180 waveforms into a set of eight orthogonal time functions, all 180 waveforms must be recorded in each individual, a requirement which constitutes a practical limitation.14 The second study is mainly aimed at the determination of the total surface potential distribution as it varies in time rather than to find the minimum number of nonredundant waveforms to be entered in a computer program for the performance of discriminant analysis.15

The object of this work is to provide the cardiologist with a convenient and practical tool which would be an improvement over the Frank leads. This tool would consist of a small set of well-defined locations where electrocardiograms, accounting for the total significant waveform information* of clinical use, can be recorded. We know that part of this total waveform information is present in lead systems currently being used, but this part has to be quantitatively determined and located with respect to the total available waveform information in normal subjects and in patients with various pathological entities.

Once the Frank leads have been optimized or have been replaced by another procedure containing complete waveform information, this can be subjected to multivariate statistical procedures similar to those extensively described by Pipberger and his coworkers.6, 7, 8, 9, 10 There should be as little overlap as possible in the waveforms fed into the computer for discriminating purposes; indeed, any redundant information, as for instance linear combinations of these waveforms, will burden the procedure without bringing to it any improvement in diagnostic classification.

Material

The material consisted of ECG recordings on 412 well-documented patients; for each patient 126 electrode sites were explored, recorded, and digitized at 500 samples per second.† The locations form 18 vertical columns, each containing seven electrodes. A potential reference electrode was placed in the right lower quadrant of the abdomen.

Within each column, the lowest electrode was at the level of the midepigastrium and the highest electrode at the level of the manubrium sterni. An electrode was fixed at any convenient location and used to obtain a synchronizing signal. Eight electrodes were recorded at a time—seven electrodes constituting a column and the fixed synchronizing electrode. Calibrating signals were recorded at the beginning and at the end of the 18 sets of ECG recordings. All the data for the seven channels were displayed sequentially to the operator, and for each electrode the operator had the choice of accepting the data if it looked satisfactory or rejecting it if it appeared unsatisfactory. Data might be rejected because of noise or inconsistency with waveforms at neighboring points. The assumption was that the set of data was identical to that which would be obtained if 126 channels could be recorded at the same heart cycle. More sophisticated automated editing procedures have proved no more satisfactory than the described technique.17

†This material was most kindly provided by J. Holt, A. Barnard, and J. Kramer (Birmingham, Alabama).

* N surface electrocardiograms are said to account for the total waveform information in a given subject when, linearly combined, they are capable of resynthesizing any of the M (M >> N) recorded electrocardiograms on the thoracic surface of this subject.14, 16 The term total waveform information is used throughout this study instead of total (surface) information. Waveform information alone fails to produce values at all surface points from a subset without a precomputed transformation matrix of coefficients.15

†This material was most kindly provided by J. Holt, A. Barnard, and J. Kramer (Birmingham, Alabama).
group of combined RVH consisted of patients with surgeons' estimates of right ventricular size. These patients exhibited various grades of RVH (dilatation or hypertrophy). These patients also presented a variety of cardiac disorders.

Group 5 consists of patients with a typical history of infarction—characteristic enzyme changes at the onset and coronary occlusion as demonstrated by angiography. Some cases were autopsied. No classification as to the site of the myocardial infarction was made, all patients being pooled into one single group.

Group 4 rests on a history typical of angina pectoris. Only in groups 6 and 7 was the electrocardiogram taken as a basis for diagnosis: these two groups were constituted on the basis of a QRS duration of more than 0.13 sec and on typical ECG right or left bundle branch block patterns.21

Methods

1. The Principle of the Method

If we assume that part of the total information is contained in the orthogonal leads X, Y, and Z of the Frank system, where on the thorax, do we find waveforms which cannot be accounted for with a linear combination of X, Y, and Z? These waveforms by definition possess additional signal content, and together with the XYZ leads, yield the "total" waveform information.22

A CDC 6400 computer performed the following calculations:

a) each of the 126 surface ECGs (Vi) was approximated with a linear combination of XYZ in order to achieve the best fit on the basis of a least squares test:

\[ V_i(t) = a_1X(t) + b_1Y(t) + c_1Z(t) + E_i(t) \]

thus \( a_1, b_1 \) and \( c_1 \) were computed in order to minimize the squared error \( E_i(t) \) for the entire

b) A resynthesis coefficient * and a correlation coefficient was computed for each lead.

The computations were performed on a test group of 207 patients (table 1). The results were then compared with an independent control group of 205 subjects to evaluate the prospective value of the study. After computation, the poorly fitted waveforms were retained and plotted on a grid representing the corresponding electrode positions. Poorly fitted curves were defined as those curves with a root mean square (RMS) error above the noise level, which was independently estimated at 40 microvolts when measured on the baseline between the end of the P wave and the beginning of QRS (fig. 1). This RMS noise level usually reached 5 to 10% of the RMS values of the original signals. The RMS values of the recorded signals ranged from 400 μV to 760 μV, with a mean value of 510 μV. The corresponding resynthesis coefficients varied accordingly between 95 and 90% when a "perfect" fit was achieved. The poorly fitted curves were concentrated in areas which were distributed over the thoracic surface. In each individual they constituted clusters where additional information could be retrieved.

2. Retrieval of the Additional Waveform Information in Each Individual

The problem now is to determine how many leads in each cluster account for the signal information contained in that particular cluster. In other words, could all the waveforms enclosed in a well-circumscribed area be represented by one single waveform? If not, we have to break the zones down into smaller areas, each constituting homogeneous "families" of related waveforms, i.e., representable by one single waveform.

This breakdown was performed for each subject in the following way: for each waveform enclosed in a given area of poor fit, its error curve (i.e., the difference between the computed and the recorded electrocardiogram as a function of time) is correlated with all other error curves. High correlation coefficients (between 0.98 and 1.00) indicate error curves (and thus original waveforms) belonging to identical waveform families. Out of each family so defined a representative

*The root mean square (RMS) of the amplitude of the actual waveform was accepted as an estimate of the total amount of information present in the waveform and the RMS of the difference in amplitude between the actual electrocardiogram and the predicted or computed ECG was accepted as an estimate of the error.14 The resynthesis coefficient (in percentage) was thus defined as follows:

\[ \text{RMS information} = \frac{\text{RMS error}}{\text{RMS information}} \times 100. \]

†The noise-level varies from patient to patient and from lead to lead in an individual patient: 40 μV represents the average RMS noise level in this series of 412 patients. This RMS noise ranges from 20 μV to 50 μV.

Table 1

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Number of patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>100</td>
</tr>
<tr>
<td>2. a) Pure left ventricular hypertrophy</td>
<td>42</td>
</tr>
<tr>
<td>2. b) Combined left ventricular hypertrophy</td>
<td>42</td>
</tr>
<tr>
<td>3. a) Pure right ventricular hypertrophy</td>
<td>25</td>
</tr>
<tr>
<td>3. b) Combined right ventricular hypertrophy</td>
<td>13</td>
</tr>
<tr>
<td>4. Angina pectoris</td>
<td>27</td>
</tr>
<tr>
<td>5. Myocardial infarction</td>
<td>13</td>
</tr>
<tr>
<td>5. a) acute</td>
<td>20</td>
</tr>
<tr>
<td>5. b) remote</td>
<td>20</td>
</tr>
<tr>
<td>6. Left bundle branch block</td>
<td>16</td>
</tr>
<tr>
<td>7. Right bundle branch block</td>
<td>26</td>
</tr>
</tbody>
</table>

| Total      | 207                |

QRS duration; a best fit coefficient matrix of 3 × 126 elements was thus obtained for each subject.
MISSING INFORMATION IN FRANK LEADS

Figure 1

This figure shows the electrocardiograms recorded on two patients. Samples from the anterior and posterior thoracic surfaces are given. The scale is in microvolts; the abscissa indicates the time (50 = 100 msec). The lower tracings are the actually recorded waveforms; the upper tracings are the residual time-functions obtained by subtraction of the computed waveforms from the original waveforms. The beginning of the QRS complex is indicated by a small vertical line: at the left of these vertical lines, the terminal part of the PQ (PR) segment is visible, disclosing the noise level. The error or residual curves resulting from the best-fit procedure are clearly within the noise range. The error-curve with an asterisk is a straight line because the corresponding waveform is one of the nine components of the linear combination and consequently fitted by itself.

The waveform was chosen. This choice was not very critical because any one of the waveforms belonging to a same family is suitable. A new linear combination, with the chosen waveform added to XYZ, will achieve a perfect fit for all the waveforms of the concerned family. In this way, the breakdown of large areas of poor fit into smaller areas of waveform families is achieved in each single individual, and the locations for additional waveform information to XYZ thus determined.

3. Common Lead Positioning for the Population Under Study

Once such locations were determined separately for each subject, common locations for the entire test population were sought by superimposing for all the individuals in each diagnostic group the locations determined for individual patients. Next, the locations for various diagnostic groups were superimposed, in order to find out which locations were most frequently encountered, and consequently, which common additional leads have to be included in order to complete the XYZ waveform information for each member of the population.

Once N common additional leads were defined for the test population, the last step was to substitute for the XYZ leads, other surface leads, which, together with these N additional leads, would account for the total waveform information. Therefore, the above outlined procedure was performed on the recordings for each individual, starting from the N leads instead of the XYZ leads. Complementary information to N leads was thus found and representative waveforms determined from this complementary information. These latter (n) leads account for most of the XYZ waveform information. These N + n waveforms constitute in each individual the building blocks capable of synthesizing, through linear combinations, any waveform on his body surface.
4. Extension of the Method to New Subjects

The validity of the method as determined on 207 test patients had to be assessed on a new independent sample. For each individual in this control group of 205 patients (table 1), the locations of the N+n waveforms were fixed. These waveforms were combined linearly in order to match the remaining 126—(N+n) leads, using the already described least squares, best fit procedure. A resynthesis coefficient for each lead, as well as a mean resynthesis coefficient calculated by averaging the resynthesis coefficients for all the leads, was computed. A mean resynthesis coefficient for each diagnostic group is also determined.

5. Influence on the Method of the Number of Recording Sites

In order to test the accuracy of the method as a function of the density of electrode positioning, we studied 14 patients* on whom recordings from about 240 recording sites (between 190 and 260), distributed throughout the thoracic area, have been taken. Additional leads representing, together with the XYZ leads, the total waveform information were determined according to the above outlined method. With respect to these waveforms, an average resynthesis coefficient (mean of the resynthesis coefficients of all the surface leads) was computed for each of the 14 patients. This electrode distribution was then uniformly reduced by deleting every second or third electrode until a grid of about 126 leads was obtained. The procedure for the determination of the number and the locations of additional leads was then repeated: the same number of leads at identical locations were found and the mean resynthesis coefficients did not differ by more than 2%.

Results

Table 2 gives the average resynthesis coefficients for all 126 waveforms with respect to the Frank XYZ leads in normal subjects and patients in various pathological groups. The areas containing the poorly fitted curves—and consequently the missing information—are depicted in figures 2 and 3. Figure 4 shows the breakdown of these areas into smaller zones from which representative waveforms were chosen (fig. 4, above).

The extent of the breakdown of the larger areas of poor fit into smaller clusters from which representative waveforms can be chosen in each subject is arbitrarily fixed by the cut-off level decided upon for the effectiveness of the curve-fitting procedure. In this study, the accepted waveform information not accounted for (residual signal) is 40 \( \mu \text{V RMS} \) for each waveform. The clusters of representative waveforms obtained after breakdown and superimposition of waveforms from the subjects from the test group are most frequently made up of three to four waveforms, a situation which left some latitude for the choice of one of them. The selection rested on practical considerations such as convenience and reproducibility of well-defined anatomical sites.

The addition of five leads (leads 38, 56, 60, 100, and 106) to XYZ achieved a fit for the data in all the patients of the test group except 14 (two normals, three myocardial infarctions, and nine RVH). In order to include the findings in those patients (7% of the test group), a sixth lead (lead 24) had to be added (fig. 4, below). These complementary leads, combined linearly with XYZ, accounted for the total surface waveform information (table 2) of the test group. The repetition of the procedure, considering these five or six additional leads as a starting set, led to the determination of three families of poorly fitted curves. Out of these clusters, three representative waveforms, were extracted (fig. 4, below), which together with the six additional leads, realized an eight or nine lead system, accounting for the total waveform information in each individual of the test group.

This system was then applied to the control group. The resynthesis coefficients from this eight or

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Frank leads</th>
<th>+ 5 leads</th>
<th>+ 6 leads</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Group</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>85%</td>
<td>94%</td>
<td>95%</td>
</tr>
<tr>
<td>Pure LVH</td>
<td>83%</td>
<td>96%</td>
<td>96%</td>
</tr>
<tr>
<td>Pure RVH</td>
<td>77%</td>
<td>92%</td>
<td>93%</td>
</tr>
<tr>
<td>Myocardial infarction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) acute</td>
<td>88%</td>
<td>95%</td>
<td>96%</td>
</tr>
<tr>
<td>b) remote</td>
<td>86%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td><strong>Control Group</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>84%</td>
<td>95%</td>
<td>96%</td>
</tr>
<tr>
<td>Combined LVH</td>
<td>79%</td>
<td>93%</td>
<td>93%</td>
</tr>
<tr>
<td>Combined RVH</td>
<td>72%</td>
<td>91%</td>
<td>93%</td>
</tr>
<tr>
<td>Myocardial infaration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) acute</td>
<td>86%</td>
<td>96%</td>
<td>97%</td>
</tr>
<tr>
<td>b) remote</td>
<td>85%</td>
<td>96%</td>
<td>96%</td>
</tr>
<tr>
<td>Angina pectoris</td>
<td>85%</td>
<td>93%</td>
<td>96%</td>
</tr>
<tr>
<td>LBBB</td>
<td>84%</td>
<td>96%</td>
<td>96%</td>
</tr>
<tr>
<td>RBBB</td>
<td>73%</td>
<td>92%</td>
<td>90%</td>
</tr>
</tbody>
</table>

*Abbreviations: LVH = left ventricular hypertrophy; RVH = right ventricular hypertrophy; LBBB = left bundle branch block; RBBB = right bundle branch block.

*N = 207.
†N = 205.
Figure 2

This figure displays the results of comparing waveforms from 126 leads with the Frank leads for the normal group (above) and the patients with myocardial infarction (below). The small numbers indicate the electrode positions from 1 to 126. Poorly fitted electrocardiograms are encircled and constitute equipercenage lines. The number of patients (in %) with poorly fitted curves corresponding to the enclosed electrode positions is given by the large numbers. For instance, the leads 30, 37, 38, 44, 45, 51 and 52 are poorly resynthesized with linear combination of the Frank leads in 30% of the normal individuals.
nine lead system in the control group can be seen in table 2. One notes that, with the exception of combined RVH and RBBB (and to a somewhat lesser extent, combined LVH), eight electrocardio-

Figure 3
This figure displays the determination of areas in patients with left ventricular hypertrophy and with right ventricular hypertrophy in which the curve obtained from Frank leads and 126 surface leads represented a poor fit.
Above) The areas of poor fit which can be represented by one single waveform are represented for each disease entity considered. N = normals; M = myocardial infarction; L = left ventricular hypertrophy; R = right ventricular hypertrophy. This figure results from the breakdown process of the original areas (depicted in figures 1 and 2) as explained in the text. Below) The solid ovals indicate electrode positions where representative electrocardiograms (that account for the corresponding areas of poor fit depicted in a) can be recorded. The dotted oval refers to the RVH group only. The solid rectangles represent the leads which can be used together with the already described ones for achievement of total waveform information replacing in this the Frank leads). 5 I.S. = fifth intercostal space; $V_1$ to $V_{10}$ = standard ECG positions.
grams can account for the “total” waveform information. Indeed, the addition of a ninth lead made little difference in the results for the other pathological entities.

Discussion

Limitations of the Method

1) The first limitation is the assumption that the total available surface information is represented by a finite number of recording sites; in this study, 126 leads are supposed to account accurately for that information. The methodology tested on a higher number of recording sites did not produce significant differences in resynthesis accuracy. The locations of leads for total waveform information were entirely superimposable whether 126 leads or more were used.,

2) The second limitation relates to the cut-off level at what we consider as “noise.” Part of that noise can be independently estimated by measuring the RMS deviations from the baseline between the end of the P wave and the beginning of the QRS complex (fig. 1). It contains mainly 60 cycles, muscle tremor, and digitizing errors. This noise level varies from lead to lead and from patient to patient and ranges between 20 and 50 μV RMS. Instantaneous peak values sometimes reach 120 μV.

Other error sources can be found in the nonsynchronous recording of the 126 electrocardiograms which, in addition, do not refer to the same systole. The quantitation of these errors was not possible.

3) Very closely related to the preceding section is the evaluation of the effectiveness of curve fitting. The methods used to describe this effectiveness are largely responsible for the discrepancy observed in the literature. Although the mathematical procedures for approximating ECG waveforms are very similar (best fit, curve fitting on a least squares basis), the description of the adequacy of resynthesis is variable. Some authors15, 16, 23 define the waveform information (and error) as the squared deviation from the baseline (in mV²), while others14, 17, 24 define the same information in terms of RMS of the deviation from the baseline (in mV).

Consequently a relative error (difference between observed and reconstructed waveforms in percent of the original waveform) of 4% (4/100) when the voltages are expressed in mV², becomes 20% (2/10) when the voltages are expressed in mV. With this in mind, we can see that the relative errors achieved in this work with respect to the nine lead system (table 2) and not exceeding 5% (ratio of RMS values) become 0.25% if mean squared ratios are considered instead of RMS ratios. This compares very favorably with the relative errors observed and reported by other workers: 4%15, 5%16. It should also be stressed that the resynthesis achieved in each individual with nine waveforms can go beyond the noise level in some of them: this results from the fact that nine leads are needed to meet the requirements of an entire population with various diagnostic conditions although a perfect resynthesis could be obtained in each single individual with a smaller number of waveforms. We indeed wish to underline that these nine electrode sites were found as a result of superimposing the leads needed for each single individual.

Because of these limitations, the determination of a small number of surface leads which account for the total waveform information implies the decisions of fixing a level for the resynthesis one wishes to obtain. If the cut-off is removed beyond the estimated noise level, significant, interpretable information can hardly be expected. However, improvement of the technical conditions can modify the number of waveforms needed to achieve satisfactory resynthesis of the original signals.

Relation to Previous Work

As many most interesting clinical and electrophysiological elements have been derived from the study of surface maps,25–29 the practical reproduction of total body surface potential distribution by means of a reduced set of measuring locations has been sought.15 This data reduction becomes a must if statistical procedures similar to those performed by Pipberger on the Frank leads4, 5 are to be incorporated into the diagnostic procedure. Indeed, both practicability and feasibility require a limited number of nonredundant waveforms.

With respect to these goals, two main approaches have to be referred to: reduction of data into only waveform information, based on principal components14, 16, 23 and retrieval of the total surface distribution as it varies in time via a smaller number of surface leads20:

a) The main issue of the principal components deals with the dimensionality of the ensemble of signals recorded on the thoracic surface as it determines the minimum number of unique postural blocks capable of resynthesizing any surface waveform. In that respect, the authors demonstrated that for a single subject, a small number (less than ten) of waveforms accounted
for the total waveform information. A variable set of coefficients permitted the determination of potential values at all surface map points. Because of this interindividual variability, this method is not suitable for prospective studies as the coefficients are not known a priori for a particular subject. On the other hand, this method seemed interesting as far as statistical waveform analysis is concerned. However, practical shortcomings weaken the applicability: first principal components can be determined only if all surface measurements are available, and second, the computations are time-consuming and very cumbersome;

b) The retrieval of the total surface distribution as it varies in time via a smaller number of surface leads is achieved by a method which permits the reconstruction of complete surface maps in new subjects without any loss of the information contained in these maps. This is realized with 24 leads and a constant transformation matrix. The main interest of this method lies in the reproduction of all the features appearing in directly recorded surface maps, presenting valuable clinical and electrophysiological interest and which statistical procedures may fail to reflect. In practice however, as stated by the authors, it often may be more convenient to simply measure potentials at all pertinent locations. Therefore, and because our study deals mainly with statistical procedures on waveforms, this waveform information was looked for only at rational and empirical sites of interest. Our approach consequently contains the capability of resynthesizing any waveform on the body surface from a minimum number of unique building blocks. These building blocks or waveforms can be recorded in each new subject at nine identical locations on the body surface as shown in the results from the control group (table 2) and account for the total waveform information in each individual. The fact that this study is restricted to waveform information only explains the requirement of nine leads instead of 24.

Relative Information Content of the Frank Leads and 126 Surface Electrocardiograms

The Frank XYZ leads, linearly combined, accounted for 75 to 87% of the total waveform information, depending on the considered diagnostic entity. The results obtained for RVH and RBBB gave the lowest figures, the results for myocardial infarctions, the highest.

Although these XYZ leads represent a first approximation of the dipolar moments of an equivalent dipolar generator, our procedure—which is the quantitative, numerical, and systematic counterpart of cancellation experiments—does not test the dipolar content of the surface electrocardiograms but rather a three-function content. Consequently, the information not accounted for cannot be considered as the nondipolar fraction of the signal. The clusters of additional information to the Frank leads are located in the upper sternal, the lower left precordial, and the upper left dorsal regions. These areas can be represented by five additional leads in 93% of all individuals under study (412 patients). In 7% of the patients, a sixth lead is found necessary (in the groups with RVH and RBBB). Together, these nine waveforms contain, for each individual, the total available waveform information.

Note that each individual, considered separately, could be satisfied with less than nine leads. That number, however, is necessary if we want to meet the requirements of all the patients simultaneously. In order to consider the presence of various pathological possibilities some redundancy for each single subject is inevitable. It should also be stressed that the additional six locations are dependent on the XYZ system considered. If another lead system than the Frank system was used, other locations would have been found. The use of a “mixed” system (three corrected orthogonal electrocardiograms, completed with five or six single surface leads) can be advocated for diagnostic purposes because we can take advantage of the abundant diagnostic criteria available in the literature for the Frank leads; the supplementary leads could then provide the clinician with additional information whenever the XYZ leads fall short. On the other hand, as far as clinical applicability is concerned, the setting up of the lead system ought to be as practical as possible. This was achieved by keeping the number of leads at a minimum and assigning them well-defined anatomical positions. This lead system was realized by replacing the XYZ leads with three other surface waveforms, which, together with the already determined five or six waveforms, account for the same total waveform information. This reduces finally the total number of leads from 13 (+1 reference lead) to 9 (+1) and achieves a uniform lead system composed of nine directly recorded surface leads without any assumptions as to an underlying model.
Prospective Studies

In this study nine leads were found to account for the total waveform information. As far as the QRS complex is concerned, this nine lead system, recording waveforms at nine identically located sites in each individual, has a predictive value for any new individual. This statement has been tested on a control group of 205 patients: in these new patients, an average resynthesis of 96% was reached by combining nine waveforms recorded at predetermined locations. It is of course always possible that diagnosis of other individuals might require one or more additional leads; but this is not very likely if one considers the great variety of disease entities represented in this study. Technical improvement, however, permitting the meaningful interpretation of potentials of less than 100 μV, might require a larger number of waveforms for the retrieval of the total waveform information.

These nine waveforms can now be fed into a computer for multivariate analysis purposes and their diagnostic value compared to the Frank leads.

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The Missing Waveform Information in the Orthogonal Electrocardiogram (Frank Leads): I. Where and How Can This Missing Waveform Information be Retrieved?

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