Computer Extraction of Electrocardiographic Parameters

By Cesar A. Caceres, M.D., Charles A. Steinberg, Sidney Abraham, William J. Carberry, Joseph M. McBride, Walter E. Tolles, and Arthur E. Riki, M.D.

This study was undertaken to demonstrate the feasibility of use of a computer program to extract automatically, without human intervention, clinically useful measurements of the parameters of an electrophysiologic tracing. The electrocardiogram was selected as the most suitable model of an electrophysiologic signal from which to extract data because of the large backlog of electrocardiographic data on subjects known to be normal or abnormal. Moreover, widespread use of electrocardiograms facilitates future statistical validation of the results of computer derived data.

Materials and Methods

In this paper, the term "parameter" is used to denote electrocardiographic waveform in an all encompassing sense. The term "variable" refers to the measurements or statistics that describe each individual waveform.

Thirty-six electrocardiographic leads obtained from 20 clinically (not necessarily electrocardiographically) normal individuals were recorded for 1 minute each, on magnetic tape with a frequency modulation system. Each lead was recorded separately and successively according to standard electrocardiographic technique. There was no attempt made to select leads that best describe the heart's electrical signal. Lead II and V3 were selected under the assumption that these two leads would give a range of graphic patterns wide enough to test whether the steps involved in human pattern recognition and measurement can be sufficiently delineated to permit accurate and automatic duplication by a computer.

Although it was desired that output should conform to accuracy in current clinical use it was decided that measurements should be as precise as consistent with practical use in a computer and possible future applications. The electrocardiographic leads were converted from analog form to digital values at a rate of 625 samples per second. Time measurements were thus accurate to 0.0016 second. The data were digitized to an accuracy of one part in one thousand. These values were stored on punch cards for later analysis by a general-purpose computer. A block diagram of the data-processing system is shown in figure 1. In order to minimize cost the initial work was performed on a small, low-speed computer. With the computer program that evolved, the task of measuring a single lead was performed in 64 minutes. It is estimated that the time required on faster computers will range, depending on type, from 15 seconds to 2 minutes.

The basis for the computer program was the logic used by electrocardiographers objectively and subjectively for waveform identification and measurement. A distinction was observed between the waveform characteristics used by electrocardiographers for diagnostic interpretation and the characteristics used for recognition of waveforms. In interpretation, that is, classification into clinical groups, the most prominent characteristics used by the electrocardiographer are duration and amplitude, but for recognition and measurement of the electrocardiographic waveform the electrocardiographer depends on the slope and amplitude and to a lesser extent on duration. These three characteristics, amplitude, duration, and slope were hence considered the basis for a logic of recognition and measurement suitable for computer use.

The parameters selected for measurement were the P, Q, R, S, T, and U waves and the PQ, ST, QT, and RR intervals. P primes, R primes, and S primes were initially intentionally excluded from the program. It was assumed that when identification of basic waves became feasible by automatic methods it would be relatively easy to change the program. Arbitrary rules and definitions based on conventional electrocardiographic criteria were initially used to define wave onset, wave peak, wave termination, significant voltage fluctuations, and time intervals in the electrocardiograms. These definitions were programed.
tested, and reprogrammed, as necessary, until final
definitions suitable for use as steps in the com-
puter program were formulated.

A constant point of reference from subject to subject and from lead to lead is needed to serve as the basis for the steps in the recognition logic programed for the computer. The point of greatest negative rate of change in the electrocardiographic signal was used and found to be satisfactory in the electrocardiograms tested. That point occurs during QRS inscription because the rate of change in potential is greatest at the time of ventricular depolarization. With the point of greatest negative rate of change as a reference, one complete heart cycle can be isolated and small amplitude QRS waves are not missed or confused with other waves in the conventional electrocardiogram.

The derivative of the electrocardiogram was used in the computer program to determine the point of greatest negative rate of change in the signal (fig. 2). The maximum negative amplitude in the first derivative was the reference constant from which the R or S waves were located by searching for maximum positive and negative values in the conventional lead in the portion of the curve preceding and following the point of greatest rate of change. After locating the R or S wave it was possible to determine where other portions of the clinical electrocardiogram may be found by referring to time intervals during which clinically significant voltage fluctuations are expected to occur and by reference to the derivatives of the lead during these intervals. The steps in the computer logic are described in the appendix.

Results

The result of this study is a system that automatically recognizes and measures clinically useful parameters in an electrocardio-
gram. The basis of this system is a set of quantitative criteria for automatically recog-
nizing and measuring these parameters. The system is not dependent on the lead or lead system used in electrocardiographic record-
ing. The computer-derived values from the lead were exactly reproduced each time the lead was fed into the computer. The measure-
ments from all leads tested were comparable in the first two decimal places to values obtained by careful direct visual measure-
ment of the standard clinical electrocardiogram. A set of measurements from the elec-
trocardiogram in figure 2 are given in table 1. These measurements were obtained from the computer without any human interven-
tion. The system is capable of recognizing and measuring the parameters although there is wide variation in the electrocardiographic waveform from subject to subject and lead to lead.

Although the initial definitions of wave-
forms were arbitrary, they were as precise as they could be made from clinical criteria. In most cases the definitions had to be re-
vised during the project to add more precision so that they could become acceptable as the working basis for the computer programmer. Many subjects had P primes and R primes of amplitude or duration that generally are dis-
missed in clinical work but steps had to be incorporated into the program to prevent erroneous labeling not only of the prime waves but also of the wave forms that followed them. Steps in the computer program to include all possible types of normal and
Table 1

Computer Derived Measurements from an Electrocardiographic Lead

<table>
<thead>
<tr>
<th>Subject 7</th>
<th>Lead II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitudes in millivolts</td>
</tr>
<tr>
<td>P-wave amplitude</td>
<td>0.1117</td>
</tr>
<tr>
<td>Q-wave amplitude</td>
<td>-0.1055</td>
</tr>
<tr>
<td>R-wave amplitude</td>
<td>0.8850</td>
</tr>
<tr>
<td>S-wave amplitude</td>
<td>-0.1915</td>
</tr>
<tr>
<td>T-wave amplitude</td>
<td>0.5403</td>
</tr>
<tr>
<td>ST-segment onset amplitude</td>
<td>0.0099</td>
</tr>
<tr>
<td>ST-segment midamplitude</td>
<td>0.0913</td>
</tr>
<tr>
<td>ST-segment terminal amplitude</td>
<td>0.1187</td>
</tr>
<tr>
<td>P-wave duration</td>
<td>0.0928</td>
</tr>
<tr>
<td>Q-wave duration</td>
<td>0.0272</td>
</tr>
<tr>
<td>R-wave duration</td>
<td>0.0448</td>
</tr>
<tr>
<td>S-wave duration</td>
<td>0.0384</td>
</tr>
<tr>
<td>T-wave duration</td>
<td>0.2016</td>
</tr>
<tr>
<td>ST-segment duration</td>
<td>0.0608</td>
</tr>
<tr>
<td>PQ-interval duration</td>
<td>0.1632</td>
</tr>
<tr>
<td>QT-interval duration</td>
<td>0.3728</td>
</tr>
<tr>
<td>RR-interval duration</td>
<td>0.8880</td>
</tr>
<tr>
<td>U-wave amplitude</td>
<td>0.0314</td>
</tr>
</tbody>
</table>

abnormal wave forms not present in the leads used are being carried out. Formulation of additional steps in the protocol during the project was helpful in demonstrating that although much change is needed to include all possible wave shapes in a logic of recognition for computers it is not too complex a task to change the program and does not overburden the over-all effort.

Since each electrocardiographic lead was recorded for 5 seconds there was a minimum of three heart beats in the data. This allowed calculation of RR interval (ventricular rate) and PP interval (atrial rate). Absence of P waves or differences in these intervals allows judgments to be made with reference to arrhythmias although no attempt was made in this feasibility study to undertake a program for arrhythmia classification.

The system is capable of recognizing and measuring the parameters of the electrocardiograms in the presence of 60-cycle noise and of skin and muscle tremor. Parabolic smoothing and other procedures were incorporated into the program to reduce noise.

Discussion

It has been pointed out that the range of differences of electrocardiographic measurements acceptable as normal is due, in part, to the wide range in degree of precision used in measurement. Variation in the degree of precision also affects accuracy of nomenclature, classification, and understanding of the clinical interpretation of electrocardiographic parameters. Davis, Acheson, and Epstein and associates have demonstrated marked differences in interpretation of electrocardiograms from one reader to another, as well as individual reader difference. In part these differences may be referable to problems of measurement and a lack of standardization of ranges of normal and abnormal values among interpreters. Machine values have the advantage that they can be calibrated to conform to the desired clinical levels of precision. Since reproducibility and precision of measurement are much greater with machine analysis than with routine clinical technics, variation in measurements is virtually nonexistent in machine-derived values.

The high degree of precision, reproducibility, and speed of operation with which computers can work suggests that they are useful in evaluation of variables from large groups of subjects. Table 2 summarizes the scope of uses for computer-derived measurements. A detailed comparison of these measurements with measurements that have been considered "standard" is one method to establish the clinical value of the computer program. The results of such comparisons could be valuable in day-to-day evaluation of tracings from individual subjects.

A computer program to take computer-derived measurements and relate them in a fashion that an electrocardiographer would relate them is another useful procedure. Any of several systems of logic for use of the automatically derived data may be selected to group curve measurements, so that the results become available as an interpretation of the type familiar to physicians. As more analyses are derived by these technics the degree to which they and the clinical diag-
Figure 2
Electrocardiogram, smoothing and differentiation.

Table 2
Utilization of Electrocardiographic Measurements

<table>
<thead>
<tr>
<th>Electrocardiographic signal</th>
<th>Automatic identification of waveforms and intervals</th>
<th>Measurements of duration and amplitude</th>
<th>Comparison with &quot;standard&quot; values*</th>
<th>Interpretation singly or combined according to &quot;standard&quot; criteria or logic†</th>
<th>Statistical tabulation of variables</th>
<th>Determination of probability that a subject falls within limits of the distribution of a population‡</th>
</tr>
</thead>
</table>

*e.g.,* Lamb,9 Grabiel,9 American Heart Association.9
†e.g., Grant,9 Blackburn,10 World Health Organization.10
‡e.g., Bayes,11 Fisher.11
nosis are congruent can be established. Such systems can provide a laboratory-derived interpretation that may be useful as an aid to the physician in making his clinical evaluation of a patient.

Electrocardiographic knowledge may be furthered by detailed analysis to obtain statistically meaningful ranges of values found in normal and abnormal conditions. A statistical study of the distribution of electrocardiographic variables in various populations to establish standards to characterize those populations would be useful as guides to improve standards of interpretation in clinical electrocardiography.

Summary and Conclusions
Since the medical importance of most electrophysiologic signals is due to empiric relations established between them and disease and gross pathology, the prime requirement for medically useful computer extraction of data is a clear-cut definition of the parameters that have been found to be useful clinically. Methods of extracting pertinent variables from each electrophysiologic signal will vary depending on the clinical value placed on segments of the signal. This study demonstrates, with the electrocardiogram as the model signal, that pertinent variables can be extracted automatically from an electrophysiologic signal when relatively precise working definitions of the useful clinical parameters of the signal are formulated.

Sets of relatively precise electrocardiographic measurements were extracted automatically by use of a computer program. For present purposes, that is, demonstration of feasibility, only principal electrocardiographic waveforms and intervals were measured. The present experience shows that the program can be expanded to include any desired electrocardiographic measurement from any lead by relatively minor modification procedures. Modifications to amplify the program to detect and exclude artifacts or arrhythmia variations also are possible without unduly taxing the project.

This model study suggests that similar computer programs will be able to extract data from pertinent clinical parameters from other electrophysiologic signals. With numerical description of these waveforms, and applicable statistical technics, computer analysis will serve the physician as an aid to establish his diagnosis.

Acknowledgment
The authors are grateful to Drs. Robert P. Grant and Wright Adams for their review and encouragement. Dr. Otto Schmitt provided consistent constructive criticism throughout the study. Dr. Alvin Freiman was helpful in reviewing the criteria for parameters to be analyzed. Mr. Mort Gilbert aided in preparation of the manuscript. Computer programming was performed by Norman F. Ogilvie.

References

Circulation, Volume XXV, February 1963
Appendix

The first step in the procedure was to smooth the original electrocardiographic signal to eliminate noise (fig. 2, A and B). Smoothing was done by fitting a nine-point least-square parabola to the data. The derivative of the smoothed data was then obtained by computing the slopes of the data (fig. 2 C).

The point of greatest rate of change in the smoothed data was used as the constant point of reference. This point is between the R and the S waves and is found by locating the greatest negative value of the derivative.

Presence of R waves is determined by checking the value of the maximum positive derivative. If it is greater than 9.375 millivolts/second (5 units) within 0.128 second (80 samples) before the maximum negative derivative, an R wave is present. If the derivative is not greater than 9.375 millivolts/second then no R wave exists. If an R wave is present then the peak of the R wave is located at the point of maximum amplitude in the smoothed electrocardiographic signal within 0.064 second (40 samples) before the location of the maximum negative derivative.

S waves are searched for by determining if the derivative is greater than 3.75 millivolts/second (2 units) within 0.128 second (80 samples) after the location of the maximum negative derivative. These criteria were chosen so that the smallest slope obtained for the R and S wave in any electrocardiogram would be recognized correctly. If the derivative is not greater than 3.75 millivolts/second S waves are not present. If S waves are present the minimum negative amplitude in the smoothed electrocardiographic signal within 0.08 second (50 samples) after the maximum negative derivative is the S wave peak. Q-wave peaks are found by searching for a minimum within 0.008 to 0.056 second (5 to 35 samples) before the R-wave peak providing the slope is less than 1.875 millivolts/second (1 unit).

The P-wave peaks are searched for in the interval 0.0864 to 0.3136 second (54 to 196 samples) before the maximum negative derivative. The maximum and minimum values of the derivative are found in each 0.016-second interval (10 samples) and the maximum positive and maximum negative values are located. All other values of the derivative within 25 per cent of the maximum positive and negative derivatives are then found. Any two successive derivatives that are not of opposite polarity are discarded. The maximum and minimum amplitudes in the electrocardiogram between the positive and negative values of the derivatives are determined. Any of these peaks that are separated by more than 0.096 second (60 samples) are discarded as not being part of the P wave. The remaining maxima and minima define the type of P wave present and the greatest maximum or minimum or both, are defined as the location of the peak of the P wave. The maximum and minimum amplitudes in the electrocardiogram between the positive and negative values of the derivative and the negative and positive values of the derivative correspond to the peak (s) of positive, negative, or a diphasic P wave. The point in the interval 0.032 to 0.128 second (20 to 80 samples) before P-wave peak(s) where the slope is less than 1.875 millivolts/second (1 unit) for 0.016 second (10 samples) is labeled as the onset of P wave.

The T-wave peak is located at the point of maximum absolute amplitude in the smoothed electrocardiographic data in the interval 0.0992 to 0.3312 second (62 to 207 samples) after the S-wave peak, or in the interval 0.1504 to 0.3504 second (94 to 219 samples) after the R-wave peak, if no S wave is present.

To conform to existing clinical criteria the baseline is constructed as the straight line connecting the start of the P wave in the second beat with the start of the P wave in the third beat and all amplitudes of the electrocardiographic signal are referred to that baseline. If no P wave is found, then the baseline is defined as the straight line connecting the Q-wave onset (or the R-wave onset if no Q is present) in the second and third heart cycles.

To find the end of the S wave, the first baseline crossing within 0.08 second (50 samples) after the S-wave peak in the smoothed electrocardiographic signal is located. The point after the S-wave peak within 0.08 second (50 samples) where the derivative is less than or equal to 1.875 millivolts/second for 0.008 second (5 samples) is found. If either a baseline crossing or the point where the derivative is less than 1.875 millivolts/second (1 unit) is found, but not both, then the S-wave end is located at whichever is present. If both a baseline crossing and a derivative less than 1 unit are found, the S-wave end is located at the baseline crossing, if this
occurs closest to the S-wave peak, or if the baseline crossing and the derivative occur within 0.016 second (10 samples) of each other. The S-wave end is located at the point where the derivative is less than 1.875 millivolts/second (1 unit) if this point occurs closest to the S-wave peak and if the baseline crossing and the point where the derivative is less than one are not within 0.016 second (10 samples) of each other.

The S-wave onset is determined as the baseline crossing point between the R- and S-wave peaks, if R waves are present in the electrocardiogram. The S-wave onset is also the R-wave end. If no R waves are present, or if no S waves are present, then the S-wave start or R-wave end is found in the same manner as the S-wave end.

The end of the T and P waves and the start of the Q wave are located at the point closest to the peak of each wave where the electrocardiogram crosses the baseline or where the derivative becomes less than 1.875 millivolts/second (1 unit) and remains less than this value for 0.016 second. If Q waves are present, the baseline crossing point between the Q-wave peak and the R-wave peak is the Q-wave end, and also the R-wave start. If no Q waves are present the start of the R wave is found by the method used for the S-wave end. The T start is located by searching 0.032 second (20 samples) before the T-wave peak for a baseline crossing or the point where the derivative is less than 1.875 millivolts/second and remains less than this for 0.016 second, whichever occurs first. However, if no baseline crossing or a point where the derivative is less than 1.875 millivolts/second is found, then the T-wave start is located at the same point as the S-wave end or at the end of the R wave if no S waves are present. The amplitude at the onset of the T wave is defined as the amplitude at the end of the ST segment. To further describe the ST segment the amplitude at the point midway between the end of the wave and the beginning of the T wave is also determined. The point of maximum amplitude between the end of the T wave in the second beat and the start of the P wave in the third beat is defined as the location of the U-wave peak.

The amplitudes and durations of all parameters are finally calculated by use of the previously determined points. The computer measurements obtained by this technic simulate those that an electrocardiographer obtains with conventional tracings. The more precise measurement allowed by electronic technics suggests that more exacting clinical definitions of the baseline and onset and termination of waveforms are desirable. Studies to determine better definitions for incorporation into the computer program are in progress.

**Counterproof**

Proof that a given condition always precedes or accompanies a phenomenon does not warrant concluding with certainty that a given condition is the immediate cause of that phenomenon. It must still be established that, when this condition is removed, the phenomenon will no longer appear. If we limited ourselves to the proof of presence alone, we might fall into error at any moment and believe in relations of cause and effect where there was nothing but simple coincidence. As we shall later see, coincidences form one of the most dangerous stumbling blocks encountered by experimental scientists in complex sciences like biology. It is the post hoc, ergo propter hoc of the doctors, into which we may very easily let ourselves be led, especially if the result of an experiment or an observation supports a preconceived idea.

Counterproof, then, is a necessary and essential characteristic of the conclusion of experimental reasoning. It is the expression of philosophic doubt carried as far as possible. Counterproof decides whether the relation of cause to effect, which we seek in phenomena, has been found. To do this, it removes the accepted cause, to see if the effect persists.—CLAUDE BERNARD. _An Introduction to the Study of Experimental Medicine_. New York, The MacMillan Company, 1927, p. 34.
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