SESSION XV COMPUTERS IN PSYCHOPHYSIOLOGY: A SYMPOSIUM

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The design, development, and implementation of a microprocessor-based ECG analysis system

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This paper describes the research effort to design, develop, and implement a microprocessor-based ECG data acquisition, reduction, and analysis system for operation in real-time. This unit can be attached to three-channel ECG carts and provide an immediate on-site analysis. The basic design and development efforts include (1) the data acquisition, reduction, and matrix assembly, (2) ECG arrhythmia, P-wave, and axis analysis, (3) ECG contour analysis, and (4) a real-time three-channel data acquisition unit. Decision tables are used in the analysis. The implementation of these projects into a small microprocessor-based unit coupled to a three-channel recorder is now in progress. This system, coupled with a small printer, will provide immediate on-site ECG analysis for most cardiovascular dysfunctions.

For the past several years, computer-based analysis has been widely applied to electrocardiograms (ECGs). This analysis has proved beneficial to both the patient and the physician. For the physician, it has meant less time spent in hand analysis, more time devoted to other diagnostic methods and treatment programs, and more routine monitoring, since the reduced cost factor and the faster interpretation rate allows for more frequent ECGs. The computer is capable of performing ECG analysis 24 h/day. The readings are very exact and always consistent, and repeated readings are constant (Cornfield, Dunn, Batchlor, & Piperger, 1973).

The precision and accuracy with which the microcomputer can measure and compare ECG waveforms is now being put to the test. Several efforts have preceded the present effort to build a microprocessor into an ECG cart along with all the memory and I/O devices necessary to perform a real-time ECG analysis (e.g., see Anderson, 1977; Budde, 1977; Cox, 1978; Sanders, 1978). The microprocessor-based ECG cart, because of its small size, is very portable and, therefore, can be located anywhere, at a low cost, to provide immediate on-line analysis.

DESIGN PARAMETERS

The advantage of using a microcomputer to perform ECG interpretation is not only the capability for rapid measurements and consistency, but also the speed with which the results can be obtained due to the on-line operation. However, the microcomputer can only process the information provided to it in the manner

in which it has been programmed (Rikli, Tolles, Steinberg, Carberry, Freiman, Abraham, and Caceres, 1961). Therefore, the ECG waveform must be classified into clinical groups for pattern recognition. The most prominent characteristics used by the cardiologist are duration and amplitude. The cardiologist also depends on the slope to recognize and measure the ECG waveform components. These three characteristics (amplitude, duration, and slope) are therefore considered the basis for the recognition and measurement of the ECG by a microcomputer (Caceres, Steinberg, Abraham, Carberry, McBride, Tolles, & Rikli, 1962).

The parameters selected for measurement in our work are the P, Q, R, S, and T waves and the PR, QT, and RR intervals. Table 1 lists the ECG parameters, chosen on the basis of the information needed by an ECG analysis program utilizing decision tables. These programs

Table 1
ECG Parameters

PA	P-Wave Amplitude
PD	P-Wave Duration
QA	Q-Wave Amplitude
QD	Q-Wave Duration
RA	R-Wave Amplitude
RD	R-Wave Duration
SA	S-Wave Amplitude
SD	S-Wave Duration
STO	ST Segment Onset
QRS	QRS Complex Duration
TA	T-Wave Amplitude
PR	PR Interval Duration
QT	QT Interval Duration
RR	RR Interval Duration

Figure 1. Relationship of parameters to ECG waveform.

provide P-wave, arrhythmia, and axis analysis and determine ventricular conduction defects, preexcitation, ventricular enlargement, and A-V conduction disorders. The data defining the ECG waveform is collected by the data acquisition program. Figure 1 illustrates the relationship between the parameters and the ECG waveform. The waveform recognition program uses quantitative criteria to automatically recognize and measure these ECG parameters. A complete ECG requires the measurement of the electrical activity of the heart using 12 different electrode leads attached to the body surface. These leads are known as I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, and V6. Once the parameters have been collected for each of these leads, they are presented in a matrix format to the analysis program. The 12 different leads are represented by the columns of the matrix, and the ECG parameters form the rows, as shown in Figure 2 (Burch & Winsor, 1972).

Preprocessing

The transformation of an analog signal into a form that can be easily handled by a digital computer creates a significant problem for on-line interpretation of the ECG waveform using a microcomputer. The main problem lies in the fact that the microcomputer normally has a limited amount of memory space immediately available for storage of the collected data points. For the presented application, three analog channels are sampled simultaneously at 500 samples/sec per channel. And to properly define the ECG waveform, at least 4 sec of data

must be taken from each channel (Steinberg, 1967). This creates a need for 1,500 words or bytes of memory per second if every point is stored for all three channels. Therefore, the minimum requirement for three ECG leads is almost 6 KB of memory and, to examine all 12 leads, 4 × 6 KB, or 24 KB, of memory.

To reduce these data, a preprocessor program known as AZTEC (amplitude-zone-time-epoch-coding) is incorporated into the system. The authors of this program recognized that the ECG is composed of low-frequency components (P and T waves, ST segments) and medium-frequency components (QRS complexes). These signal components normally have amplitudes ranging from low frequencies (respiration at about .2 Hz) to high frequencies (muscle noise up to about 200 Hz). The AZTEC program suppresses the low-amplitude signals to reduce the effect of the undesirable signals (Cox, Nolle, Fozzand, & Oliver, 1968). A more detailed description of how the AZTEC program was utilized can be found in Budde (1977).

The resulting data reduction from this software preprocessor program is from a rate of 500 samples/sec to an average of 25 word pairs. This represents a reduction of about 10 to 1. The program interprets high-frequency but low-amplitude noise simply as a line, as long as the peak-to-peak amplitude does not exceed the threshold. This method of data compression offers the advantage of on-line smoothing as well as data reduction. In other words, the undesirable noise, which is relatively low in amplitude, is smoothed and the major ECG components, which are relatively larger in amplitude, are retained. The data reduction process is shown in Figure 3. In addition, the line-slope coding permits rapid searching of the stored data to locate the higher frequency QRS complexes.

ECG Waveform Recognition

There are several reasons why it is very difficult to program a computer to match the human ability to recognize an ECG waveform. First, there is a tremendous amount of variation in data from lead to lead, as well as from patient to patient. These variations create the

	I	II	III	aVR	aVL	aVF	V1	V2	V3	V4	V5	V6	
PA	.05	.13	.09	-.06	.04	.03	.04	.05	.06	.04	.08	.06	PA
PD	.06	.10	.11	.05	.10	.06	.06	.05	.07	.04	.08	.07	PD
QA	-.04	.00	.00	-.06	.00	.00	.00	.00	.00	.00	-.08	.00	QA
QD	.02	.00	.00	.00	.02	.00	.00	.00	.00	.00	.02	.00	QD
RA	.72	.60	.06	.05	.52	.00	.11	.06	.00	.00	.69	.95	RA
RD	.07	.05	.02	.02	.06	.00	.03	.01	.00	.00	.04	.07	RD
SA	.00	-.09	-.20	-.64	.00	-.12	-.94	-.94	.81	-.79	-.06	.00	SA
SD	.00	.02	.07	.06	.00	.02	.07	.08	.10	.09	.02	.00	SD
STO	-.01	-.06	-.06	.01	.05	-.03	.06	.09	.08	-.03	.01	-.02	STO
QRS	.09	.07	.09	.08	.10	.02	.10	.09	.10	.09	.08	.07	QRS
TA	.12	.10	-.06	-.12	.13	.06	.00	.16	.09	.09	.07	.06	TA
PR	.13	.15	.16	.12	.11	.21	.15	.13	.15	.12	.14	.12	PR
QT	.30	.33	.31	.34	.33	.28	.00	.33	.31	.29	.36	.32	QT
RR	.75	.75	.91	.68	.71	.75	.73	.72	.75	.73	.73	.72	RR

DURATIONS ARE MEASURED IN SECONDS AND AMPLITUDES ARE MEASURED IN mV

Figure 2. ECG parameter matrix format.

Figure 3. Data reduction.

Figure 4. Normalization of ECG data.

need for a clinical understanding of the ECG waveform components. Second, electrical noise on the ECG leads can obscure small waveforms, such as the P wave (Bonner & Schwetman, 1968a).

Several general approaches address the problem of computer recognition of ECG waveform components. First, the desired characteristics to be used in defining the ECG patterns can be established upon the experience of trained cardiologists. The cardiologists must develop a conceptual organization of those steps in their logic that are subjectively performed by them. Second, the ECG waveform patterns can be based on purely mathematical techniques (e.g., by performing Fourier series analysis on the collected data). A third approach, which combines the advantage of the other two methods, is a highly desirable technique in ECG waveform recognition. This final method of combining clinical criteria with mathematically extracted parameters is the best suited technique for computer recognition (Wartek, Milliken, & Karchman, 1970).

Normalization

The true electrical zero must be determined for each lead so that the amplitudes of the ECG waveform

components may be accurately measured. Establishing the true electrical zero or baseline of the ECG waveform has been an area of controversy created by the fact that there are two regions in the ECG waveform at which the baseline can be determined. The area between the T wave and the P wave can be selected as the baseline, or the point immediately before the QRS onset can be chosen. The area between the T wave and the P wave is often unpredictable, since the presence of U waves or overlapping P and T waves can induce error. The point immediately before the QRS onset is also imperfect due to the fact that it is affected by the presence of a little bit of atrial repolarization. However, the amount of error produced by the second case is small and predictable, whereas the first case can produce very unpredictable results. For this reason, the point immediately before the QRS onset is selected as the possible baseline value.

The possible baseline values for two consecutive cycles can then be used to determine the true electrical zero. If the difference between the baseline values for two consecutive cycles is greater than .4 mV or 10 converter units, then the first QRS complex is eliminated. If the difference between the baseline values for two consecutive cycles is less than .1 mV or 3 converter units, then the histogram method is used to determine the baseline. For this method, a histogram is calculated for the amplitude values in the region between the first corner point of the first QRS complex and the first corner point of the second QRS complex, and the most popular amplitude is chosen as the baseline or true electrical zero. Otherwise, a straight line must be fit to the baseline estimates in order to normalize the data (Figure 4). When the histogram method is used, the collected data points are normalized to the most popular amplitude. However, when a straight-line fit must be used, the normalized value for the i th data point is represented by the following formula: $Y_i^* = Y_i - (Y_2 - Y_1/X_2 - X_1)(X_i - X_1) - Y_1$, where Y_i^* is the normalized amplitude of the i th data point (Wartek et al., 1970).

DATA ACQUISITION SYSTEM

The ECG waveform is an analog signal that reflects the electrical activity of the heart. In order to allow the microcomputer to analyze this signal, the signal must be digitized. This entails sampling the signal and converting the sampled voltage to a corresponding digital code so the microcomputer can process the individual sample points. The data acquisition system is shown in block-diagram form in Figure 5 (Cox, 1978).

Sampling

According to information theory, a sampling rate twice the highest frequency component will reproduce

Figure 5. Block diagram of data acquisition system.

Figure 6. Successive approximation circuit.

the original signal provided the sampling is optimally coded. But if the sampling is not optimally coded, that is, if the samples are not taken at the peak values of the signal, then as a result, only the frequency is defined, and not the amplitude of the signal. Consequently, in practical systems, the sampling rate is usually made to give 10 times the highest frequency to assure that the critical points of the waveform are sampled.

Frequency analysis of the ECG shows that the practical frequency range may be considered to approximately .4 to 80 cycles/sec, assuming the heart rate is between 40 and 150 beats/min. Therefore, a sampling rate of 500 samples/sec is sufficient.

Interrupt Controller

A priority interrupt system controls the process of data acquisition. The highest priority interrupt is assigned to the stop interrupt, which concludes the data sampling operation and initiates the waveform 12-lead recognition program. The sample interrupt is assigned the second highest priority. This interrupt is driven by an external clock of 500 Hz. When the processor receives a sample interrupt, it jumps to the control program and samples three channels of the ECG waveform.

The priority interrupt system is based on the INTEL 8214 (priority interrupt control unit) and an 8-bit latch (INTEL 8212). When an interrupt is received, a restart instruction is placed on the data bus, which causes control to be transferred to the address specified by n times 0008A, where n is the priority of the interrupt encoded by the 8214.

Sample-and-Hold Units

Three sample-and-hold units are needed to sample three leads of the ECG simultaneously. When the hold command is issued from the microcomputer, the units stop tracking the waveform and hold the signal until

the microcomputer completes the analog-to-digital conversion. The sample command is used to initiate the tracking mode of the sample-and-hold units. The sample-and-hold units implemented is the inexpensive analog device Number AD582. The AD582 features the following: (1) 10-microsec acquisition time to .1%, (2) TTL control, (3) 3-V/microsec slew rate, (4) $\pm 0.01\%$ linearity, and (5) .05-mV/microsec droop rate.

Analog Multiplexer

An analog multiplexer is needed so that each sampled value may be passed to the analog-to-digital converter separately for digital conversion. A CMOS 4016 accomplishes this. The 4016 consist of four analog switches that can be electrically controlled. After the hold command has been issued to the sample-and-hold units, the microcomputer turns on each channel one at a time until all channels are converted to digital form.

Analog-to-Digital Converter

A successive-approximation analog-to-digital converter circuit (Figure 6), operates by comparing an unknown voltage to a series of binary weighted voltages. The unknown input voltage is first compared with the most significant bit (MSB). If it is less than the MSB, then it is turned off. Otherwise, the MSB is left on. The remaining bits are tried in the same manner until the least significant bit (LSB) has been tried. Once the process has been completed, the output register of the processor contains the binary of the unknown inputs. Successive-approximation converters are capable of high speeds and high resolutions. Also, since the conversion process is independent of the analog input, the conversion time is constant.

MICROCOMPUTER ECG ANALYSIS APPROACH

Diagnostic procedures and evaluation of ECG patterns are discussed and described in many textbooks, but it is obvious that there is a difference between the logic found in textbooks on ECG diagnosis and that which can be used in computers. First of all, when a person examines a record, there are many things he does subconsciously and easily, such as pattern recognition. The textbook takes these abilities for granted; it is difficult to tell a computer how to perform reliably the pattern recognition needed as input to an ECG diagnosis. Many checks need to be made in order to receive valid data from the computer. On the other hand, the computer will examine each beat thoroughly, whereas a person might skim and miss significant differences (Bonner & Schwetman, 1968b).

Another consideration in using textbook logic on ECG diagnosis is that, for a computer, it is incomplete. When a person performs a diagnosis, there are many steps in such a manner and order that are not described by textbooks, if they are mentioned at all. To simulate these steps in a computer, many arbitrary decisions must be made. For example, there are rules by which to deter-

mine whether two complexes are similar, or whether intervals are regular. A computer must have exact instructions on what to do and when to do it. It has to have an ordering of tests; in a textbook, there are usually only lists of tests.

Because of this lack of exact tests for purposes of diagnosing an ECG the Medical Systems Development Laboratory of the U.S. Public Health Service (1969) published a bulletin on computer-processed ECG diagnostic criteria.

This bulletin sets up the criteria for just above all associated heart conditions. As an example, if the statement "TACHYCARDIA" were printed on an ECG computer printout, it would be due to the criterion "rate exceeds 100 on any two leads." The condition printed out is more severe than that which is suppressed (i.e., "rate exceeds 100 on any one lead").

Common Methods of ECG Analysis Programs

There are three common methods to implement the criteria in a computer analysis of an ECG: a statistical procedures approach, a logic tree approach, and an approach utilizing concepts of binary logic.

Only two of the three methods could be used on a microcomputer such as an 8080 system successfully. Because programming is accomplished in assembler language, and high-level math packages are not available, this rules out any type of statistical approach. The logic tree approach presents the problem that if a mistake is made in the first tests, the effect is likely to be more disastrous than if it had been made near the end of the tree, when a final decision has almost been made. Therefore, the program should be written so that the more reliable tests are performed first. This is a very natural way to think about programming the relations between ECG data and ECG diagnostics, but it has a rather unclear control path and usually produces a very complicated program (Bonner & Schwetman, 1968a). The binary logic system may be used to create decision tables that provide a clear and very compact means for expressing complex relations between ECG items and ECG diagnostic categories (Wartek, Milliken, & Karchman, 1971). This last method was the one chosen to develop the ECG analysis program on the 8080 microcomputer system.

Decision Tables

Decision table methods are practical and have a tremendous impact on medical diagnosis. In the past years, decision tables have been used effectively to assist in commercial and scientific data problem solving. The applicability of decision tables for medical diagnosis stems from the fact that the diagnostic process is primarily logical, rather than computational, and decision tables are an ideal means for expressing complex logical relations between symptoms and diseases in a compact and readily understandable form (Wartek, 1970). How decision tables were functionally developed for this

project and the analysis procedures are described by Anderson (1977) and Sanders (1978).

The Use of Decision Tables in Medicine

The use of decision tables provides an excellent way of describing the relationship between symptoms and diseases. This relationship may be expressed as a sequence of statements that fit the pattern "if . . . and if . . . and if . . . [conditions are true], then . . . and . . . and . . . [actions that are to be taken]" (Wartek, 1970). For example, a rule may read if the RR intervals are regular, and if the QRS complexes are similar, and if the heart rate is less than 40 beats/min, then idioventricular rhythm should be diagnosed.

Decision tables can be used as a medical diagnostic tool in the following manner. Clinical data obtained from a patient are compared with values listed in the condition stub of the table. This is then checked with the rules to make certain that all conditions are valid for that rule. Having reached the first rule that matches with the patient data vector, one may ignore any further columns to the right. At this time, the actions dictated by the rule that matches are then acted upon. If no rules in this table are satisfied, then the ELSE rule comes into action and the diagnostic process is transferred to another part of the program (Wartek, 1970).

Incorporating Decision Tables Into a Microcomputer Program

The use of decision tables in a microcomputer involves translating them into machine-readable code by using a "bit" (a binary digit). The descriptors are used and ranked in this order: (1) ventricular regularity, (2) QRS complexes similar, (3) ventricular rate, (4) presence or absence of P waves, (5) association of P waves with QRS, (6) atrial rate, and (7) QRS width.

The following is an example translation of nodal rhythm into a decision table format. A description of nodal rhythm from a textbook might be: The rhythm is regular with a rate of 40-60 beats/min. The characteristic ECG findings are P waves inverted in Leads II and aVF and upright P waves in aVR (retrograde conduction). The PR interval is short, usually .12 sec or less. The abnormal P wave is in front of the QRS complex if the pacemaker is in the upper extremity of the AV node. The P wave follows the QRS complexes if the pacemaker is situated in the lower extremity of the AV node. If located in the center of the node, the P wave usually is lost in the QRS complex and becomes invisible (Bernreiter, 1963). This, combined with U.S. Public Health Service (1969) diagnostic criteria for computer-processed ECG produces a decision table.

Two cases are created for nodal rhythm because of the P wave that might or might not exist. This is a good example of the provisions provided by decision tables.

If decision tables are ascertained for all arrhythmia cases and then combined into one, many condition checks would almost be the same. These duplications

[illegible]

Figure 8. Decision table for arrhythmia II.

[illegible]

Figure 9. Decision table for arrhythmia III.

CONCLUSION

This paper describes the research effort to develop a microprocessor-based unit and programs to provide arrhythmia P-wave and axis analysis and contour analysis of a standard patient ECG. The contour analysis program will determine ventricular conduction defects, preexcitation, ventricular enlargement, and A-V conduction disorders. Decision tables are used to establish a set of decision rules that can be logically linked together for ECG analysis. These tables provide the means to implement minimum-size microcomputer software programs. The microcomputer, with these programs and the data acquisition and compressions programs, can be attached to a standard three-channel ECG cart and provide immediate on-site ECG interpretation.

REFERENCE NOTES

1. Flowers, N. Personal communication, 1977.
2. U.S. Department of Health, Education, and Welfare. *Diagnostic statements and criteria for ECG evaluation study* (Working document). Washington, D.C: Author, 1977.

REFERENCES

- ANDERSON, S. W. *Development of a real-time ECG arrhythmia, P-wave and axis analysis program utilizing a microprocessor system*. Unpublished master's thesis, University of Louisville, Speed Scientific School of Engineering, Department of Applied Mathematics and Computer Science, 1977.
- BONNER, R. E., & SCHWETMAN, H. D. Computer diagnosis of electrocardiograms. II. A computer program for EKG measurements. *Computers and Biomedical Research*, 1968, 1, 366-386. (a)
- BONNER, R. E., & SCHWETMAN, H. D. Computer diagnosis of electrocardiograms. III: A computer program for arrhythmia diagnosis. *Computers and Biomedical Research*, 1968, 1, 387-407. (b)
- BUDDE, S. R. *Development of a data acquisition system and pattern recognition program for on line ECG analysis using a microcomputer*. Unpublished master's thesis, University of Louisville, Speed Scientific School of Engineering, Department of Applied Mathematics and Computer Science, 1977.
- BURCH, G. E., & WINSOR, J. *A primer of electrocardiography* (6th ed.). Philadelphia: Lea & Febiger, 1972.
- CACERES, C. A., STEINBERG, C. A., ABRAHAM, S., CARBERRY, W. J., MCBRIDE, J. M., TOLLES, W. E., & RIKLI, A. E. Computer extraction of electrocardiographic parameters. *Circulation*, 1962, 25, 356-362.
- CORNFIELD, J., DUNN, R. A., BATCHLOR, C. D., & PIPBERGER, H. V. Multigroup diagnosis of electrocardiograms. *Computers and Biomedical Research*, 1973, 6, 35-47.
- COX, J. R. *A real-time data acquisition unit for a microprocessor-based three channel ECG analysis system*. Unpublished master's thesis, University of Louisville, Speed Scientific School of Engineering, Department of Electrical Engineering, 1978.
- COX, J. R., NOLLE, F. M., FOZZAND, H. A., & OLIVER, G. C. Aztec, a preprocessing program for real-time ECG rhythm analysis. *IEEE Transactions on Biomedical Engineering*, April, 1968, 128-129.
- RIKLI, A. E., TOLLES, W. E., STEINBERG, C. A., CARBERRY, W. J., FREIMAN, A. H., ABRAHAM, S., & CACERES, C. A. Computer analysis of electrocardiograph measurements. *Circulation*, 1961, 24, 643-649.
- SANDERS, C. *Development of a real-time contour analysis program utilizing a microprocessor system*. Unpublished master's thesis, University of Louisville, Speed Scientific School of Engineering, Department of Applied Mathematics and Computer Science, 1978.
- STEINBERG, C. A., & PAYNE, L. W. Methods and techniques of data conversion. *Annals of the New York Academy of Sciences*, 1967, 115, 614-626.
- U.S. PUBLIC HEALTH SERVICE. *Computer processed electrocardiogram diagnostic criteria*. Washington, D.C: U.S. Government Printing Office, October 1969.
- WARTEK, J. A practical approach to automated diagnosis. *IEEE Transactions on Biomedical Engineering*, 1970, 17, 37-43.
- WARTEK, J., MILLIKEN, J. A., & KARCHMAN, J. Computer program for pattern recognition of electrocardiograms. *Computers and Biomedical Research*, 1970, 3, 344-360.
- WARTEK, J., MILLIKEN, J., & KARCHMAN, J. Computer program for diagnostic evaluation of electrocardiograms. *Computers and Biomedical Research*, 1971, 4, 225-238.