# Mayo Clinic Electrocardiography (ECG) Laboratory System

In the late 1960s, Mayo Clinic automated their ECG Laboratory with an IBM 1800 computer. This machine was connected to several recording rooms to acquire the patient's electrocardiogram. The diagnostic program was the Smith/Hyde Mayo/IBM ECG analysis program developed initially on the IBM SYS/360 and later converted to the 1800. Ralph E. Smith was the director of the Mayo ECG laboratory, and Clyde M. Hyde was his IBM collaborator. Eugene Strand was an IBM programmer on the project.

This program analyzed an ECG using modified Frank leads, and prepared a report with a diagnosis and the ECG signals. Initially the cardiologist made an independent diagnosis and then compared it to the computer diagnosis producing the final report. Later as the program improved in accuracy, the cardiologist read the computer diagnosis and the signals simultaneously and edited the diagnosis as needed, reducing the time it took to read an ECG.

The MAYO/IBM ECG program was made available to several other hospitals. There were two releases, one in 1968 and one in 1970.

# CENTRAL COMPUTER TELEPROCESSING OF REMOTE ELECTROCARDIOGRAMS

Using the Smith-Hyde-Mayo-IBM analysis program, a system has been developed which provides for high volume, remote, on-line, real-time access to a central computer facility for performing comprehensive measurements and interpretations of clinical electrocardiograms. Processing time per ECG is less than one minute. Continuous operation on a 24-hour mass production basis can handle over 1,000 ECG's per day assuming adequate scheduling. More typically the system hands only a small fraction of the maximum ECG load. The time-sharing interrupt feature allows the central computer power to be allocated and pro-rated on an assigned priority basis to a wide variety of other jobs during non-ECG periods. Such a system can be economically justified on either high volume mass screening jobs or multiple low volume remote hospital and clinic assignments yielding per ECG computer cost of less than one dollar. To provide these services special input-output programs have been written for the IBM 1800 computer to effect an on-line status of the remote ECG terminal. The remote terminal, regardless of its distance, transmits data and receives computer results immediately thereby eliminating the ambiguity of delays associated with tape recording. Three 0-100 Hertz channels of scalar and vector lead ECG data are automatically lead switched and transmitted in parallel over the nation-wide dial up telephone new work using Marquette Electronics C-205 Patientransmitters. Appropriate computer messages to the remote ECG technician and ECG analysis results are returned via the same telephone connection to the sender using a miniaturized remote alphanumeric printer.

Robert A. Stratbucker, M.D.
Associate Professor, Internal Medicine
Director of Medical Research Computer Center
University of Nebraska College of Medicine
Omaha, Nebraska 68105

THIRD ANNUAL ROCKY MOUNTAIN BIOENGINEERING SYMPOSIUM

IEEE CONFERENCE RECORD

University Memorial Center
University of Colorado
Boulder, Colorado.

May 2-3, 1966

LIBRARY OF CONGRESS CATALOG CARD NUMBER 66-19758



Additional Copies May Be Purchased From:

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street New York, N. Y. 10017

Printed in USA

Price: Libraries $7.50
Individuals $6.00

# A COMPUTER SYSTEM FOR ELECTROCARDIOGRAPHIC ANALYSIS

R. E. Smith, M.D., Consultant
Mayo Clinic
Rochester, Minnesota

C. M. Hyde, Ph. D., Advisory Engineer
IBM Advanced Systems Development Division
Rochester, Minnesota

## Summary

A clinical system for the machine analysis of ECG's has been developed jointly by the Mayo Clinic and IBM. The data acquisition system is initiated at patient beds when multiple electrodes are placed on patients. With the system, 300 electrocardiograms can be recorded on one console each day. An operator at the control console selects the proper patient by a switching device, and monitors the multi-channel recording on an oscilloscope, the last human intervention into the system. Frank lead system voltages are digitized and entered into the IBM 7040 Data Processing System. A recognition and measurement program determines heart rate, P and R duration, and PR and QT intervals. Magnitude and angles of the voltage vectors are determined. These measured values constitute a set of quantities upon which the analysis program is based. The program output consists of time interval measurements, narrative diagnostic statements, and graphic plots.

## Introduction

Computer measurements of ECG parameters have a high degree of accuracy. They can be made rapidly and provide a basis for quantitative analysis of the ECG which is void of intra- and inter-human variations.

Such an ECG analysis system is being developed jointly by IBM and the Mayo Clinic. The overall system consists of four parts:

- Data acquisition,
- Conversion,
- Data reduction, and
- Analysis.

The data acquisition equipment has been in operation at the Mayo Clinic for about four years. By its use, the 12 leads of the usual electrocardiogram are recorded along with modified Frank X, Y, and Z leads in quick succession. The 3 Frank leads are recorded simultaneously for 8 sec on both oscillographic paper and FM magnetic tape at a speed of 3-3/4 in./sec. Using this equipment, over 300 patients can be recorded with one electrocardiographic console in an 8-hr period. A special patient identification code is recorded on an additional channel. At the end of each day, the tapes are delivered to the computer facility. Using an analog tape recorder in the reproduce mode, the tape is "played back" through signal lines to the analog-to-digital converter. A digital tape is written and the data are processed in the data reduction program called STORE. The STORE program identifies the different electrocardiographic complexes, makes interval and voltage measurements, and writes a digital library tape of the reduced data.

This library tape provides an input to the analysis (ANALYS) program. This segment of the ECG system produces a narrative output which includes the patient clinic number, patient name, data, section to which he is assigned, age (if under 15), and commonly used measurements. A statement then follows categorizing and recording as NORMAL, BORDERLINE, or ABNORMAL, and one or more of over 50 diagnostic classification statements. In addition to the narrative output, a graphic output is available which includes patient identification, frontal, horizontal and right sagittal vector loops of the R, P, and T vectors independently, as well as separate plots of the initial forces of the R wave. Scalar plots and ladder diagrams are also available.

## Input Signal Requirements

Electrocardiographic signals must meet certain minimal specifications if they are to serve as input signals to a computer. Accordingly, certain minimum specifications must be met by the signal acquisition processing and recording equipment.

The program described here requires that the recorded ECG voltages have reasonably steady baselines without extreme low frequency variations such as might be caused by a coughing patient or other severe muscular artifact. Noise on the signal must be low enough to allow the predescribed routines (or rules) of the program to locate the small voltage signals of certain parts of the electrocardiogram, such as the small P waves.

The quality of the signal delivered at the output of any system element can be no better than the signal at the input of that element. Thus, each system element should perform its job with minimum distortion to the signal. To insure that the signals sent to the computer are within limits of the input requirements, automatic alarm signals aid an operator (who introduces the last human intervention).

In certain types of arrhythmia cases, the proper analysis can be obtained only after examining many cycles of the ECG. To treat these cases properly, more than 8 sec of input data may be required.

Data Reduction or Storage Program (STORE)

The Fortran IV computer programs described below are used at the Mayo Clinic in conjunction with an IBM 7040 Data Processing System. The routines have been tested on IBM 7090 and 7094-II Computers.

We decided at the onset that the program should be written so that other users might easily adopt it to their particular use. Accordingly, it was written with:

- Fortran IV language, for adaptability to the IBM 7090, 7040, and other computers.
- Variable sample rates (350-357-500 have been tested).
- Program control of signal levels using calibration signals.
- Program measured noise level.
- Easily changeable diagnostic statements and criteria.
- Features to allow high speed ECG storage and retrieval via computer systems.

The data acquisition system provides the desired orthogonal signals to the computer. An INPUT subroutine of the STORE program loads the computer with the necessary data. At the Mayo Clinic, the INPUT subroutine works in conjunction with the analog-to-digital converter and loads the computer memory directly from the analog FM tape.

Figure 1 indicates the sequence of system functions. The operations provided by the computer consist of digitization, production of a digital tape for temporary storage of all the input data (saved for one day), and generation of the permanent storage tape and output, consisting of both printed and graphic results.

A summary flow chart of the ECG computer program is indicated in Figure 2. The major steps of the program consist of input, signal conditioning, and finding R waves, T waves, and P waves. Eight seconds of data or a maximum of 12 complexes are analyzed.

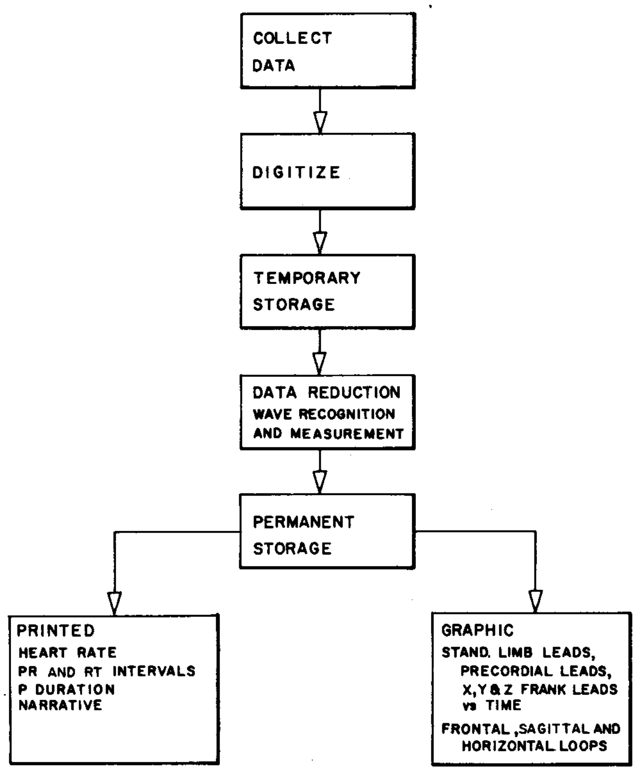



Figure 1. Computer operations

The important time intervals are then determined and the wave segments are, in effect, redigitized to reduce the amount of digital storage required. These data are placed on a digital tape for permanent storage. The digital tape provides the input to the ANALYS program which produces a diagnostic narrative and graphic output.

During the input function of the program, 8 sec of data from the Frank lead system are read into the computer. A calibration indicator is checked. If the indicator is true, the input is a calibration signal and a calibration multiplier is determined. Then the next segment of data is called. Subsequent electrocardiographic signals from patients are multiplied by the previously determined calibration multiplier. These data are then collated with the label data consisting of the patient name, clinic number, and other labeling data previously mentioned. From the input, a difference function is generated. Using this function, the flat segment preceding the R wave is located. The baseline is straightened from cycle to cycle with respect to this point. The noise on the signal is also measured on this flat region where absence of the electrocardiographic signal is assumed.

The R waves are located and a magnitude function, R(J) is determined. The maximum value and its

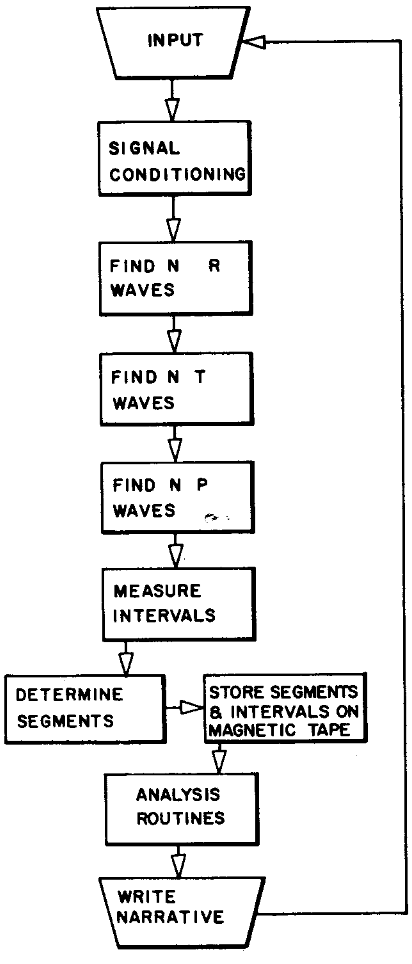



Figure 2. Mayo ECG recognition, measurement, and analysis program

time location are ascertained. The onset and termination of the R wave are also located.

Next the T waves are found by searching for voltage changes from the end of the R wave to a point approximately half way between the R waves. P waves are located in the region between the onset of the R wave and the end of the preceding T wave. Then the onset and termination of P waves are determined.

After the T, P, and R waves are located, the P duration, PR interval, RT duration, and R-R interval, as well as R duration, are computed for each cardiac cycle. Mean values and standard deviations for each of these measurements are calculated. Each individual value is then compared with the mean. If 75% of the individual values are within 1. 2 standard deviation of the mean, a confidence of high is indicated. If not, the confidence is considered low and additional steps are taken to ascertain the representative value.

Storage is accomplished by obtaining a sample every 5 msec during the rapidly changing portion of the electrocardiogram, that is, during the R wave. During the rest of the cardiac cycle, samples are stored at 20-msec intervals, as illustrated in Figure 3.

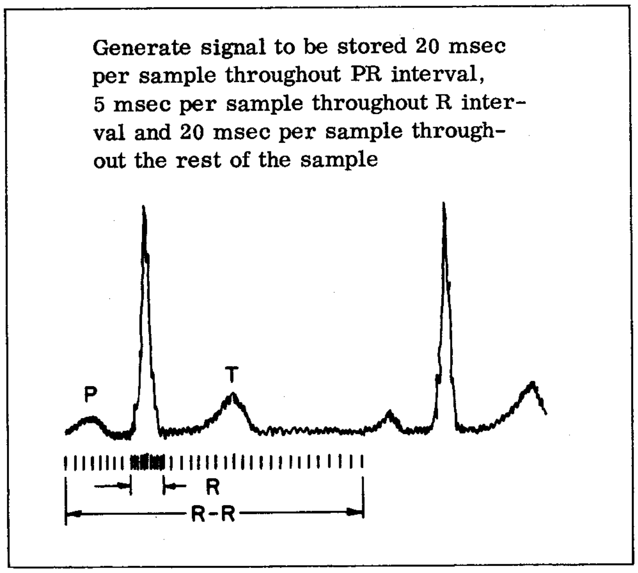
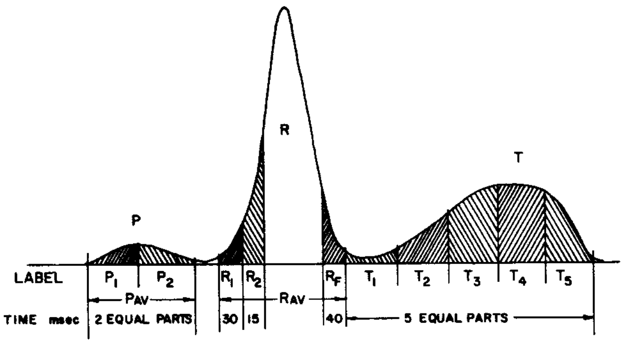



Figure 3. Segment determination

In summary, the STORE program has proceeded by finding each of the R waves, straightening the baseline, measuring the noise, finding each T wave and each P wave, measuring the intervals, finding the most likely values, checking for arrhythmia and types of waves, and finally generating the storage data. The storage data consist of patient identification, heart rate, the various intervals and durations and voltage values at the time intervals previously described in each of the three leads for one complete cardiac cycle. For the case of arrythmia, one cycle of data is stored for each type of complex present and each of the R-R intervals, PR intervals, and R durations. Thus, about 30, 000 bits of information per ECG are stored on a library tape which is capable of retaining approximately 10, 000 ECG's per reel.

## Analysis

The ANALYS program uses as input the output of the STORE program. The first phase of the program calculates mean vector quantities at certain time intervals. These vectors, depicted in Figure 4, represent the initial and terminal P-wave activity, diagnostically important intervals of R wave activity, and five equal interval ST-T wave segments. These stereovectorial electrocardiographic parameters provide the basis for the quantitative analysis.




$$P_1 = \sqrt{\left(\sum_0^{P/2} X_n\right)^2 + \left(\sum_0^{P/2} Y_n\right)^2 + \left(\sum_0^{P/2} Z_n\right)^2} \left(\frac{Z}{P}\right)$$

$$\Theta_{P_1} = \mathrm{Tan}^{-1} \frac{\sum_0^{P/2} Y_n}{\sum_0^{P/2} X_n}$$

$$\mu_{P_1} = \mathrm{Tan}^{-1} \frac{\sum_0^{P/2} X_n}{\sum_0^{P/2} Z_n}$$

Figure 4. Analysis program, labels for intervals of summation

The next phase of the analysis resolves the broad classification, NORMAL, BORDERLINE, or ABNORMAL, of the ECG. To define these classifications as well as abnormal categories, logical IF statements of Fortran IV are employed. Statements defining NORMAL (paraphrased for clarity) follow:

IF (.10 .LT. DPR .LT. JP .AND. 260 .LT. FPP .LT. 15 .AND. .09 .LT. PP .LT. 14 .AND. 105 .LT. HROR3 .LT. 280 .AND. FROR3 .GT. 196 .AND FR (4)) .GT. FROR3 .AND. R4MVS .LT. .2 .AND. (FROR3 - FROR(4)) .GT. 90 .AND. 180 .LT. (HROR3 - HR (4)) .LT. 112 .AND. DRR .LT. 82 .AND. R6MVA .GT. .06 .AND. 180 .LT. HR(1) .LT. 40 .AND. HR(2) .LT. HR (1) .AND. HR (2) .GT. 180 .AND. HR(3) .LT. HR(2) .AND. HR(3) .GT. 180 .AND. 15 .GT. FRR .GT. 260 .AND. DRR .LT. 112 .AND. RMAX .LT. 2.1 .AND. DRT .LT. JIN .AND. YT1 .LT. .085 .AND. YT2 .LT. .075 .AND. T2 .LT. .075 .AND. T6 .LT. .135 .AND. (.150 .GT. ABS (FT2 - FT6) .GT. 200 .OR. 150 .GT. ABS (HT2 - HT6) .GT. 200) .AND. XT1 .LT. .075 .AND. YT1 .LT. .075 .AND. ZT1 .LT. .075 .AND. 5 .GT. FTMAX .GT. 265 .AND. HTMAX .LT. 110 .AND. TMAX .GT. .095 .AND. .NOT. AF)
Write NORMAL.

In the statements, JP and JIN are computed values and AF is a logical indicator of atrial fibrillation. The first letter in the code is D, F, H, T, R, P, X, Y, or Z representing duration; frontal plane angle; horizontal angle; T, R, or P wave; or x, y, or z projection respectively; R(4) refers to the fourth 10-msec segment of the R wave, ROR 3 is the first 30-msec segment of the R wave, RR is the mean R wave, and R4 MVS is the magnitude in mv of the fourth 10-msec segment of the R wave. Right-hand positive angles start with zero at the left arm in the frontal plane, anteriorly in the horizontal plane.

This test insists that the PR and QT intervals and R and P durations be within specified limits for the ECG to be classified as NORMAL. Segments of the R and T waves are tested for magnitudes and directions. If all conditions are satisfied, the statement NORMAL is written. If normal rhythm exists, the rate is written and another ECG record is called.

Assuming one or more of the NORMAL conditions are not met, the requirements or limits are relaxed somewhat and the BORDERLINE test is executed. This test consists of an IF statement similar to the NORMAL IF statement. These IF statements are usually less complex. The logic associated with the diagnostic decisions includes restrictions such that non-compatible diagnosis statements cannot occur in the narrative output. Statements of diagnostic classifications are then written.

If arrhythmia exists, an arrhythmia subroutine is called. For the NORMAL cases, appropriate statements such as premature complexes, sinus arrhythmia, etc. are written. In complex abnormal arrhythmias, one or more of the arrhythmia statements may be written.

If the ECG is classified as BORDERLINE or ABNORMAL, a PLOT subroutine is called which plots the vector loop, one cycle of the Frank X, Y, and Z voltages, and if arrhythmia is present, a ladder diagram is constructed.

Figure 5 shows a comparison between the computer plotted loops and photographs of standard VCG

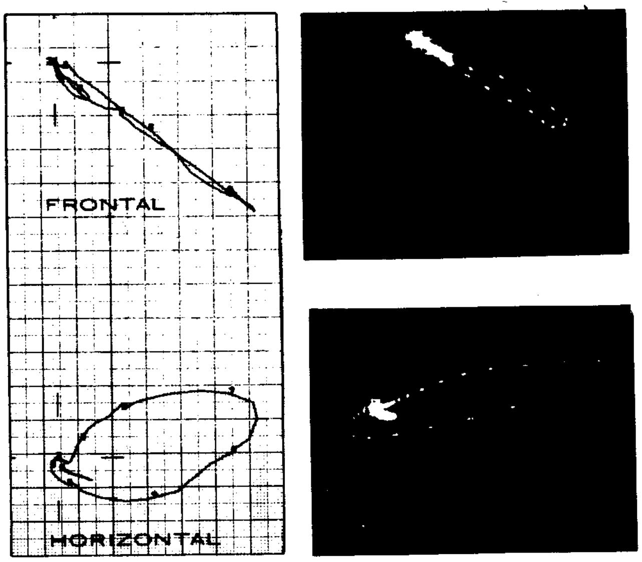



Figure 5. IBM 1627 loops vs oscilloscope loops

oscilloscope loops. The oscillographic loops were obtained from the Frank lead system with the patient in a sitting position. The computer loops were recorded with a modified Frank system with the patient supine.

## Results

Approximately 50,000 electrocardiograms have been analyzed using the Mayo-IBM ECG analysis system. Recently 1191 computer analyses were compared with the results provided by a reading team of cardiologists (see Table 1). Eight hundred and thirty-six ECG's were classified NORMAL by the team. Sixty-six of these were called ABNORMAL or BORDERLINE by the computer. Ten of the 355 classified ABNORMAL or BORDERLINE by the team were called NORMAL by the computer. Of the BORDERLINE or ABNORMAL ECG's, 92 were incompletely described by the computer.

Table 1. Analysis results

| Classification | Cardiographer | Computer Disagreement |
|---|---|---|
| Normal | 836 | 66 (7.8%) |
| Abnormal or Borderline | 355 | 10 (2.8%) |
| Incomplete Description | -- | 92 |
| Total | 1191 | 168 (14%) |