COMPUTER ANALYSIS OF THE TREADMILL EXERCISE ECG

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Summary. A computer program for analysis of the exercise electrocardiogram has been developed at the LDS Hospital, Salt Lake City, Utah. This program is used to enhance the electrocardiogram, extract parameters and classify the test as positive or negative. A study involving 68 patients who underwent cardiac catheterization and selective coronary arteriograms has been conducted to test the effectiveness of this program in properly classifying these patients. Using a parameter based on the frequency of abnormal conditions, the program agreed with the cardiologist's classification of the test in 67 of the 68 patients. In comparing the classification with the evaluation of the coronary arteriograms there were 4 false-positive patients and 7 false-negative patients.

Complete computer processing of exercise electrocardiographic data consists of three tasks. These tasks are:

1. Reduction of noise in the electrocardiographic signals (e.g., time coherent averaging).
2. Extraction of quantitative parameters from the signal.
3. Interpretation of the test (i.e., the test is positive or negative).

A computer program which performs each of these tasks is now in routine clinical operation at the LDS Hospital. Signal processing techniques were used to solve the first two tasks so that reliable data could be collected to test the effectiveness of the solution to task three which is a decision problem.

The program at the LDS Hospital is an on-line program, which samples three leads of ECG data simultaneously at 200 samples per second for 20 seconds. Currently the leads being sampled are V4, V5, and lead 2. The data can be sampled at any time by the cardiologist, but generally a protocol is followed in which data is sampled at the end of each stage of exercise as defined by Bruce. This 10 second set of data (excluding all premature complexes) is time coherent averaged on each lead to generate a single complex from each lead which is the "noise free" complex on which the parameter extraction will take place.

The extraction of parameters is dependent on the location of the onset and end of the QRS in each lead since the onset of QRS is assumed to be the isolectric point for purposes of calibration and because the ST segment to be analyzed by the program is defined as the 80 millisecond interval following the end of the QRS. Using this ST segment, the average ST level is measured in the interval and the slope of the "least-square" line through the ST interval is determined. These two parameters from each lead, together with the patient's heart rate at that stage of exercise, become the basic data set stored on the patient's record during the exercise test. To insure the accuracy of location of QRS onset and end an assumption has been made that the duration of the QRS complex does not significantly change during exercise. Based upon this assumption, the program locates the onset and end of the QRS relative to the fiducial point (point on QRS with minimal first difference) used for time coherent averaging only once during the entire exercise procedure. This is done during the first analysis, which is while the patient is lying at rest prior to the initiation of exercise. At this point the signal to noise ratio is maximum and thus the accuracy of the computer algorithm for measurement of onset and end is optimized. Even with this optimization, however, a feedback mechanism is provided to the cardiologist at this point to allow him the option of changing either the onset or end of the QRS if he feels that the computer algorithm for location is in error. Once these locations are accepted by the cardiologist their position relative to the fiducial point is recorded and all subsequent determination of those locations is accomplished by merely locating the appropriate fiducial point on the averaged complexes and arbitrarily assigning the onset and end of the QRS to their relative positions with respect to that fiducial point. This technique has proved to be extremely successful and insensitive to noise even in the presence of extreme noise during maximal exercise conditions. On completion of the test a report of the averaged complexes is printed by the computer. Figure 1 is a copy of a report showing the averaged complexes with the vertical marks on the complexes indicating onset and end of the QRS and the ST interval used for analysis. The column on the left is the stage of exercise. The ST level and slope are recorded under each complex and the heart rate for that stage is recorded at the left.

In order to develop diagnostic algorithms for automatic interpretation of the exercise test using the parameters recorded by this program, data on a series of normal patients and patients with coronary artery disease (CAD) was collected. All of the patients included in the study have undergone heart catheterization where selective coronary arteriograms were recorded and evaluated. All patients in the study had a normal resting electrocardiogram and had not taken digitalis for at least one week prior to the study. During exercise each patient reached at least 80% of his predicted maximal heart rate. Based on the coronary arteriograms the patients were divided into two populations. The first population being those with significant coronary artery disease, which was defined as having greater than 75% occlusion of at least one major vessel. This resulted in 29 CAD patients and 39 patients without significant CAD. Using an interactive clinical research system at the LDS Hospital called STRATO, a set of criteria for interpretation of the exercise test was evaluated. It is possible, using this system, for a researcher to easily define and test various diagnostic criteria. The criteria are written in a higher level language called HELP, which has been developed at the LDS Hospital specifically for medical decision-making. Figure 2 shows the criterion which has proved most successful on the present population. The figure is a copy of the actual HELP decision block showing the structure required to write the criterion. In values. The final evaluation (FVAL) for this sector is the sum of frequencies of the individual search items, i.e., A through F, thus generating a parameter which is the cumulative number of times during the test (in all leads) following stage 2 that there was an ST segment depression of .075 mv or more with a flat or negative slope or an ST segment depression of .2 mv or more. This parameter was chosen because of its relative insensitivity to errors in measurement of the stored parameters. A simple comparison of the robustness of this parameter is seen by considering the difference between the mean and the median, where the mean can be severely biased by a single outlier. This new parameter is similar to the median in that a measurement outlier resulting from excessive noise has the effect of influencing the frequency by only one count, which would not result in classifying the test as positive. The true positive patient, however, would be expected to exhibit numerous leads with the abnormal condition. Figure 3 is the distribution of this new parameter for the "normal" and CAD patients. The normal patients are labeled Control and the CAD patients Test. From this distribution a threshold frequency of 3 was chosen as the criteria for a positive test.

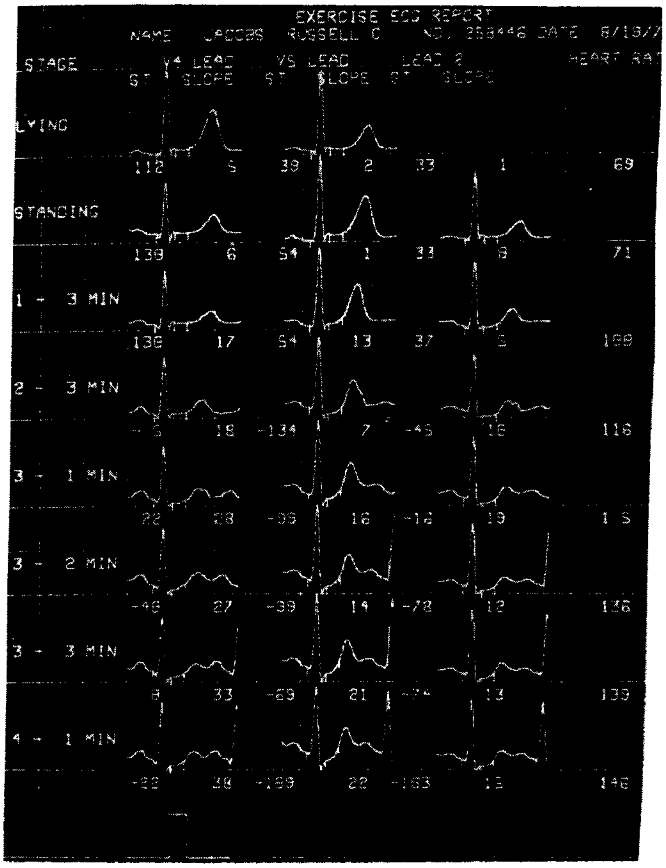

Figure 1

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SECTOR      4
FREQUENCY OF ABNORMAL ST SEGMENT **
INHIBIT LOGIC = ALWAYS PRINT
FVAL  A+B+C+D+E+F
A  (A) AVERAGE ST LEVEL IN LEAD V4,(B) AVERAGE ST SLOPE IN V4,(C) EXERCISE
   STAGE BOL (A LE -75) AND (B LT 2) AND (C GE 2) FREQ
B  (A) AVERAGE ST LEVEL IN V5,(B) AVERAGE ST SLOPE IN V5,(C) EXERCISE STAGE (
   (A LE -75) AND (B LT 2) AND (C GE 2) FREQ
C  (A) AVERAGE ST LEVEL IN LEAD 2,(B) AVERAGE ST SLOPE IN LEAD 2,(C) EXERCISE
   STAGE BOL (A LE -75) AND (B LT 2) AND (C GE 2) FREQ
D  (A) AVERAGE ST LEVEL IN V5 BOL A LE -200 FREQ
E  (A) AVERAGE ST LEVEL IN LEAD V4 BOL A LE -200 FREQ
F  (A) AVERAGE ST LEVEL IN LEAD 2 BOL A LE -200 FREQ

FINAL EVALUATION(1), SECTOR LOGIC(2), COPY SECTOR(3), NEW SECTOR(4),
OTHER OPTIONS(5)
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Figure 2

ACTUAL DISTRIBUTION OF RAW DATA

FROM	TO	NUMBER CONTROL	NUMBER TEST	PERCENTAGE CONTROL	PERCENTAGE TEST
0-	2	35	7	90	24
3-	4	0	4	0	14
5-	6	1	3	3	10
7-	8	0	5	0	17
9-	10	1	3	3	10
11-	12	0	2	0	7
13-	14	0	0	0	0
15-	16	1	1	3	3
17-	18	0	2	0	7
19-	20	0	1	0	3
21-	22	1	0	3	0
23-	24	0	0	0	0
25-	26	0	0	0	0
27-	28	0	0	0	0
29-	30	0	0	0	0
31-	32	0	0	0	0
33-	34	0	0	0	0
35-	36	0	0	0	0
37-	38	0	0	0	0
39-	40	0	1	0	3

Figure 3

viewing this criterion, statements A through F are statements which cause data searches to be initiated on a patient's medical record. For example, statement A requests a search be made on this patient's data to determine the frequency (indicated by the FREQ at the end of the statement) of occurrence of the conditions indicated by the search parameters and Boolean logic of the search. The parameters to be searched are the average ST level in V4, the slope of the ST segment in V4, and the stage of exercise. The Boolean logic states that the search is true (i.e., add one to the frequency count of this condition) if the ST level in V4 is less than minus .075 mv with an ST slope less than .2 mv/sec and the stage of exercise being stage 2 or greater, including post exercise

This criteria gave a 98% (67/68) agreement with the cardiologist in his interpretation of the exercise test with the disagreement occurring in only one patient who was clearly borderline. In reviewing the correlation of the exercise test with the arteriograms, there were 4 false-positive patients from the 39 "normals" and 7 false-negative patients from the 29 patients with a significant CAD. Analysis of the false-positive patients indicated that in each case the patient exhibited a condition known to cause diagnostic ECG changes. Figure 4 is a summary of these patients. With the false-negative patients it was found that 6 out of the 7 patients had only single vessel disease, did not develop angina during the test, and did not have a history of typical angina. The seventh patient was that patient where the cardiologist and the computer disagreed.

COMPUTERIZED TREADMILL ECG ANALYSIS

FALSE POSITIVES (10%)

	AGE	COMMENTS
F.S.	48M	LVEDP = 16 mm Hg (REST)
G.H.	43M	EXERCISE PAIN, S4 IN RECOVERY
W.H.	51 M	ORTHOSTATIC & HYPERVENTILATION ST-T WAVE CHANGES
J.L.	46M	MITRAL VALVE PROLAPSE ON ECHO

Figure 4

Figure 5 summarizes these patients.

COMPUTERIZED TREADMILL ECG ANALYSIS

FALSE NEGATIVES (24%)

	CORONARY ANGIO	PAIN HISTORY	EXERCISE PAIN
R.E.	100% $RCA_{(c)}$	ATYPICAL ANGINA	NO
W.C.	100% $RCA_{(c)}$	NONE	NO
L.B.	100% $RCA_{(c)}$	NON-ANGINAL	NO
R.H.	75-90% RCA	NONE	NO
J.O	75-90% LCX	ATYPICAL ANGINA	NO
T.W.	75-90% LAD	ATYPICAL ANGINA	NO
F.S.	75-90% RCA 90-99% Branch of LCX	TYPICAL ANGINA	YES

Figure 5

These results suggest that computer interpretation of exercise data based upon the application of standardized criteria in evaluating this test is valid. It now remains to build into the diagnostic model for prediction of CAD factors beyond the exercise test. As these factors which include the history, risk factors, etc. are developed, the ability of the computer in diagnosing ischemic heart disease should become effective.