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Computer Methods and Programs in Biomedicine 63 (2000) 147–155

Computer Methods and Programs in Biomedicine

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ECG Variable Cine: computer program for presentation of temporal changes in ECG variables over different number of ECG leads☆

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Received 27 August 1999; received in revised form 26 January 2000; accepted 24 March 2000

Abstract

The analysis of exercise electrocardiogram (ECG) is based on the alteration of the measured variables in the detection of coronary artery disease (CAD). In its existing form the analysis of the exercise ECG is laborious and requires much time. The temporal analysis of the ECG variable and the comparison between different phases of the exercise test is difficult and time consuming, especially the simultaneous examination of the variables over several leads. In this article we present a computer program, ECG Variable Cine, for the visualization of the temporal changes of values of exercise ECG variables over the selected ECG lead system. The program includes the stationary 3-D presentation for the variables' alteration simultaneously in all selected leads over the time of exercise test. In addition, the program determines two parameters; the average value of the variable over the selected leads at every sample moment, and the chronotropic index, a parameter that indicates heart rate response to exercise. According to the results the average value of ST-segment deviation at the end of the exercise over the leads and chronotropic index are clinically more competent than the maximum value of ST-segment depression in the detection of CAD.

Keywords: ECG; Exercise test; Computer program

1. Introduction

Coronary artery disease (CAD) is still the main cause of death in developed countries. Exercise test is the first clinical examination when CAD is suspected. Electrocardiogram (ECG) is the most important factor during the exercise test. The exercise ECG test is simple, cheap and a relatively accurate method. In CAD detection, the main interest during the exercise ECG test is focused on the ST-segment alterations during the exercise and recovery phases [1]. Also the changes in the R- [2,3] and T-waves [4,5] have shown to have an importance when detecting the CAD based on the

☆ The program written in C++ for Windows (Borland 4.50) is available from the author.

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0169-2607/00/$ - see front matter
PII: S0169-2607(00)00084-5

exercise ECG. In a conventional presentation the signals and the variables of the ECG leads are temporally and spatially showed separately and the printed report usually contains a large number of pages. Thus the comparisons in the alteration of the variables between the several leads and between the different stages are difficult, confusing and particularly time consuming. If the alteration of an ECG variable is presented as a function of time during exercise test the diagram includes only one lead at a time. However, it is possible to present the values of ECG variables over several leads simultaneously next to each other and chronologically from the beginning to the end of the exercise test. Then the comparison and the comprehensive examination of the variable alteration at the specific moment of an exercise test between the used leads and temporally throughout the whole exercise test would be easier, faster and allow more detailed analysis of the exercise ECG variables.

In this study we have constructed a computer program, ECG Variable Cine, for the continuous presentation of the ECG variable simultaneously in all measured ECG leads during the exercise test. In addition to the Cine mode, the program includes a display mode for stationary pictures of variable alterations during the whole exercise test at the same time in all leads, the 3-D presentation mode. Furthermore the program determines and displays a novel parameter, average (Ave), which is an average value of the variable over the selected leads at every sample moment, and a parameter that indicates heart rate response to exercise, the chronotropic index [6–8] (CRI). The CRI is assessed by calculating the ratio of maximum heart rate reserve achieved to the age-predicted maximum heart rate reserve (i.e. it describes the percentage of the heart rate reserve used). The values of these parameters can be saved to separated files for further processing (e.g. scientific research).

2. Program description

The program is designed for the PC with Microsoft Windows version 3.1 or later. It was implemented by using Borland C++ 4.50 for Windows and basic Windows libraries.

2.1. Input format for data

Observing the versatile utilization and compatibility with other programs the input format used for ECG Variable Cine is identical as in the previously published computer program [9]. The input data format should be ASCII file with the extension *sth*. Before the measured patient data the file should include the global header that is common to all data of individual patient(s). The first three rows of the global header include the identification code for the program, the name of the variable used and the number and names of descriptive characteristics of the patients (the maximum number is eight). The number of ECG leads, the duration of each exercise stage in seconds, the sampling interval in seconds both for the exercise phase and for the recovery phase, and the names of the leads are also indicated in the global header. The maximum number of ECG leads is 20.

Each patient data begins with a patient header including the identification code of the patient, the total number of samples and the ordinal number of the end-exercise sample. In addition to these, the patient header can include descriptive characteristics of the patient (such as age, weight, height, medication, symptom, etc.), which were defined in the global header. The measured values of the variable are presented after the patient header each sample in its own row. Each data row starts with heart rate in beats/min, followed by variable values (number of columns will be the same as the number of ECG leads in the global header.). The *sth*-file can contain data of several patients (number of patients is not limited by program), but there should be two empty rows between the data of consecutive patients.

2.2. Program properties

2.2.1. Cine presentation

According to the initial settings the program starts with the main window in the Cine mode (Fig. 1). The order of the leads is the same as those in the global header of *sth*-file and the scale is automatic, from minimum to maximum for each patient. During the presentation the exercise

and recovery phases are distinguished by different colors. The heart rate values through out the exercise test are shown as a column with a changing grade level in the right-hand side of the main window. The horizontal lines between the variable diagram and the heart rate column present the average values of the variable over the leads (denoted with $\bar{x}$). The control buttons for the Cine presentation are located in the lower left-hand margin of the main window. Pressing the Play button the Cine presentation starts and the consecutive samples appear in the main diagram window at the fixed interval. The value of the presentation speed (frame frequency) is indicated on the right-hand side of the control buttons. The speed can be increased or decreased from 0.1 to 1.0 s using the small upper/lower arrow buttons adjacent to the speed value. The double arrow buttons ($<<$ or $>>$) allow the user to go forward or backward frame by frame. The double arrow buttons with vertical line ($|<<$ or $>>|$) enable a direct shift to the beginning or to the end of the exercise test. The Cine presentation can be halted at any time with the Stop button. Selecting the Play button again the Cine presentation proceeds from the halted situation. The displayed parameters and the different features of the presentation can be selected from Edit/Settings and View menus.

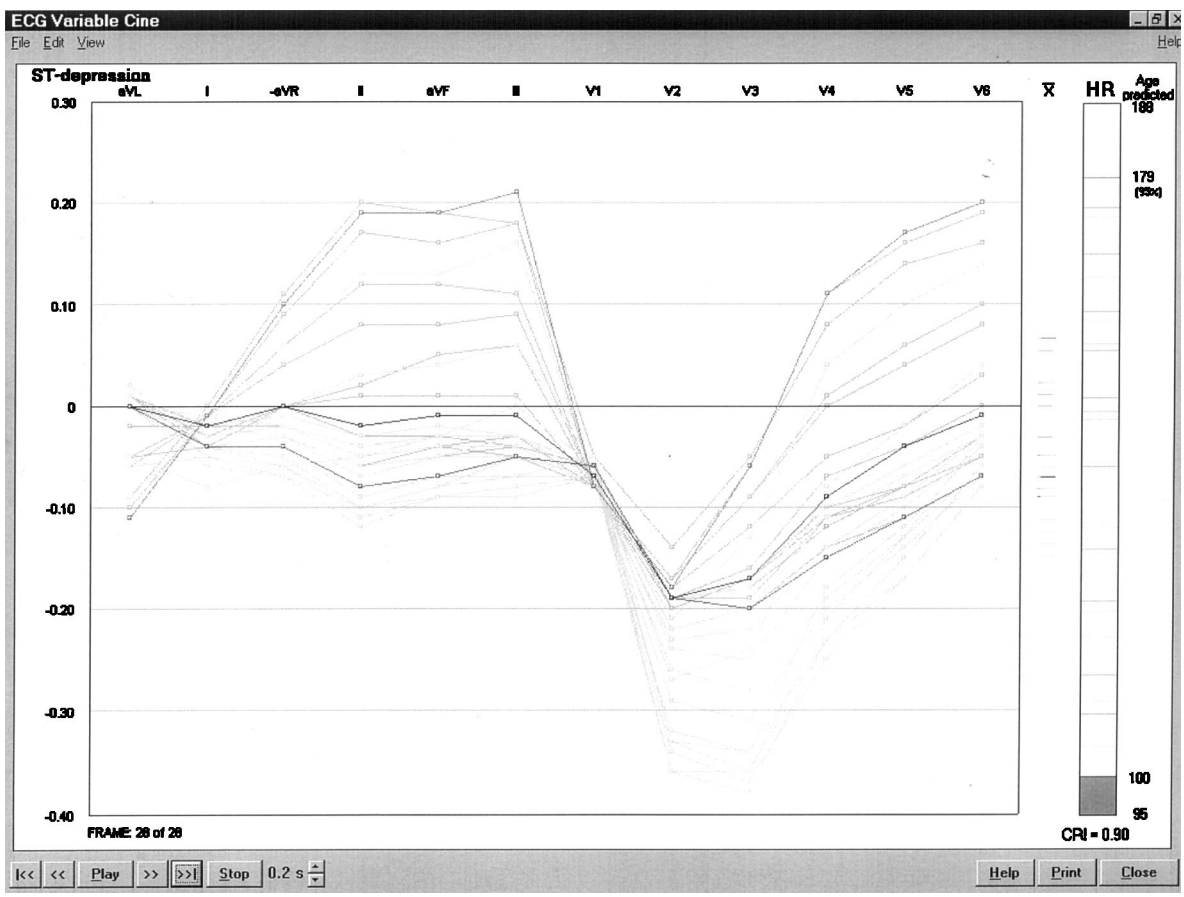

Fig. 1. ECG Variable Cine presentation. Control buttons are located in the lower left-hand margin. Exercise and recovery phases are distinguished by different color and the previous values are presented as a shadow on a screen.

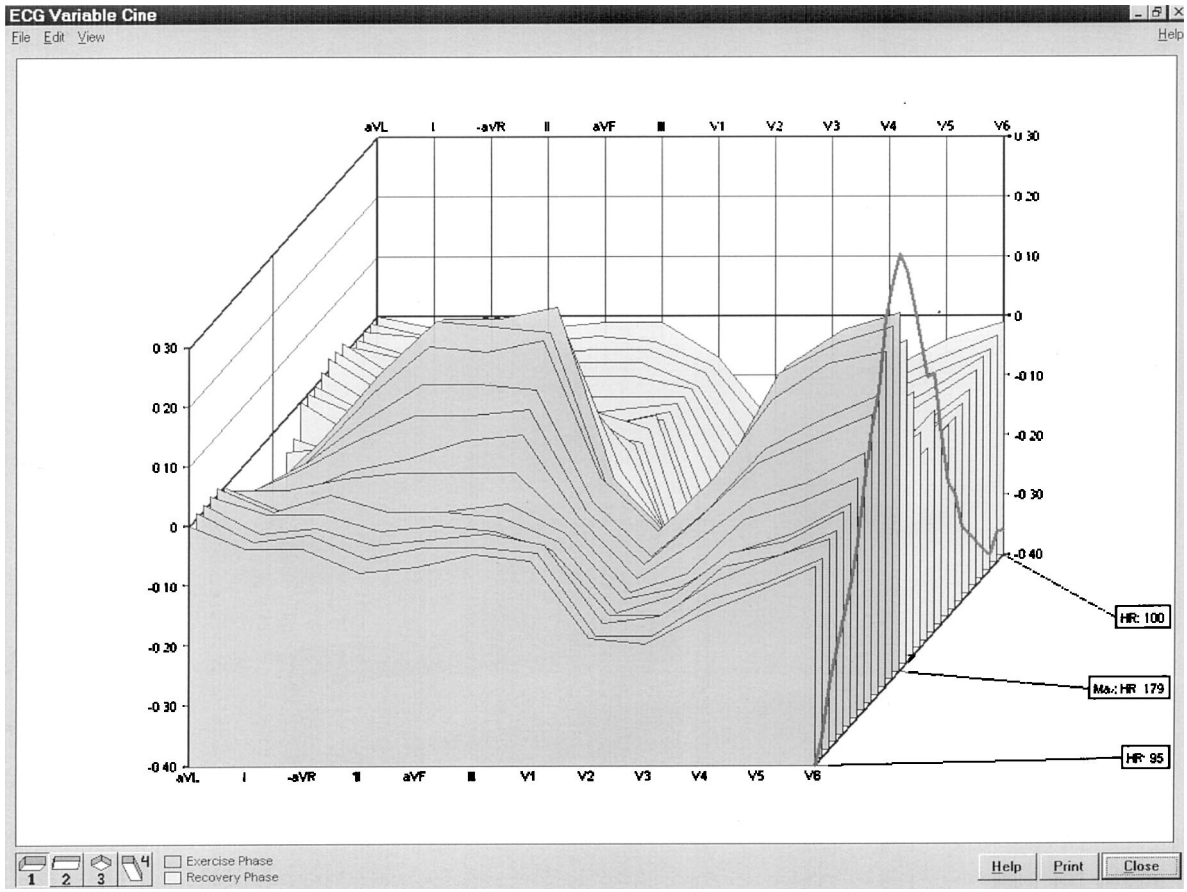

Fig. 2. 3-D stationary picture of the ECG Variable Cine presentation. From the lower left-hand buttons user can select four different observation angles. The continuous curve adjacent to the last ECG lead (right-hand) indicates the heart rate values during the exercise test.

2.2.2. 3-D presentation

The change to the 3-D presentation mode takes place when selecting the 3-D Graphics option from the View menu. Fig. 2 presents the 3-D Graphics window using the initial settings of the 3-D presentation mode with the optional heart rate curve. In the 3-D presentation mode all the measured values from the beginning to the end of exercise are presented with a stationary picture having all the selected leads in the same graphics. It is possible to examine the 3-D presentation from four different observation angles. The control buttons for the different observation angles are located in the lower left-hand margin of the main window. The 3-D diagram includes three heart rate values, those at the beginning, at the end and the maximum heart rate value achieved during the exercise test, next to the time axis. In addition all the measured heart rate values can be presented as a continuous curve adjacent to the last ECG lead. As in the Cine mode the values of the exercise and recovery phases are indicated with different colors. Furthermore, the time axis or lead order can be presented in the reverse order in the 3-D presentation mode. In addition to the plain 3-D Graphics, the 3-D presentation mode includes the 3-D Mesh option when the data is presented as the net-like graphics (Fig. 3).

2.2.3. Menus and features of the program

Three user menus, File, Edit, and View, are located in the upper left-hand corner of the main program window. In addition to Open, Print and Exit commands, the file menu includes the Save Ave and CRI command that allows the user to save the values of average and chronotropic index determined by the program into the separated files. The average value is determined from all the leads (initial setting) or from the selected leads. The CRI is defined by formula $[(HR_{stage} - HR_{rest})/(\text{age-predicted HR} - HR_{rest})]$ where HR refers to heart rate, stage refers to any given stage of exercise and age-predicted HR is determined using the formula selected from the Settings. The maximum achieved heart rate value and the heart rate value at the beginning of the exercise test were used as HR_{stage} and HR_{rest}, respectively.

The Edit menu includes Copy and Settings commands. By selecting the Settings the user can (a) change the colors and the limits of the axes for the ECG variable, (b) select the displayed leads and define their order, (c) choose whether the age-predicted maximum heart rate is determined and displayed and (d) select the displayed descriptive characteristics of the patient from the separate windows (Fig. 4). The Age-Predicted HR option requires that the value for age has been given in the patient header (the heart rate scale in graphics will be adjusted with the maximum value determined by chosen formula).

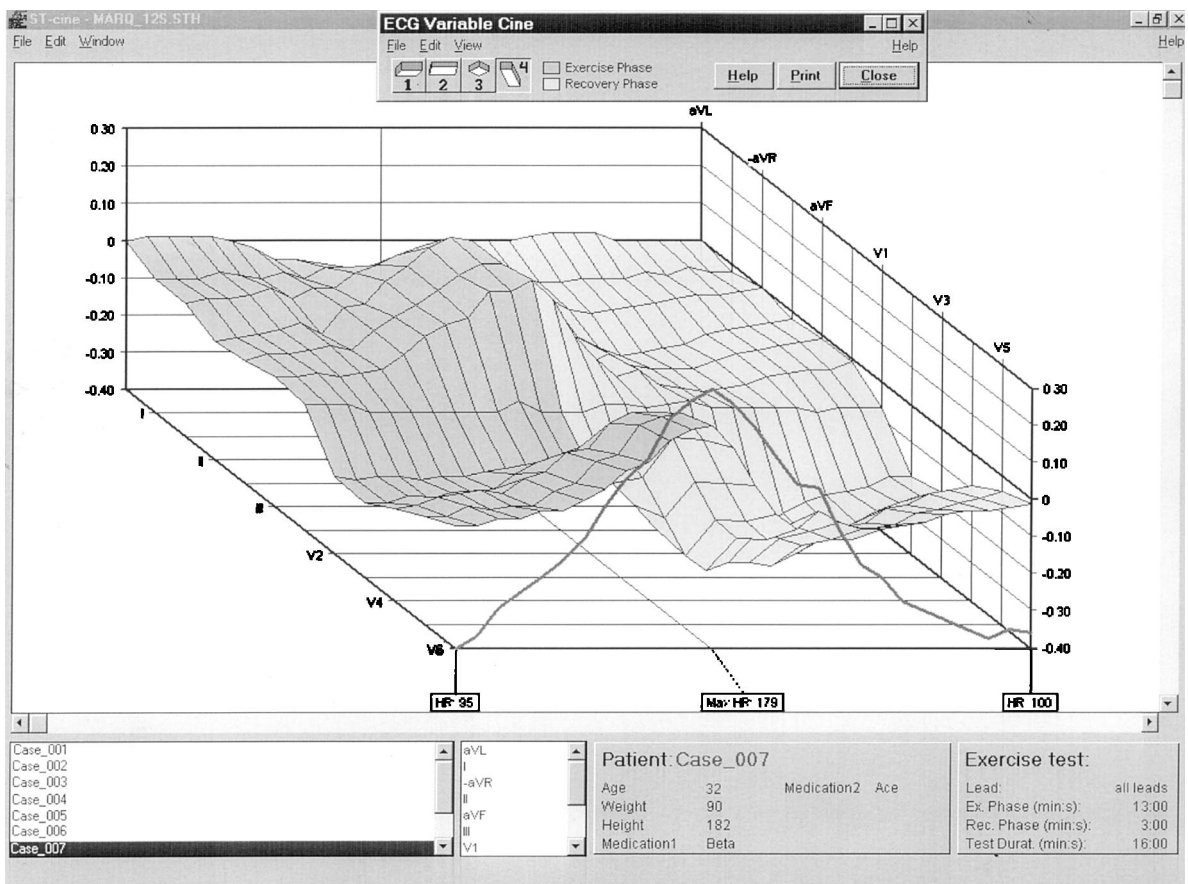

Fig. 3. 3-D Graphics as a mesh presentation and with a continuous heart rate curve. Lower left-hand window is patient menu (identification codes for the patients) adjacent to which is the lead menu (the names of the leads). Two data boxes display the selected descriptive characteristics of the patient and duration of the exercise test.

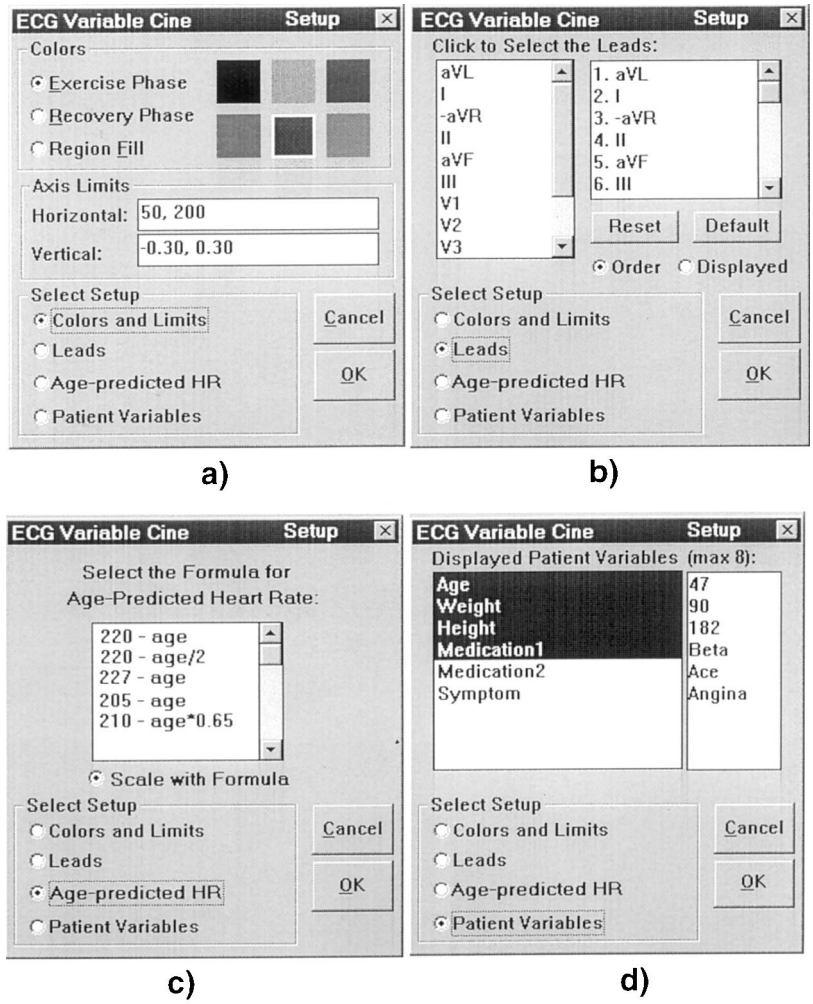

Fig. 4. Four different setup windows for the selection and changing of the displayed variables.

The View menu includes the tools for the Cine and the 3-D presentations of the variables. From that menu user can select two different layouts for the program window. One option displays only the main diagram window with operation buttons on the screen (as in Figs. 1 and 2) and the other option displays two supplementary windows with the patient and the lead menus and two data boxes with the descriptive characteristics of the patient and the duration of the exercise test below the diagram window (as in Fig. 3). If the latter option is selected the control buttons are located in the separated movable box, which floats over the main diagram window. From the View menu the user can choose the Autoscale option when the axes are scaled from the minimum to maximum value of the variable. The Invert Variable option inverts the values of variable (changes the sign). In the Cine presentation each variable value and heart rate presented are possible to leave on the screen as a shadow, different color (as in Fig. 1). The values at the beginning and at the end of exercise are also able to present with different colors. Furthermore, the average values and the

CRI determined by the program are possible to display in the Cine window. The changing to the 3-D presentation mode takes place also from the View menu.

3. Study population determined parameters

3.1. Material and methods

The importance of the average value defined from different lead sets and the CRI was evaluated in the detection of the CAD using a study population comprised of 201 male patients, 101 with CAD and 100 clinically normal. The ST-segment depression during exercise test was used as an ischemic response. Computer-determined ST-segments amplitudes at a point 60 ms after the J-junction were measured to the nearest 10 μV considering the end of PR-segment as the isoelectric line. A detailed description of the patient material is presented in our previous study [10]. The averages of ST-segment alteration were defined for each patient from all 12 leads (Ave12), from six chest leads (Ave6V), and from six limb leads (Ave6L) at the end of exercise. The end-exercise maximum values of ST-segment depression over the selected lead systems (Max12, Max6V, and Max6L) were used in reference variables. The CRI was determined using the formula given in Section 2.2.3 where the age-predicted maximum heart rate was defined by (220-age). The sensitivity values at fixed 90% specificity and the area under the receiver operating characteristics (ROC) analysis were used when comparing the diagnostic capabilities of the average, maximum and CRI variables. The statistical differences of the sensitivity values at the fixed 90% specificity were compared using McNemar's modification of the chi-square method for paired proportions and differences between the areas under two ROC curves were compared using non-parametric analysis of correlated ROC curves [11] with a routine written by Vida [12] (version 2.5).

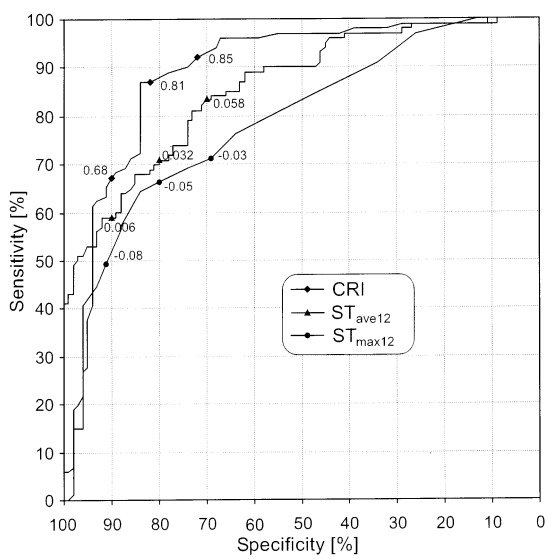

Fig. 5. ROC curve for the chronotropic index (CRI), average of end-exercise ST-segment alteration from all 12 leads (Ave12) and maximum value of end-exercise ST-segment depression from all 12 leads (Max12). The nearest partition values at 90, 80 and 70% specificity are indicated for each variable. The units for Ave and Max are mV, whereas the CRI is unitless.

3.2. Results

Fig. 5 presents the ROC curves for the CRI, Ave12 and Max12. The areas under the ROC curves for the CRI, Ave12 and Max12 were 88.7, 85.8 and 79.1%, respectively. The CRI and Ave12 had a significantly higher area under the ROC curve than the Max12 ($P = 0.0176$ and $P = 0.0290$, respectively), but the difference between CRI and Ave12 was not significant ($P = 0.3560$). The sensitivity values at the 90% specificity were 67.5, 59.4 and 49.4% for the CRI, Ave12 and Max12, respectively. Statistical comparison showed significant difference only between the CRI and Max12 ($P = 0.0271$). The areas under the ROC for the Ave6V and Max6V (i.e. from chest leads) were 83.3% and 81.6% ($P = 0.5605$) and for the Ave6L and Max6L (i.e. from limb leads) were 85.3 and 74.9% ($P = 0.0004$). The sensitivity values at the 90% specificity were 56.4 and 55.5% for the Ave6V and Max6V ($P = 0.755$) and 58.4 and 37.8% for the Ave6L and Max6L ($P = 0.0005$).

4. Discussion

The ECG Variable Cine program was developed for the analysis of the ECG variables gathered during an exercise test. The program enables the presentation of discrete ECG variables as a continuous cine presentation over measurement interval. In addition to Cine presentation the program also includes fast and easy observation of the ECG variable as a stationary picture, 3-D presentation. The Cine and 3-D presentations facilitate observation of the ECG variable throughout the entire exercise test and over the selected lead system at a glance enabling a faster and more detailed analysis of the exercise ECG. The user can define the number and order of the displayed leads. Therefore the user can focus more effectively on the leads desired and can compare the values between the leads as well as the temporal changes in each lead.

In addition to visualization the program determines two diagnostic parameters, the average value of the ECG variable over the selected leads and the chronotropic index, CRI. The summing method over all 12 leads, similar to the average method, has been previously used in the analysis of the ST-segment alteration when evaluating patients with myocardial infarction during and after percuntaneous transluminal coronary angioplasty (PTCA) [13–15]. However, the crucial difference of our method is that in the summing method the absolute values (values without sign) of ST-segment deviation were summed over 12 leads. The CRI has been shown to improve the performance of the traditional and heart rate-adjusted ST-segment depression criteria for identification of CAD [8] and to be predictive of increased coronary heart disease incidence [6]. The program enables a saving of the values of average and CRI into separate files, which makes it a very useful tool for scientific researches.

Due to the Windows based implementation the ECG Variable Cine program is easy to use and easy to implement to PC based ECG apparatus and analyzers.

5. Conclusion

The ECG Variable Cine program provides a new method for the examination of the ECG variables gathered during exercise test over the ECG leads and over the duration of exercise test. According to the results two diagnostic parameters, the average value of ST-segment deviation at end of exercise over the selected leads and the CRI, determined by the program are clinically more competent than the traditional maximum value of ST-segment depression in the detection of CAD.

Acknowledgements

This work has been supported financially by the Academy of Finland, Ella och Georg Ehrnrooth Foundation, the Emil Aaltonen Foundation, Finnish Cultural Foundation (Pirkanmaa Fund), the Ida Montin Foundation, Ragnar Granit Foundation, and Wihuri Foundation.

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