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EDITORIAL

Quantitation of Exercise Electrocardiography

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EXERCISE TESTING is an established method for detecting coronary artery disease, evaluating the severity of disease and prognosis in patients with coronary artery disease and assessing the effect of therapy. The ECG responses can be used as an indicator of exercise-induced myocardial ischemia[1] in context with the patient's history and other data obtained during exercise (table 1).

The diagnostic value of exercise electrocardiography may be enhanced by computer-assisted quantitative analysis of the ECG[2-6] (table 2). This improvement is due in part to a reduction of the noise level and to application of special criteria, such as a combination of ST amplitude and ST slope.[2-5] Various systems have been designed for computer processing of exercise ECGs. These systems generally aim at better measurements through improvement of the signal-to-noise ratio in the ECG recorded during physical exercise, more accurate diagnostic classification of the exercise ECG and reduction in the total time involved in the execution and reporting of the test. Details of the various systems have been described.[7] The first programs were developed and implemented on medium-size computers or minicomputers. Application of these programs remained restricted to the hospitals where they were designed. In recent years, microprocessor-based systems have been introduced commercially.[7, 8]

This commercial availability has created a new situation. The user of a system developed in the same hospital is usually aware of the strengths and the limitations of that system. However, the clinician who buys a system from a manufacturer has, at best, an incomplete understanding of the hardware and software provided. This may lead to errors, especially if the results of the ECG analysis are printed in pseudo-quantitative statements such as "ST-segment depression, compatible with myocardial ischemia."

During the conference on "Optimal Electrocardiography" in 1977, sponsored by the American College of Cardiology and the Department of Health, Education and Welfare, standards were proposed for quality control of ECG recording[9] and for the application of computers to diagnostic electrocardiography.[10] In addition to these standards, further specifications are needed for computer-assisted interpretation of exercise ECGs.

In this editorial we present a set of such recommendations. We hope that these or similar requirements will be adopted by the American Heart Association, the American College of Cardiology and the European Society of Cardiology. We also urge designers and manufacturers of systems for computer-assisted exercise testing to comply with such recommendations and to provide documentation on the reliability and diagnostic accuracy of such systems, as well as the results of field tests with each proposed sale.

General Design of a System for Computer-assisted Exercise Testing

A system for computer-assisted interpretation of exercise ECGs contains a number of hardware subunits and software programs.[7] The hardware includes ECG amplifiers, analog-to-digital converters and the user interface. The software includes programs for signal conditioning, feature extraction and diagnostic classification. Finally, the system generates a report in graphics or in printed text or both. These features are discussed below. A summary of the recommendations is presented in table 3.

Hardware

The ECG amplifiers and analog-to-digital converters for exercise electrocardiography should meet the same specifications and safety standards as those for electrocardiography at rest.[9, 11] A sample frequency of 250 Hz is sufficient for analysis of the QRS and

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TABLE 1. *Information to be Obtained by Noninvasive Exercise Testing*

Physical capacity	
	Symptoms which limit standardized exercise
	Maximal tolerated work load
	Measured or estimated maximum oxygen uptake
Hemodynamic adaptation	
	Heart rate response
	Blood pressure response
Myocardial ischemia	
	Development of angina during the test
	ECG changes (ST segment)
	Thallium scintigraphy
Left ventricular dysfunction	
	Insufficient increase or decrease of systolic pressure
	ECG changes (R wave)
	Blood pool scintigraphy (reduction of ejection fraction)
Arrhythmias and conduction defects	

TABLE 3. *Recommendations for Computer-assisted Interpretation of the Exercise Electrocardiogram*

Hardware	
	Adequate frequency response and safety
	Sample frequency 250 Hz or greater
	User interface in the exercise laboratory simple to operate
Signal conditioning	
	Computation of averaged or median representative beats after rejection of premature complexes and other beats with an abnormal configuration
	Warning messages when signal quality is poor
Measurements	
	Definition of onset and end of the QRS complex, preferably in multiple, simultaneously recorded leads
	Measurements of both ST depression and ST elevation
Diagnostic classification	
	Special measures should be included to prevent errors in classification due to excessive noise or baseline shift, as well as certain conditions that may interfere with the measurement program, such as intraventricular conduction delay
	The whole system should be tested in a series of patients with independently documented presence or absence of disease
Report	
	Graphic representation of representative ECG complexes should be included with marks that indicate the fiducial points from which the measurements have been taken
	Graphic or numerical output of the measurements should be available in addition to diagnostic statements

ST changes during exercise. Much attention should be given to the user interface. The computer system should aid the doctor and the nurse or technician who supervise the procedure and not distract them from the patient. When a standard protocol is used, the system should run by itself, with little or no operator intervention.[12]

Signal Conditioning

Although application of an algorithm for improvement of the signal-to-noise ratio of the exercise ECG may provide a better signal for measurements, utmost attention should still be paid to skin preparation and fixation of electrodes and leads. Warning messages should be provided whenever the signal quality is too poor for proper analysis.[12, 13] Representative complexes can be computed as a median beat,[14] as an

TABLE 2. *Comparison of Visual and Computer-assisted ECG Interpretation*

		Visual		Computer		
		Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)	Lead system and computer criteria
McHenry et al.[2]		10/35 (29)	25/26 (96)	31/35 (89)	22/26 (85)	CC_5, ST amplitude and slope
Ascoop et al.[3]	L	14/57 (25)	30/30 (100)	40/57 (70)	27/30 (90)	CC_5, ST amplitude and slope
	T	11/39 (28)	21/21 (100)	25/29 (64)	20/21 (95)	
Simoons[4]	L	26/52 (50)	81/86 (94)	44/52 (85)	78/86 (91)	X, ST amplitude and slope, heart rate
	T	22/43 (51)	41/43 (95)	36/43 (84)	38/43 (88)	
Hollenberg et al.[5]		44/59 (75)	9/11 (82)	50/59 (85)	10/11 (91)	V_5, ST amplitude and slope, heart rate, treadmill time
Sketch et al.[6]		35/59 (59)	44/48 (92)	34/59 (58)	42/48 (88)	V_5, ST area

Four studies[2-5] showed improved diagnostic classification by computer analysis, based on measurement of ST amplitude and ST slope in combination with heart rate[4] and treadmill time.[5] In two studies,[3, 4] data obtained in a learning group (L) were reproduced in independent test groups (T). In one study,[6] the computer measurement of ST area was not better than visual analysis. This corresponds with other observation using this measurement.[4] In most studies,[3-6] the coronary arteriogram was used as a reference method for the presence of coronary artery disease. One study[2] used other clinical data as a reference, while two studies[4, 5] included normal subjects without coronary arteriography.

average,[13, 15] or as a running average.[16] The system should detect beats with abnormal wave forms and prevent incorporation of such beats in a representative complex. For verification of such computations, both the original signal and the representative beats should be available for inspection by the user in the final printout.

Measurement Program

Classification of normal and abnormal ECG responses during exercise will depend on the accuracy of the measurements used — ST (or J) amplitude, ST slope[2-5] or ST area.[6] The reliability of such measurements depends on the algorithms for location of the baseline and of the ST segment itself. Basically, two approaches have been used for this purpose (fig. 1). The simplest method for definition of measurement points requires a single fiducial point in the QRS complex, such as the peak of the R wave[2] or the nadir of the S wave[17] in a single lead. The baseline is then chosen at a fixed interval before this fiducial point, while ST measurements are taken at fixed intervals after this point (fig. 1A). This method has been incorporated in three of the four systems that are commercially available.[7, 8] Although the measurements in many patients will be acceptable, severe errors may occur in patients with an abnormal QRS complex. Consequently, the future user of these systems must restrict these programs to patients with normal QRS complexes.

The more sophisticated programs search for the real onset and termination of the QRS complex in multiple, simultaneously recorded leads.[13, 15, 16, 18, 19] The baseline can then be defined at a known interval just before the onset of the QRS complex, while the ST measurements are made at well-defined intervals after the end of QRS (fig. 1B). However, careful comparison of the results of different algorithms for detecting the onset and end of the QRS complex has shown that various programs differ considerably.[20] The mean difference in the detected ends of QRS by two such programs was approximately 11 msec (table 4). Thus, the amplitude 60 msec after QRS, which according to one program[15] contains most information, corresponded to the amplitude approximately 70 msec after QRS by the other program.[18] On the other hand, the definition of the onset of the QRS complex by the two programs was virtually identical. Similar systematic differences were found when experienced electrocardiographers indicated the onset and the end of QRS in enlarged plots of ECG tracings (table 4). The message from these observations is clear: In many ECGs, there is no indisputable end of the QRS complex. Accordingly, criteria for interpretation of exercise ECGs derived from one computer program should not be transferred to another program unless the wave-form analysis programs are identical. This principle has been advocated previously by Rautaharju.[21] The diagnostic errors that may result from an improper combination of wave-form analysis algorithms and classification rules are illustrated in table 5. Similar errors can even occur when a set of programs is translated from one computer system to another.[10]

In practice, it is almost always necessary to change a program when it is transferred from one system to another. The manufacturer of the latter system should then provide data that show that the measurements or the final interpretation of the data are not affected by the changes in the program.

Lead Selection

Computer processing has been applied to various lead systems, including single bipolar leads,[2, 14, 17] two bipolar leads,[3] single or multiple standard leads[5, 6, 16, 22]

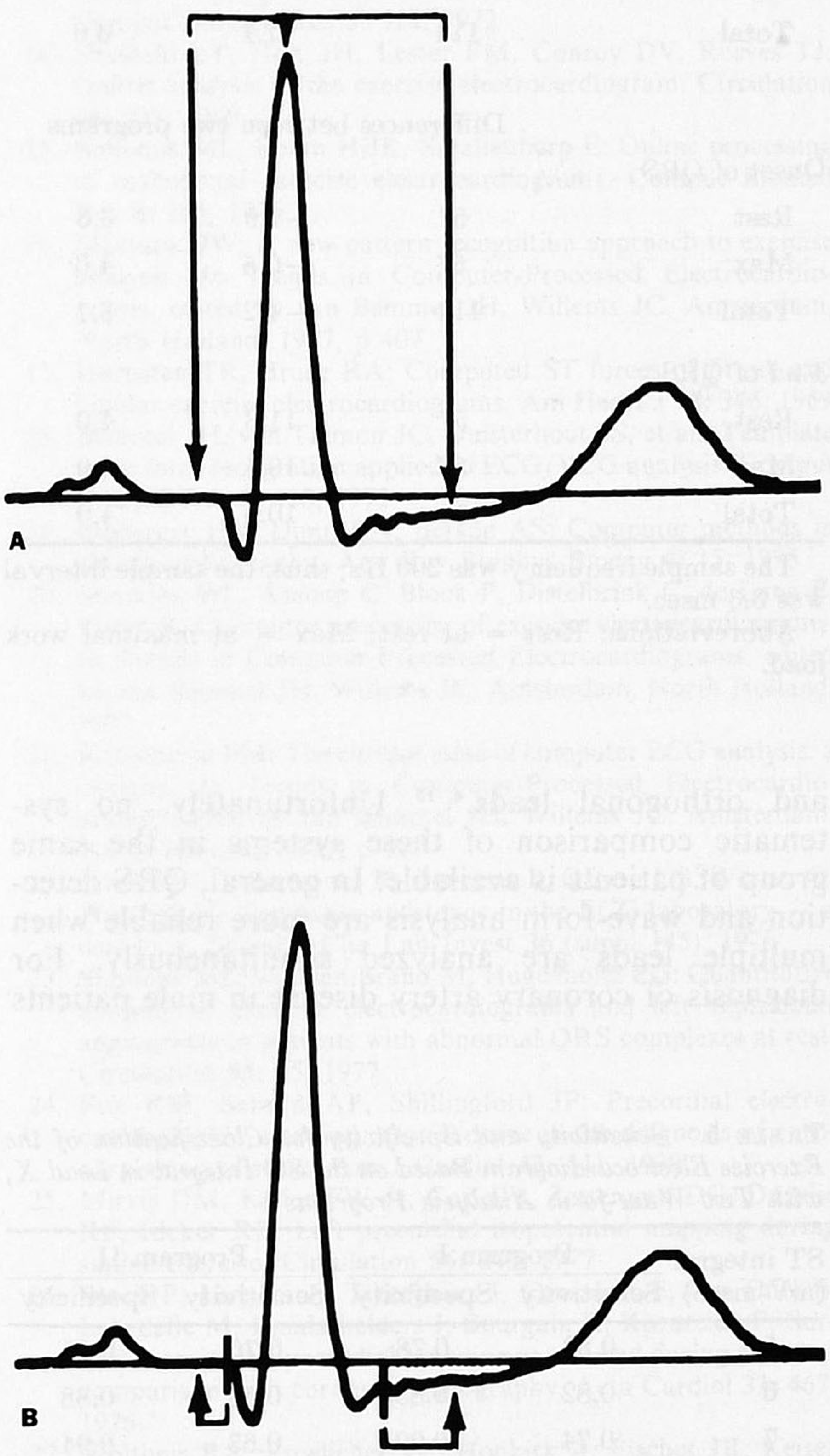

FIGURE 1. *(A) Determination of baseline and of ST measurements at fixed intervals before and after a single fiducial point in the QRS complex. In this example, the peak of the R wave is chosen as a reference point. (B) Determination of the baseline at a fixed interval before QRS onset and ST measurements at selected intervals after the end of the QRS complex. Both the onset and the end of the QRS complex are defined by the computer program.*

TABLE 4. *Differences in Determination of Onset and End of QRS Between Two Experienced Electrocardiographers and Differences Between Two Computer Programs[8, 12, 14] Measured in 57 Electrocardiograms at Rest and During the Maximal Work Load*

	n	Mean (msec)	SD (msec)
Differences between two observers			
Onset of QRS			
Rest	57	−3.4	2.8
Max	57	−3.1	2.7
Total	114	−3.3	2.7
End of QRS			
Rest	57	6.0	6.8
Max	57	8.3	4.9
Total	114	7.1	6.0
Differences between two programs			
Onset of QRS			
Rest	57	−1.9	3.3
Max	57	−0.5	4.0
Total	114	−1.2	3.7
End of QRS			
Rest	57	11.3	4.0
Max	57	10.5	4.0
Total	114	10.9	4.0

The sample frequency was 300 Hz; thus, the sample interval was 3.3 msec.

Abbreviations: Rest = at rest; Max = at maximal work load.

and orthogonal leads.[4, 13] Unfortunately, no systematic comparison of these systems in the same group of patients is available. In general, QRS detection and wave-form analysis are more reliable when multiple leads are analyzed simultaneously. For diagnosis of coronary artery disease in male patients

TABLE 5. *Sensitivity and Specificity for Classification of the Exercise Electrocardiogram Based on the ST Integral in Lead X, with Two Wave-form Analysis Programs[15].*

ST integral (mV-msec)	Program I Sensitivity	Program I Specificity	Program II Sensitivity	Program II Specificity
5	0.82	0.78	0.76	0.85
6	0.82	0.83	0.68	0.88
7	0.74	0.90	0.63	0.94
8	0.68	0.92	0.58	0.97

The data are from 163 subjects.[20]

The end of QRS as defined by program I was on the average 11 msec earlier than that defined by program II; thus, for the same criteria, the sensitivities were higher and the specificities were lower with program I than with program II. The result obtained with a threshold value of 8 mV-msec in program I were similar to those with a threshold of 6 mV-msec in program II.

with a normal resting ECG, a single bipolar lead (CM_5) may be sufficient.[20] However, in other patients, the ECG changes may be more pronounced in other leads.[23, 24] Thus, the optimal system should contain a minimum of three orthogonal or pseudoorthogonal leads, including lead CM_5 or an equivalent lead. In the future, more specific recommendations can be based on the quantitative analysis of the potential distribution on the chest wall[24, 25] or the whole body surface[26] in a sufficiently large number of patients.

The normal range of ECG measurements depends as much on the lead positions as on the wave-form analysis.[27] Thus, special criteria should be developed for each combination of leads and for each computer program.

Diagnostic Classification

The ECG response during exercise has been classified in different ways. Some systems provide only measurements, or a simple classification similar to the Minnesota code.[22] Other authors have developed more complicated scores based on ST amplitude and ST slope[2, 3] combined with heart rate[4] or functional measurements such as treadmill time.[5] However, the criteria that have been proposed were developed in small groups of subjects.[2, 5, 6, 14] Evaluation of the developed criteria in independent test groups was done in two studies only;[3, 4] much more work in this area is clearly required before the future user can rely on the interpretation of exercise ECGs by a computer system (table 2).

Computer processing offers the possibility of grading the ECG response in various degrees of abnormality.[5, 28] However, such subtle ways of interpretation are only valid when accurate measurements are used in combination with the proper method of wave-form analysis. Moreover, criteria developed for interpretation of the exercise ECG in one group of patients cannot always be applied to other groups of patients. In particular, special criteria should be developed for patients with abnormal QRS complexes or abnormal repolarization at rest.[23] As a minimal requirement, the ECG analysis by the computer system should include both ST-segment depression and ST-segment elevation.

The computer system should not print a diagnostic classification if this is inappropriate, as in left bundle branch block. In addition, warning messages should be provided when conditions arise that invalidate the computer interpretation, such as excessive noise or baseline drift. Finally, to provide the user of a system with proper data regarding the sensitivity and specificity of the ECG classification, each complete system should be tested in a series of patients with independently documented presence or absence of disease.[10, 29] This data should be provided with the documentation of the system.

Exercise ECG Report

The report of the test should contain sufficient information such that the user can verify the performance of the computer system. In particular, the computed representative complexes should be plotted, together with markers that indicate the measurement points or fiducial points, such as the onset and end of the QRS complex. Further, the original ECG tracings should be available for inspection by the user. Graphs of heart rate and ST measurements throughout the test facilitate recognition of possible measurement errors. Diagnostic statements such as "abnormal ST response" may be printed by the system in addition to the ECG and measurement plots, but because the exercise ECG is only one bit of information that can be obtained during the test, other information such as exercise tolerance, heart rate and blood pressure response, and symptoms during exercise also should be included in the report (table 1). It is recommended that conclusions that may be generated by the computer system should be based on all available data[5, 30] and that such comprehensive conclusions should be stated in terms of the probability of a normal or abnormal response.[5, 28]

The physician who attends the test should always review the computer-generated report, because even with the aid of the most sophisticated computer system, errors will be present in some tests.

Conclusion

Computer systems can be used to advantage in the exercise laboratory. They can facilitate the control of the ECG writer and the bicycle or treadmill. In particular, computer processing can improve the diagnostic classification of the exercise ECG. The gain in terms of sensitivity, related to coronary arteriography, varies from 10–45%, with a small loss of specificity, from 3–10% (table 2).[3, 5] However, precautions should be taken to prevent errors that may result from careless implementation of insufficiently tested computer programs. Such errors cannot easily be recognized by a user who is not an expert in computer-assisted ECG interpretation. Therefore, standards for such computer systems should be developed and adopted by professional organizations as well as industry.

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