A computer-assisted system for clinical use in maximal exercise testing

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The three types of diagnostic tests used in clinical evaluation are for discovery of disease, confirmation of disease, or exclusion of disease.[1] Maximal exercise testing as is currently employed for detecting coronary atherosclerotic heart disease (ASHD) and evaluating patients receiving either medical or surgical treatment for coronary artery disease can be classified as a discovery test. Although graded exercise testing falls short of perfection in the process of differentiating between normal subjects and ASHD patients, the test is clinically useful in the discovery process both for asymptomatic patients and for those in whom there is a suspicion of ASHD based on the clinical history, physical examination, or interpretation of the resting electrocardiogram.[2-11] In addition, quantitative exercise testing is used with increasing frequency for the serial evaluation of patients before and after myocardial revascularization.[12-16] In the past 11 years a variety of technological improvements have resulted in increased sensitivity and specificity for exercise testing in patients with ASHD.[17-24]

This paper describes an on-line, real-time minicomputer-based maximal stress testing system. Technical solutions for improved signal quality, signal analysis, and clinical reporting are described.

Multiple lead electrocardiography

Multiple lead exercise electrocardiograms increase the yield of positive tests when compared to single lead systems.[7, 18, 19, 21] Nevertheless, most patients who have abnormalities in cardiac repolarization during exercise have these changes in a lead similar to V_5.[18, 19] By recording the Frank lead Orthogonal electrocardiogram and a bipolar precordial lead (CM_5), the spatial and proximity chest lead S-T segment changes are obtained. We apply these concepts and record Frank leads X, Y, and Z and lead CM_5.

Electrode specifications and skin preparation

By using small electrodes (Beckman Bioelectrode, Beckman Instrument Company) we have eliminated much of the D-C offset problem associated with changing distances from the electrode to skin interface caused by a hanger-rocking motion associated with muscular motion during exertion. Careful skin abrasion with a 25-gauge needle for reducing skin impedance is employed. A double adhesive collar is used for stable fixation of the electrode position.

Test protocol

Maximal exercise testing rather than submaximal testing is utilized for improving the sensitivity of the test.[7, 19, 21] It has been demonstrated that a maximal test resulting in a heart rate attainment of at least 160 beats per minute improves detection of ASHD.[21] In this regard, we have found the bicycle to be as good as the treadmill for maximal work load production, and have found the bicycle to be superior to the treadmill in terms of patient acceptance, quantitation of work load, cost, and space requirements. More importantly, the bicycle test yields additional signal enhancement for data acquisition, since there is less muscular motion artifact on the electrocardiogram.

Following acquisition of resting data, work begins at 300 kilopond meters (KPM) for 3 minutes. Work is incremented every 3 minutes by a 300 KPM increase in load until leg fatigue supervenes or exercise induced indicators of myocardial ischemia are provoked.[7]

Signal averaging and computer signal preprocessing

With the introduction of computer averaging for improvement of signal to noise ratios and signal enhancement, we have employed the averaged electrocardiogram[17, 21, 23, 24] and the averaged phonocardiogram[7] as essentially noise-free records for analysis of both S-T segment abnormalities as well as for the detection of atrial and ventricular gallop sounds provoked during muscular exercise.

A laboratory minicomputer (Lab 8E, Digital Equipment Corporation, Maynard, Mass.) performs analog to digital conversion on the four electrocardiographic leads and the phonocardiogram at a sampling rate of one point every 5 msec. Analog triggering using lead Z band passed from 10 to 30 H_z is performed with the level detector on the minicomputer firing a Schmitt trigger on the basis of the initial R wave slope.

Figure 1 shows the laboratory panel, computer terminal, and the oscilloscope display used for data acquisition and physician dialogue with the computer system. A prime requirement for the acquisition of resting and exercise electrocardiograms

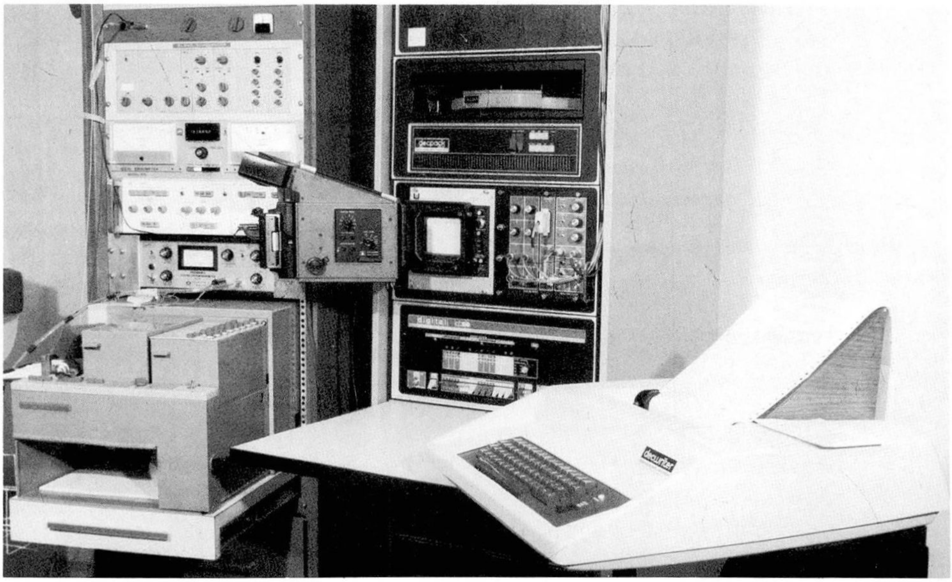


Fig. 1. The minicomputer laboratory panel, storage oscilloscope, and terminal are shown. Polaroid photography is employed for hard-copy reports. The terminal serves as a physician computer interface during the test and generates the final clinical report (see text and *Figure 4* for explanation).

for computer averaging is the editing of adequate arrhythmia and noise artifact. The system must eliminate the flow of premature complexes or major noise artifacts. The algorithm we use for this program is presented in the Appendix. We have found this algorithm, developed by Blomqvist, to be effective and simple in utilizing computer time which is at a premium in a minicomputer system utilized on line.

Fixed time frame averaging rather than an average of a set number of beats is utilized. The direct relationship between heart rate and the amount of noise on a given record is the rationale for time frame averaging. For example, at heart rates less than 100 beats per minute, there is a good signal to noise ratio, thus fewer beats need to be preprocessed, and the set time frame employed (25 seconds) proves to be adequate with 30 to 45 beats usually averaged at rest. During exercise at higher heart rates muscular noise increases, and with a 25-second time frame for averaging utilized, more beats are obtained. The improved signal to noise ratio for signal enhancement in "noisy" exercise electrocardiograms depends on the acquisition of more beats.[17–23] Since a set time frame is used, more beats will be acquired as the heart rate increases. The signal to noise ratio then appears to be clinically stable, and the signal enhancement technique does not change with increased work. In addition, signal enhancement techniques employed with averaging allow one to acquire an essentially noise-free phonocardiogram for detecting gallop sounds as is demonstrated in *Figure 2*. The elimination of 60 cycle noise is also attained (*Fig. 3*).

Data storage and clinical reporting

The minicomputer system employs a disc cartridge storage system and all data are buffered by the disc car-

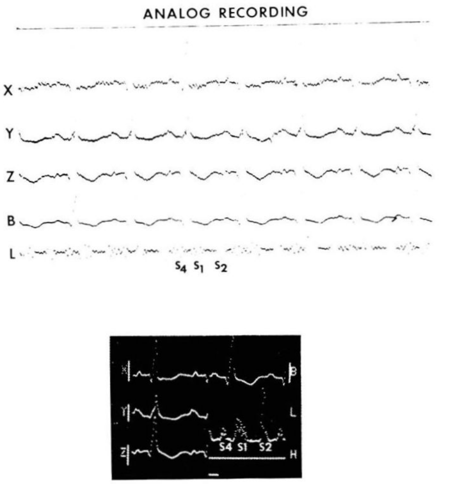


Fig. 2. Analog electrocardiogram and phonocardiographic tracings are illustrated with simultaneously averaged digital recordings. The averaged phonocardiogram shows the noise-free tracing quality and the presence of an atrial gallop (S_4).

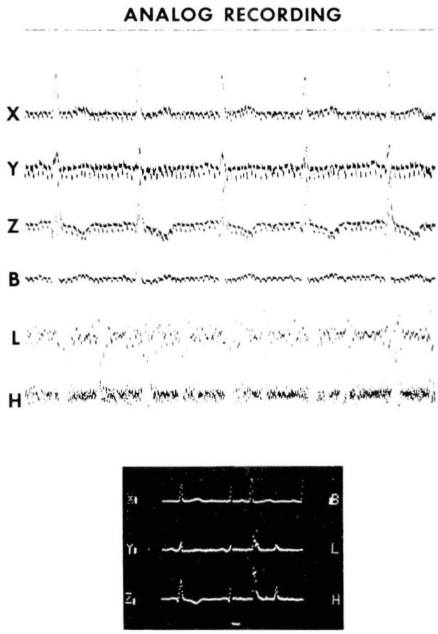


Fig. 3. This illustration demonstrates the elimination of 60 cycle noise by averaging techniques. The noise is random in relation to the QRS and is thus "averaged out."

tridge. Patient demographics, clinical information, and the averaged data from each work load, the maximal work load (last 25 seconds), the immediate postexercise tracing, and the 3-minute postexercise tracing are stored on the disc system. All digitized records are permanently stored on magnetic tape.

The utility of the minicomputer based system is best demonstrated to the clinician by employing the computer for clinical reporting. In addition, research reports are generated by the computer after each exercise test for storage in a large data bank (Cleveland Clinic Cardiovascular Information Registry).

Figure 4 shows a clinical report obtained from the system which uses physician coding of the electrocardiographic interpretation, symptoms, arrhythmia analysis, and the input of certain information not obtainable by the computer, such as the blood pressure levels. This information is collated, correlated, and printed out in the clinical report sheet as shown in panel A. The reverse side of the clinical reporting sheet is used for mounting the averaged electrocardiogram and phonocardiogram data as shown in panel B.

Figure 5 demonstrates the appearance of the S_4 gallop along with angina pectoris without electrocardiographic repolarization abnormalities during graded exercise testing. This demonstrates the utility of the stress provoked S_4 as an indicator for ASHD detection when this finding is associated with angina. *Figure 6* demonstrates the usefulness of the computer system, since the S-T abnormalities were present only during stress and would have been missed by standard postexercise recordings.

CARDIAC FUNCTION LABORATORY EXERCISE TEST REPORT

AGE 62 SEX M	NUMBER 1380599 DATE 03/ 08/ 76
FUNCTIONAL CLASS 0	REQUESTING PHYSICIAN SIEGEL
	EXERCISE TEST NUMBER 010285

MEDICATIONS NO NTG, INDERAL, ISORDIL, SORBITRATE OR DIGITALIS
CLINICAL DIAGNOSIS R/O ASHD

WORK LOAD	HEART RATE	BLOOD PRESSURE	WORK TIME	ARRHYTHMIAS	LIMITING SIGNS OR SYMPTOMS
REST	89	100/ 75	0 0	NONE	NONE
0300	134		3 0	UNIFOCAL PVC'S OCCASIONAL	NONE
0600	169	140/ 70	2 23	UNIFOCAL PVC'S OCCASIONAL	LEG FATIGUE

ELECTROCARDIOGRAM LEFT ANTERIOR HEMIBLOCK
NORMAL RESTING AND EXERCISE ST RESPONSE

INDIRECT HEMODYNAMICS NORMAL BLOOD PRESSURE AT REST AND DURING MAXIMAL EFFORT
NORMAL HEART SOUNDS AT REST AND DURING MAXIMAL EFFORT

CONCLUSIONS
1) THE PATIENT HAD A NORMAL EXERCISE TEST
2) MODERATE IMPAIRMENT OF PHYSICAL WORK CAPACITY
3) LEG FATIGUE WAS PROVOKED DURING MAXIMAL EXERCISE
4) THE PATIENT HAD NO ARRHYTHMIAS AT REST AND OCCASIONAL UNIFOCAL PVC'S DURING STRESS
5) NORMAL EXERCISE ELECTROCARDIOGRAPHIC RESPONSE

COMPUTER AVERAGED RECORDS (25 Seconds)

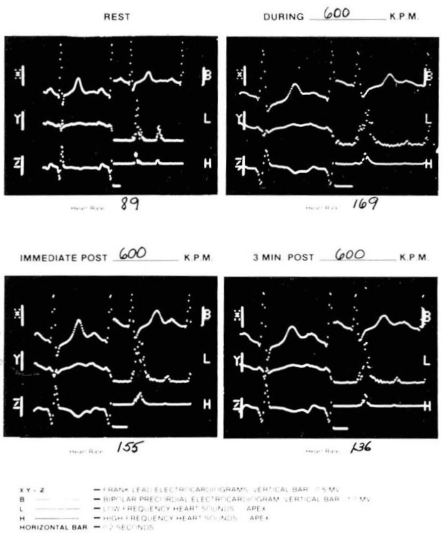


Fig. 4. At the completion of the test the report generated by the computer terminal is shown in panel A. The hard copy averaged ECG-PCG data are shown in panel B, and mounted on the reverse side of the automated report.

Summary

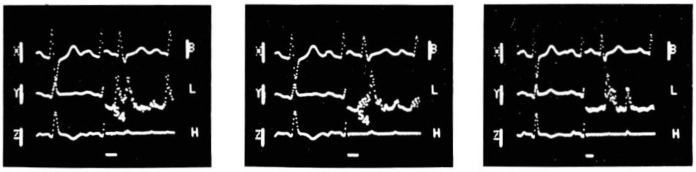
The Cleveland Clinic Cardiac Function Laboratory uses a minicomputer assisted maximal exercise testing system with bicycle ergometer stress protocol. In the past 5 years more than 10,000 tests have been performed with excellent clinical acceptance. A large digital storage file has been developed for angiographic quantitative correlations.

Appendix. Electrocardiographic triggering scheme and arrhythmia editing

The purpose of this arrhythmia editing program is to discard (prior to any other computer analysis) premature ventricular and atrial beats as well as large amplitude artifacts occurring between normally conducted cardiac depolarization wave-forms.

The programs utilize the following two sets of criteria for eliminating these unwanted beats and artifacts from the logical analysis of the single lead (lead Z) electrocardiogram. Both of these two criteria may be manually disabled: (1) R-R interval variation equal to or greater than 20% excludes the beat. (2) QRS amplitudes of lead Z, beginning with ventricular depolarization and ending at 200 msec thereafter will cross-correlate using a subtraction technique with plus or minus 5% correlation or better.

The R-R interval variation and QRS initial 200 msec vectors from lead Z will be compared to a model which is obtained from the first eight beats of the resting electrocardiogram under physician manual control. If the first eight beats are not of sinus mechanism and of reasonably consistent R-R intervals, manual intervention by the physician is required for rebuilding the model of the R-R interval and QRS initial 200 msec forces. The input to the basic computer will consist of analog sig-



DURING 600 KPM ANGINA AND S_4 NO ST CHANGES | IMMEDIATELY POST 600 KPM DIMINISHED ANGINA AND S_4 | 3 MINUTES POST 600 KPM ABSENT ANGINA - SOFT S_4

Fig. 5. The clinical importance of exercise induced S_4 gallop sounds associated with angina pectoris, in the absence of S-T segment abnormalities, is illustrated. The rapid disappearance of this finding after stress indicates the need for an on-line computer averaged record obtained during exercise.

nals from Frank lead Z.

Lead Z is connected in parallel to Schmitt Trigger input No. 1 and to analog digital channel No. 3. Prior to its input into the Schmitt Trigger input, it is amplified with an RC time constant of 0.006 seconds (to obtain a derivative of lead Z) and filtered with a low pass up to 30 cycles per second to avoid high frequency artifacts. Schmitt trigger No. 1 is initiated by positive threshold crossing which is manually set.

The analog signal presented to the analog to digital converter for Frank lead Z is not filtered and ranges from 0.5 volts negative to 0.5 volts positive. The analog signal presented to the Schmitt Trigger is filtered and amplified as discussed in the preceding paragraph.

All real time intervals are added to a double precision buffer and divided by 8 to determine the average R-R interval for the eight beats preceding the arrhythmia editing. If the current beat duration varies more than 20% from the average duration of the immediately preceding eight beats, it is rejected. The first eight beats at rest are always accepted under manual control. The resting record is obtained using R-R interval editing only (no cross correlation of 200 msec vectors).

During exercise all beats are tested for R-R interval variation, and if they do not exceed the 20% limits in R-R interval variation the beat is then tested for the initial 200 msec vectors. The beat is correlated with the averaged values from the 25-second resting tracing as follows:

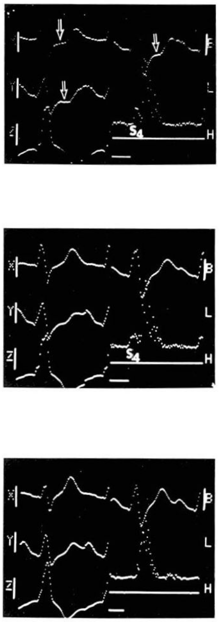
$$A = \frac{\sum_{i=1}^{40} (U_i - \bar{U}) V_i}{\sum_{i=1}^{40} (U_i - \bar{U})^2}$$

Ui = individual averaged values for points during the previous sample interval.

Vi = Individual points for this current wave form.

$$\bar{U} = \frac{\sum_{i=1}^{40} Ui}{40}$$

If 0.5 is less than the absolute value of A is less than 1.5, the set of points is accepted ($0.5 \leq A \leq 1.5$). Since our sampling rate is one point at every 5 msec and there are 20 points on each side of the trigger, a total of 200 msec is covered by the analog to digital converter "window." Note that lead Z is the basis for accepting or rejecting all analog channel inputs to the averaging program to follow.



DURING 900 KPM
HEART RATE 181

IMMEDIATELY
POST 900 KPM
HEART RATE 160

3 MINUTES
POST 900 KPM
HEART RATE 137

Fig. 6. The rapid disappearance of marked S-T segment abnormalities after exercise demonstrates the need for on-line computer averaged records obtained during stress.

This program excludes premature ventricular beats, premature atrial beats with aberrant conduction, and artifacts from the logical flow of data for computer averaging programs.

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