GE Healthcare

Physician's Guide to GE Stress Systems

2051167-002 ENG Revision C

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Revision History

This manual is subject to the GE Medical Systems *Information Technologies* change order service.

The revision code, a letter that follows the document part number, changes with every manual update.

The initial version of the manual has the letter A.

Part No.	Revision Code	Date	Comment
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2051167-002	Rev C	2014-01	New: Exercise devices in exercise test interpretation (XTI). Graphical XTI output

Contents

1 Introduction

Computerized Stress ECG Analysis and Interpretation

The first analysis of the ECG signal on a digital computer was performed by Taback in 1959[3]. At that time he and his group reported the benefits of this revolutionary technology as: an ability to make more precise measurements, a reduction in the distortion of the ECG signal, and accessibility to storage techniques.

Computerization of the stress ECG has evolved greatly since that original attempt. There are four generally recognized benefits to the computerization of the ECG signal:

1. The advanced signal-processing techniques make it possible to present clean electrocardiograph tracings in the presence of severe artifact and noise.
2. Computer-generated measurements are consistent and eliminate the well documented interobserver variability.
3. Properly constructed algorithms have the ability to accurately recognize and remove aberrant beats from the signal processing.
4. The application of computers is making it possible to generate more, and better, criteria for positive exercise tests, for example, automatic Exercise Test Interpretation, Duke Treadmill Score, and ST/HR Criteria.

The *Physician's Guide to GE Stress Systems* has been written to provide the practitioner with a conceptual insight into GE's innovative methods of signal processing and exercise test interpretation. Our hope is that it will enhance the application of computerized exercise electrocardiography to your practice.

The software that is at the heart of GE stress systems is in its third decade of continued development. While it encompasses many aspects of advanced signal processing, data is presented in formats that preserve continuity with traditional clinical methods.

The functionalities described in this guide are provided by the GE software package **HEART Exercise** containing the XTI exercise test interpretation feature. It is installed in different GE Stress Systems and has a separate, device-independent 510K FDA approval. The specifics presented in this guide refer to GE Stress Systems, e.g., CASE, CardioSoft*, CS*, MAC 1200, and MAC 1600. They describe the capabilities of GE stress products. Depending on whether the device is a

high end or a low end product, or whether options have been purchased or not, some of the functions described may not be available on your device. Consult your operator's manual for details.

Note

Please note that the products CardioSoft and CS may not be available in some countries.

2 Acquisition of the ECG Signal

ECG Signal Acquisition with GE Stress Systems

GE stress systems simultaneously acquire all 12 leads of the conventional ECG. Eight of the leads are acquired directly (I, II, and V1 through V6). The remaining four (III, aVR, aVL, and aVF) are derived via Einthoven's law.

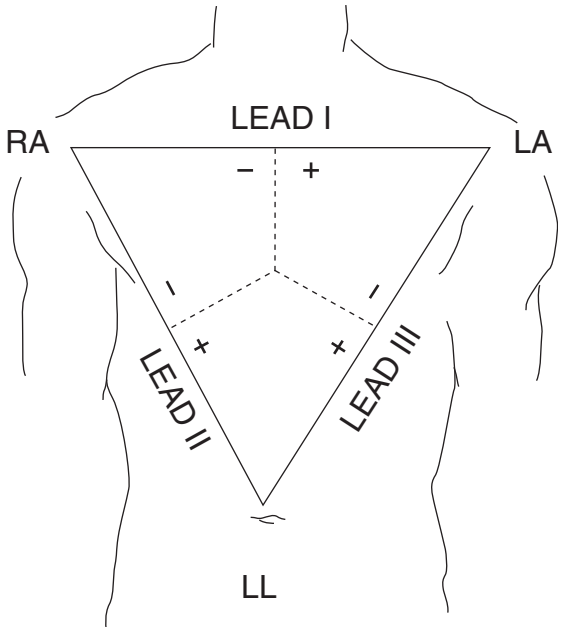


Figure 2.1 Frontal plane leads shown with reference to Einthoven's triangle

Because of the inherent relationship of the standard limb leads to each other, Einthoven stated that at any given instant during the cardiac cycle, the sum of the potentials of leads I and III equals the potential of lead II. (This complies with American Heart Association recommendations[1].)

Most report formats show only a portion of a 10-second ECG strip. For example, the standard 12-lead presentation displays only 2.5 seconds from each of the four lead groups. Regardless of the data seen on hard copy reports, GE stress systems simultaneously acquire and process the complete database of 12 leads for the duration of the complete procedure.

Note

For those clinicians interested in testing with more or less than the conventional 12-lead electrocardiogram, GE systems provide the capability for simultaneous acquisition of 3, 6 or 15 leads. Consult your operator's manual for details.

GE systems with color capability indicate the signal quality of the applied electrodes on-screen, using different colors:

green: the electrode is properly applied

yellow: poor signal quality

red: electrode disconnected, high impedance, or lead break

white: not used

Sometimes pacemaker spikes are not visible in the ECG signal. This can occur when the spikes have a low amplitude, e.g., less than 2 mV, and a short duration, e.g., less than 0.1 ms. GE stress systems are able to detect small pacemaker pulses and provide the possibility to enhance them, i.e., the user can enable the pace enhance function.

Characteristics of the ECG Signal

The raw electrocardiograph signal is obtained in analog form. An analog signal is defined as a continuous signal which varies in amplitude with time. Figures 2.2 and 2.3 illustrate analog signals.

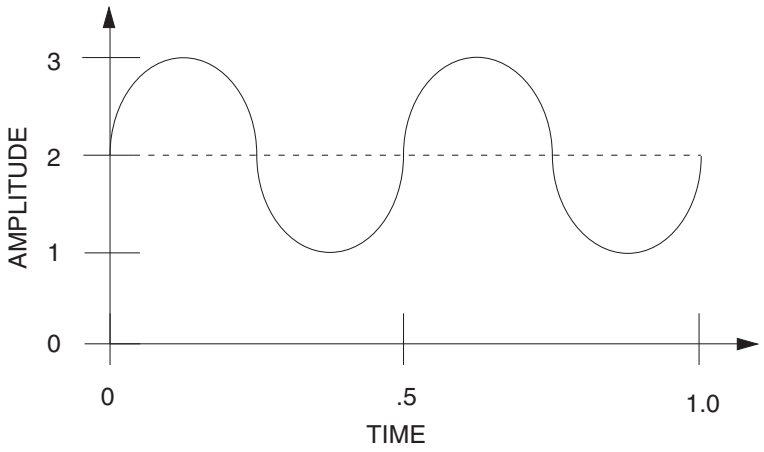


Figure 2.2 A 2-Hz analog signal

The frequency of an analog signal is defined as the number of complete cycles that occur per second. The frequency of a signal is labeled in Hertz (Hz). Figure 2.2 is an example of a low-frequency wave. Notice that it does not repeat rapidly. The frequency is 2 Hz (2 cycles per second).

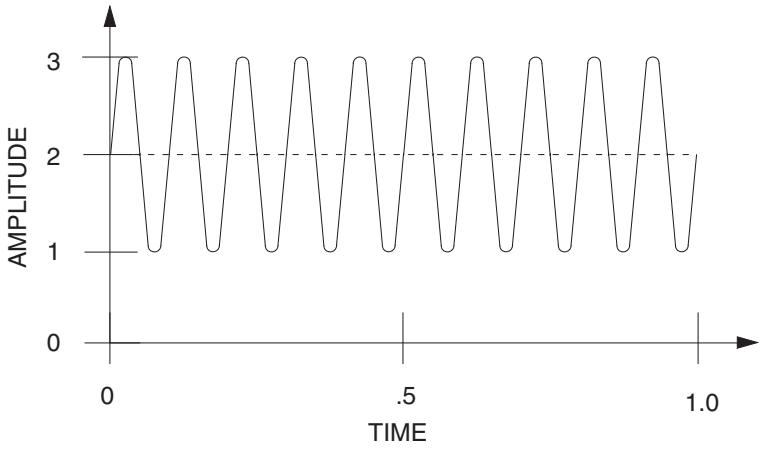


Figure 2.3 10-Hz analog signal

A higher frequency wave is shown in Figure 2.3. It is compressed and repeats more often. The frequency is 10 Hz.

Figure 2.4 presents a raw (analog) ECG signal. The typical ECG representation of the cardiac cycle consists of various waveforms that vary in frequency. The general frequency characteristics of ECG data are presented in Table 2.1.

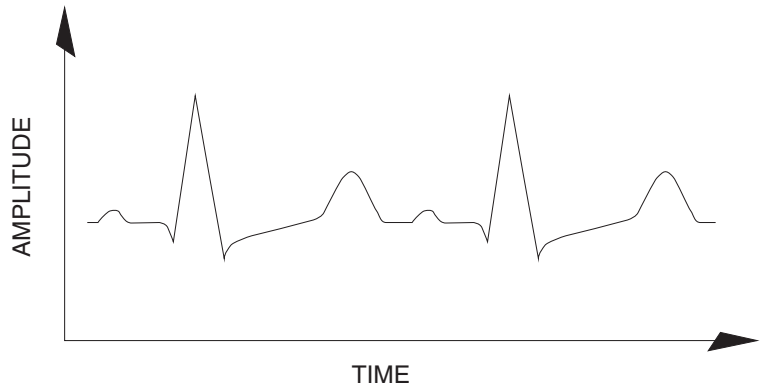


Figure 2.4 The ECG waveform shown as a continuous analog signal with both amplitude and time components

ST Segment	—	0.05 Hz to 5 Hz
Baseline Roll	—	< 1 Hz
P Wave	—	< 5 Hz
T Wave	—	< 5 Hz
QRS Complex	—	10 to 40 Hz
Muscle Artifact	—	> 35 Hz

Table 2.1 General frequency characteristics of an ECG signal

Digitization of the ECG Signal

Digitizing an analog signal such as the ECG requires periodic sampling at fixed time intervals.

Figure 2.5 shows the effects of analog-to-digital conversion. Note how the sampling rate affects the resolution of the signal. In general, the greater the sampling rate the better the resolution.

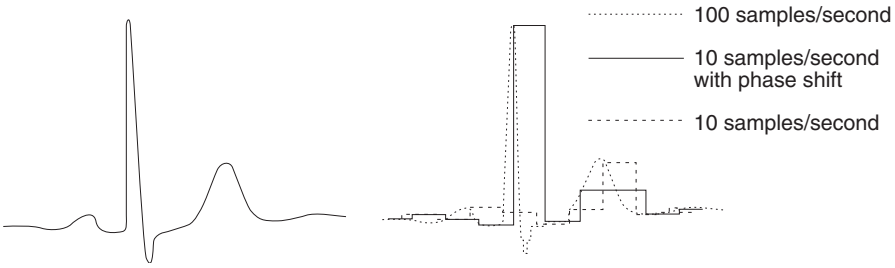


Figure 2.5 The effects of different sampling rates on the analog-to-digital conversion of the ECG signal (Froelicher, V. F., Exercise and the Heart 3rd edition[2])

Incoming analog signals are digitized with GE's unique patient acquisition module. Data is acquired at a rate of more than 1,000 samples per second resulting in values every 0.05 mm at standard chart writer speed. (GE systems comply with and exceed American Heart Association recommendations.)

Environmental Noise Elimination

To acquire cardiac waveforms accurately, we have taken great care to design our systems to exclude environmental noise. For the purposes of this publication, we will define environmental noise as that artifact which originates outside of the system. Several noise-exclusion mechanisms are employed.

Let us first discuss noise generated by signals external to the patient's body; that is, in addition to the small voltages generated by the myocardium, the ECG equipment receives signals coming from electrical equipment in the environment. These signals are called common mode because all of the leads on the body "see" them: they are common to all of them. A common mode signal can be many times greater than the ECG. Therefore, it is important to eliminate.

The ability of the electrocardiograph to reject this signal is called common mode rejection. Due to practical limitations, it is not possible to entirely eliminate the common mode signal. However, we are able to greatly reduce it. The amount of reduction is called the *common mode rejection ratio*.

With GE's common mode rejection ratio only 1 part in a million is left. For example, if the common mode signal is 100 volts, only 100 microvolts would be left in the ECG recording.

In addition to the high quality rejection circuitry, there is another way to minimize the deleterious effects of the common mode signal. Imagine we could perfectly couple the system and patient together; both system and patient would experience the same common mode signal. In absolute terms, the common mode signal would still exist, but the acquisition hardware would not see it in relation to the patient's body.

GE achieves this by taking the acquisition function out of the system hardware. Acquisition is performed within the patient cable. Since the patient acquisition module is small and close to the patient's body, it can track the common mode signal of the patient. There is almost no voltage difference between them. This, in addition to the use of the right leg electrode, results in almost no common mode signal relative to the patient acquisition module.

Finally, as a result of the digitization of the ECG signal within the patient acquisition module, analog cable noise is eliminated. Thus, regardless of cable movement or length, GE systems receive the cleanest data possible for processing.

3 Conditioning the ECG Signal

The Importance of Noise-Free ECGs

A fundamental requirement of any system designed for exercise electrocardiography is the ability to present noise-free ECGs without distortion of the waveforms. In the absence of aggressive filtering, this presents a formidable challenge as measurements of the smallest ECG wave (the ST segment) in minute increments (tenths of millimeters) under trying circumstances (strenuous exercise) are attempted.

The diagnostic value of stress testing is enhanced by computer-assisted systems. GE systems aim at producing accurate measurements through an improved *signal-to-noise ratio* in the ECG recorded during exercise. Signal-to-noise improvements are achieved by the application of filters and/or signal processing algorithms.

Filtering

Filters, in the traditional sense, are mechanisms for removing certain frequencies of an analog signal. *Low-pass* filters permit the passage of frequencies below a specified value to be reflected in the waveform. Conversely, *high-pass* filters permit only those frequencies above the specified value to be included in the process.

The American Heart Association requires diagnostic ECG instrumentation to be capable of recording waveforms with a fidelity of 0.05 to 150 Hz, or more challengingly, instead of 150 Hz, it must be capable of processing triangle pulses of 1.5 mV (15 mm) amplitude and 20 ms width, according to ANSI/AAMI standard EC11[74]. GE stress systems exceed the American Heart Association specifications. The plurality of GE's stress systems, such as CASE, have a non aggressive low-frequency response of 0.01 Hz, in order to prevent artifactual ST segment abnormalities[5,8].

Noise Filters

The QRS complex represents the high-frequency component of the electrocardiogram. Low-pass filters of 20, 40, and 100 Hz are user selectable on GE stress systems for the purpose of attenuating muscle noise from the baseline. Figure 3.1 illustrates the effects of successively more aggressive low-pass filters on the ECG signal. These filters significantly reduce muscle artifact and have essentially no effect on the low-frequency components of the ST segment. R-wave amplitude, however, will be attenuated with the 20-Hz and 40-Hz filters.

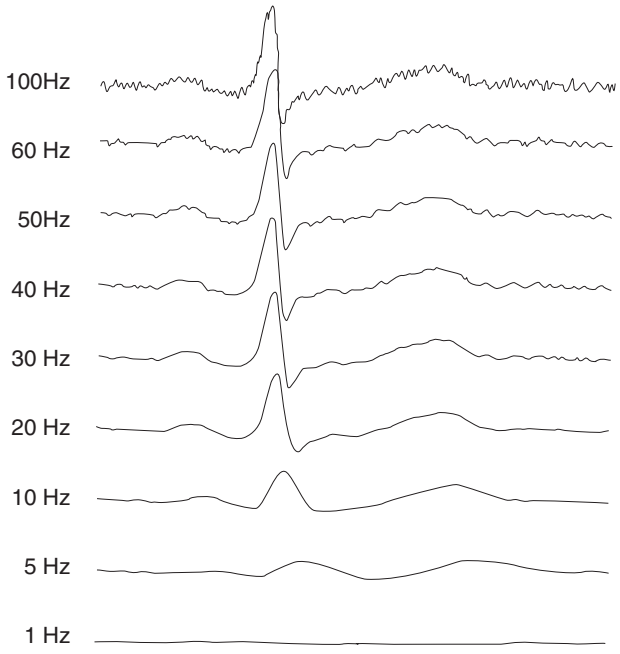


Figure 3.1 The effects of successively more aggressive low-pass filters on the ECG signal (H. Blackburn (ed), Measurement in Exercise Electrocardiography: The Ernst Simonson Conference. Charles C. Thomas Publisher, Springfield 1969[4]. Froelicher V.F, Exercise and the Heart: 3rd edition[2])

Baseline Roll Filters

Filters at the low end of the frequency spectrum of electrocardiographs are called baseline roll filters. Those as aggressive as 0.25 Hz or even 0.5 Hz effectively reduce baseline roll due to respiration. However, some potentially introduce a phase shift in the QRS complex resulting in artificial changes in the region of the ST segment. Filters such as these should never be employed in instruments designed to reproduce physiologic ST segment changes. GE systems exceed AHA recommendations by employing a non-aggressive high-pass filter at the low end of the frequency range. Instead, baseline roll is controlled with the implementation of a baseline correction algorithm. (See "Cubic Spline Baseline Correction" on page 18 and "FRF (Finite impulse response Residual Filtering) Algorithm" on page 19.)

GE's incrementally updated median QRS complexes are presented at the full diagnostic frequency response. Regardless of the noise and baseline roll filters chosen for the ECG data, ST-segment and R-wave amplitude measurements are made on unfiltered data. This provides the highest level of accuracy possible with the greatest reproducibility.

50/60-Hz Line Filters

Despite all of the methods used to reject common mode signals, power line interference (often referred to as 50/60 Hz "buzz") will continue to be part of the acquired signal. This is due to magnetic field induction of differential signals in loops formed by a lead connection to the body. Since digitization takes place at the patient, lead wire length is very short, minimizing these signals. Nevertheless, GE uses a line frequency filter, removing any remaining 50/60-Hz buzz.

This filter must know the line frequency, 50 or 60 Hz, at which the system operates. The appropriate filter is preset at the factory prior to shipment. Your system removes the line frequency noise by monitoring for, locking in on, and subtracting the opposite sinusoidal wave. This filter has a dramatic effect. Notice its operation on the following signal below.

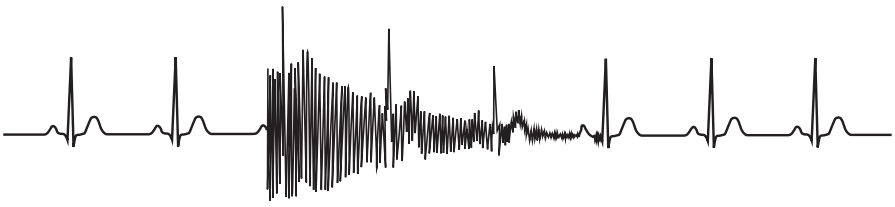


Figure 3.2 The elimination of AC line frequency interference with application of a 50/60-Hz line filter.

Cubic Spline Baseline Correction

GE's stress systems feature a *cubic spline* algorithm for removing baseline roll. This is employed as an alternative to aggressive baseline filtering. The technical details of this method are described in "Electrocardiogram Baseline Noise Estimation and Removal Using Cubic Splines and State-Space Computation Techniques", *Computers and Biomedical Research*[7].

The cubic spline algorithm requires that three consecutive isoelectric points be reliably detected. The onset of the QRS is ideal for this purpose. At low heart rates, a point in the isoelectric area between the T and P waves is used in addition. The three consecutive points are used to establish and estimate the baseline roll. This estimate is then subtracted from the original ECG to yield a baseline-roll-reduced ECG with no waveform phase distortion. Figure 3.3 demonstrates the capability of the cubic spline.

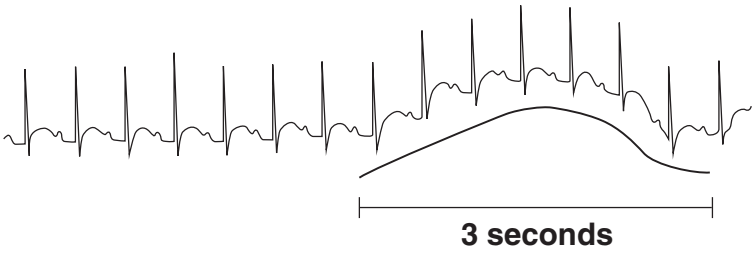


Figure 3.3 Application of the cubic spline to an ECG signal that exhibits respiratory induced baseline roll.

As three isoelectric points are required for the cubic polynomial to operate, the ECG is delayed 2 seconds, for example rhythm reports recorded with the spline engaged are delayed by these 2 seconds.

FRF (Finite impulse response Residual Filtering) Algorithm

Most GE stress systems feature the FRF algorithm for removing noise and baseline roll. This is employed as an alternative to aggressive noise and baseline filtering. Also it is an alternative to the Cubic Spline Baseline Correction which only reduces the baseline roll. The method was published in "Artifact Processing during Exercise Testing", *Journal of Electrocardiology*[13].

The FRF algorithm reduces the artifacts in the ECG stream, but with much less distortion of the QRS complexes. It consists of a block that updates the median beat and a function that subtracts the median beat from the ECG and then outputs a residual signal. The residual signal is fed into a low-pass filter, a high-pass filter, and finally into a function that adds the median beat (see Figure 3.4).

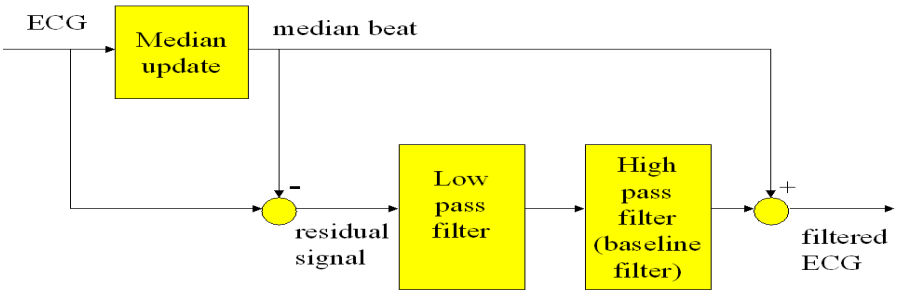


Figure 3.4 Block diagram of the FRF algorithm

The median beat is continuously updated only if the current QRS complex correlates with the median beat. The chosen correlation limits guarantee continuous updating. The subtraction function subtracts the median beat only if there is a reasonable accordance between median beat and current beat. If the current beat is a PVC, for example, no subtraction is done. The median beat is subtracted from the QRS onset to the T end. The P wave is not subtracted. In cases of PSVCs, atrial fibrillation, atrial flutter, AV block II (Wenckebach, Mobitz), and AV block III, for example, a subtraction of the P wave of the median beat would be erroneous.

The result of the subtraction function is the residual signal. This signal is filtered by a low-pass filter to reduce muscle noise and a high-pass filter to reduce baseline wander. The cutoff frequencies of the filters are set to values that avoid unacceptable distortion of the remaining P waves and PVCs in the residual signal. The constant delay of the filters enables the addition function to add the median beat to the filtered residual signal at the exact position, i.e., the position where it was subtracted before. The addition function does not add the P waves. If a median beat is not available or in case of a pace ECG, the filters are switched off.

For your notes

4 Signal Processing

Mathematical Algorithms

Signal processing employs mathematical algorithms to

- effectively detect beats,
- classify their morphology, and
- properly superimpose normally conducted beats.

The most prevalent method of signal processing takes an average of a defined time window or block of consecutive beats. This process, termed arithmetic averaging, produces a mean QRS complex.

GE uses a unique noise-rejection algorithm called *incremental updating*. This mechanism, sometimes called *incremental averaging*, produces a median QRS complex. The technical aspects of this program were described in *Trends in Computer-Processed ECG's*, North Holland Press, 1977.

In a perfect world where stress ECGs would not be affected by random noise – muscle artifact in particular – one might be hard-pressed to label a single approach to signal processing as superior. However, under actual conditions where noise is a fact of life, the *median QRS* complex produced by the incremental update process steps to the front.

Signal processing consists of five consecutively applied algorithms:

- First, the best leads for QRS detection must be selected.
- Second, the incoming beats must be detected, and heart rate updated.
- Third, the incoming beats are classified on the basis of RR intervals and QRS morphology.
- Fourth, a correlation and alignment algorithm overlays the incoming beat to the dominant template for best fit and determines the degree of agreement between the incoming beat and the template.
- Finally, successfully correlated beats incrementally update the dominant template.

During exercise testing and especially in the high exercise phase, it occurs very often that only a few of the applied leads deliver a reasonable ECG quality.

It is obvious that by selecting only good leads, the QRS complex detection quality can be improved. Instead of using an algorithm, which combines leads without taking account of their quality, GE developed a new algorithm, the *Intelligent Lead Switch algorithm*.

Intelligent Lead Switch Algorithm

The advantage of the algorithm is a more reliable QRS detection, even in the high exercise phases. The method was published in "Artifact Processing during Exercise Testing", *Journal of Electrocardiology*[13].

Initially, after application of all relevant electrodes, the algorithm selects the two best leads. During exercise testing, the selection process is restarted when the best leads become disconnected or the signal quality of the selected best leads becomes insufficient.

During exercise testing the algorithm switches between the two best leads, always selecting the artifact-free lead. In the presence of special arrhythmias the algorithm also switches to the lead that is better suited for QRS complex detection, e.g., in the case of a bigeminy with very big premature ventricular complexes and small normal complexes or ventricular tachycardia with very small complexes.

During exercise testing the algorithm looks at the arrhythmia results of the alternative lead and corrects the result of the current lead if necessary. This would be the case when a premature ventricular complex in the current lead is very small (then the algorithm recognizes a pause), but displayed more clearly in the alternative lead.

The algorithm consists of:

- up to 15 independent and equivalent units for QRS detection, ECG quality evaluation, and event classification
- a logical unit for starting/restarting the selection process of the two best leads, for selecting the results of the best channel, correcting the event classification of the best channel, and correcting the trigger points (times where the QRS complexes are located) of the best channel

The ECG quality is calculated on the basis of the QRS complex amplitudes, the levels of middle and high frequency noise, and the electrode status (e.g., connected or disconnected electrodes). Examples for classified events are pauses, premature supraventricular complexes and premature ventricular complexes. If a pause is detected in the best channel, and the algorithm finds premature ventricular complexes in other channels, it will correct the event classification and the trigger points of the best channel.

Detection of Cyclic Artifact Algorithm

During an exercise test the patient normally walks or runs on a treadmill or rides a bicycle. In both cases the patient produces cyclic artifacts. With increasing exercise, the artifacts increase as well.

The origin of those artifacts is muscular activity or changes in electrode position, caused by the movement of the patient. Electrode position changes produce artifacts whose frequency content is very often similar to the QRS complexes. For this reason, the artifacts are very difficult to detect. Furthermore, they are dangerous because they disturb the detection of QRS complexes. This can lead to wrong heart rate values, to wrong arrhythmia results, and to erroneous interpretation of the exercise test.

Once a cyclic artifact rhythm is detected the information is used as an input for the Intelligent Lead Switch Algorithm for selection of other ECG channels with reduced artifact levels, for example, to ECGI and ECGV6 in Figure 4.1. The method was published in "Novel Signal Processing Methods for Exercise ECG", *International Journal of Bioelectromagnetism*[14].

ECG and the cyclic artifacts are two independent rhythms. During exercise both, the RR intervals and the intervals of the cyclic artifacts, do not vary very much over a short time range. To identify and separate the two independent rhythms an algorithm is used which tries to find independent chains of intervals. Cyclic artifacts are detected when the algorithm has found another independent chain in addition to the chain of RR intervals. Leads containing two independent chains are of poor quality.

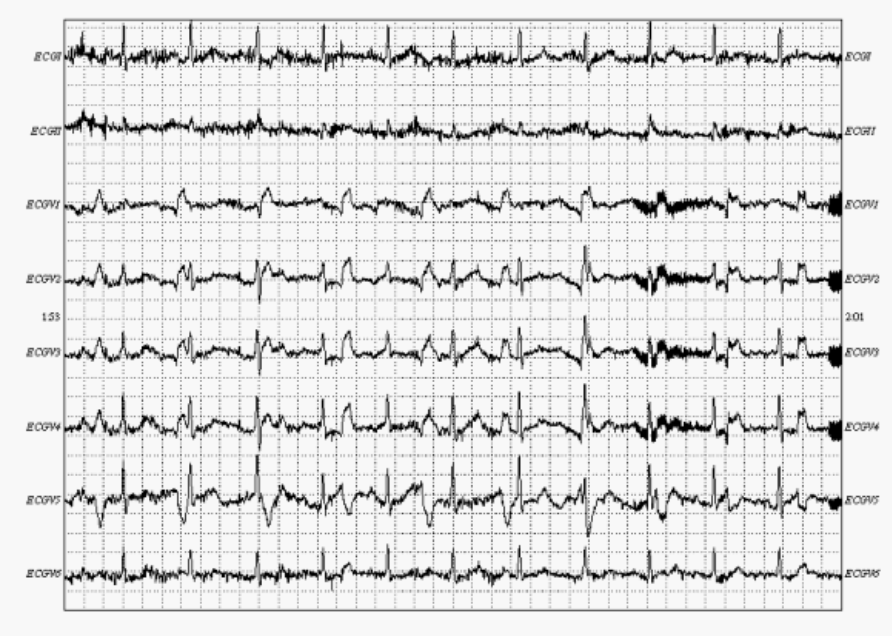


Figure 4.1 ECG with cyclic artifacts. In leads ECGV2 to V5 both rhythms are visible, in ECG leads I and V6 only the ECG rhythm is visible, and in ECG lead V1 only the cyclic artifacts are visible.

QRS Detection

In GE stress systems the QRS complexes are detected independently in different leads. Then the information about the detected QRS complexes of every lead is combined in a logical way depending on artifacts, amplitudes, etc. (see preceding "Intelligent Lead Switch Algorithm" on page 22). The combined information results in an accurate and reliable QRS detection, even in the high exercise phase.

Detecting QRS complexes in each individual lead has the advantage of not loosing any information about the QRS complex, T wave, and P wave. Since the morphology of the ECG waves is not destroyed, the discrimination of QRS complexes and artifacts is very high.

QRS detection algorithms used earlier and by the competition transform the ECG leads and combine them to one signal for QRS detection. All these transformations eliminate important information with the effect that QRS detection will be more disturbed by artifacts or will be less sensitive.

The new QRS detection algorithm adapts to the current QRS complexes, to T waves, to P waves, and to the overshoots or undershoots of a pacemaker ECG. The knowledge about the T waves and P waves is used to avoid the misclassification of a T wave, or a P wave as a QRS complex, for instance, and provides a higher tolerance to artifacts.

Correlation and Alignment

After QRS detection, the correlation and alignment algorithms form the basis for the incremental update. The process begins by selecting an incoming beat. This beat becomes the seed for the dominant median template. The following beat is superimposed on the dominant template. The beat is aligned horizontally and vertically until the maximum possible correlation coefficient is attained. If the correlation coefficient is considered to be insufficient, the incoming beat is classified as an ectopic beat and is not considered for further processing. If the correlation coefficient is high, the beat is used to update the dominant median template. If the process begins by selecting an ectopic beat, the ensuing normal beats will not correlate. In this case further complexes are collected. Then the resulting ECG pattern is analyzed for selection of the correct (normal) beats for the dominant template. This will occur when ventricular ectopic beats, e.g., bigeminy and trigeminy, are found in the ECG.

The template is held in a buffer of 1200 milliseconds. The QRS trigger point is arbitrarily placed at 400 milliseconds into this buffer (see Figure 4.2). This large buffer ensures that QT and PQ intervals, even when they are extremely long, can be stored and processed in their entirety.

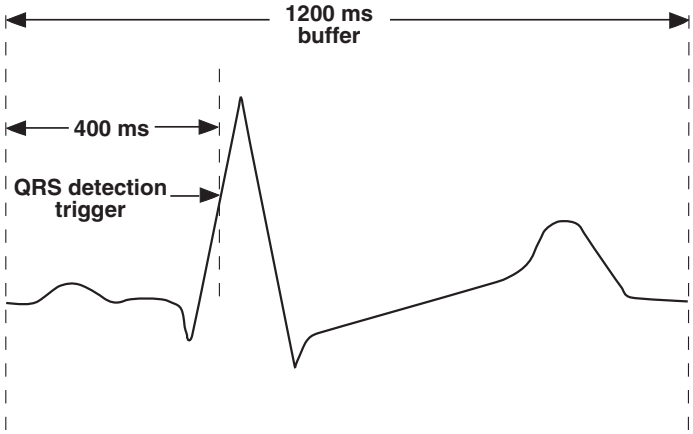


Figure 4.2 Placement of the median template into a 1200-millisecond buffer

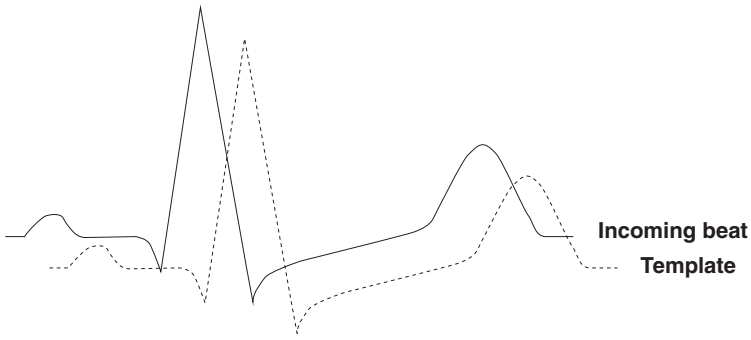


Figure 4.3 Incoming beat superimposed on the median template and shifted for maximum alignment

Incremental Updating

Whenever the incoming beat correlates with the median template, the template is updated (positively or negatively) by a fixed increment or a fraction of the difference between the median template and the incoming beat, whichever is less. With this process, the median morphology tends in the direction of consistent, non-random changes in amplitude, for example, ST segment depression. The process assumes that noise is random, and the erratic amplitude changes associated with noise are limited to immeasurably small changes in the median beat.

Relearn

If the QRS morphology changes during stress testing in a normal way, the median update algorithm will be able to follow these changes. Occasionally patients present significant changes in QRS morphology. GE stress systems recognize these changes and “relearn” the median template. During this process, the ST segment measurement points are also relearned. An automatic relearn also occurs after reapplying disconnected electrodes. A manual relearn can be initiated by the user.

When relearning, an incoming beat is established as the dominant template. If the next beats do not correlate with the first beat, the relearning procedure starts again. In case of ventricular ectopia, e.g., bigeminy and trigeminy, the algorithm is able to select the normal beats for creating the new dominant median beat.

During the relearn phase, a question mark (?) appears after the ST measurements of the median complex on the screen. Also, any reports run during this period will display question marks after the ST measurements. This indicates that the values may be unreliable during the relearn phase.

As the system monitors each beat for proper shape discrimination, a record of the last beats is constantly updated to determine the number of beats successfully updated. If 20 of the last preceding beats fail to align, the warning “Median Update Ceased” will appear on the screen, and an automatic relearn occurs. Prolonged, excessive artifacts may cause this message to appear. The median beat and the ST measurements remain on the screen. If within a one-minute period a new median beat cannot be created, the median beat and the measurements are deleted, and the automatic relearn function is repeated . The manual relearn may be used at this time if visual inspection of the raw rhythm shows discordance with the median.

Pace Enhance

Displaying pacemaker pulses is sometimes difficult. In some cases the pacemaker pulses are narrow and cannot be displayed; in other cases they are large and disturb the readability of the ECG. The pace enhance function solves these problems.

When enabled, the pace enhance function will replace the pacemaker pulse with a marker of the same polarity as the ECG signal in each lead. If the pacemaker pulse is small (in the range of ±0.1 mV) a positive marker is added to the pacemaker pulse.

This is what the pace enhance function does in detail:

It adds a marker (1.5 mV amplitude, 6 ms duration) of the same polarity as the pacemaker pulse to the ECG electrode signal.

It limits the added sum of pacer pulse and marker to 0.5 mV in the ECG lead signal.

For your notes

5 Measurement Values

Heart Rate

The heart rate is calculated as a 16-beat sliding average and the display is updated every second. This provides stability to the rate during sinus arrhythmia and atrial fibrillation, yet allows rapid tracking of dramatic rate changes as in paroxysmal tachycardia.

In the initial learn mode, the heart rate is calculated by averaging the RR intervals of the available beats. The heart rate is displayed when at least four beats are detected.

Evaluation of the accuracy of the heart rate is based on the results from annotated databases consisting of exercise ECGs from treadmill tests and exercise ECGs from bicycle tests.

Database	average mean error	average RMS value
Bicycle ECGs	- 0.14 bpm	0.76 bpm
Treadmill ECGs	- 0.2 bpm	0.99 bpm

Table 5.1 Heart rate performance (DOC0996283)

Note

On GE systems, the leads used for the QRS detection are selected automatically, but they are also user selectable before and during the stress test. Consult your operator's manual for details.

The heart rate HR is one of the most important outcomes of an exercise test. The HR course during exercise contains valuable information about coronary stenosis[64,79] and cardiovascular mortality risk[33,39,41]. But it is an indirect method and, therefore, other factors, such as the exercise device used—treadmill or bicycle—also influence the HR values. Most patients achieve higher peak HR values on treadmills than on bicycles[87].

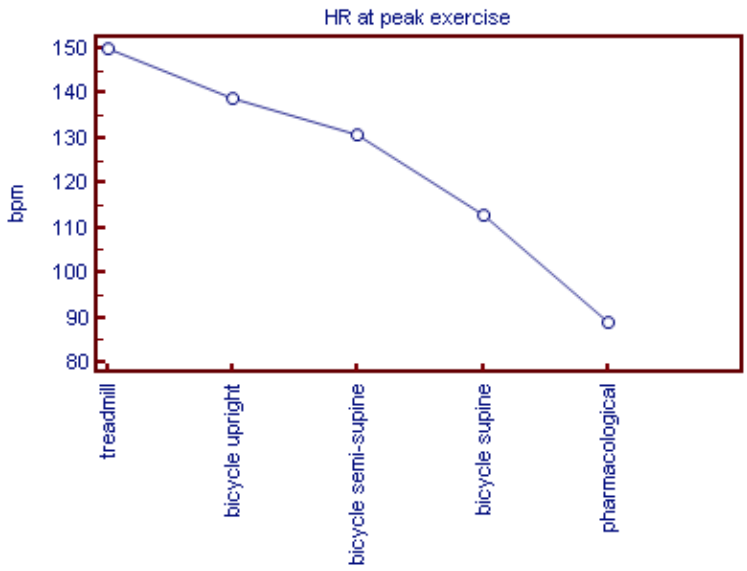


Figure 5.1 Mean values of "HR at peak exercise" of different exercise devices and pharmacological Adenosine stress test, based on the GE-Healthcare exercise/stress test database, containing more than 20.000 patients.

ST Segment Values

GE's methodology involves locating an isoelectric reference (E point) and the QRS offset (J point), and measuring the ST segment at a user-defined or heart-rate related distance x past the J point. (See Figure 5.2) It is identical in approach to the manner with which one would manually measure the values.

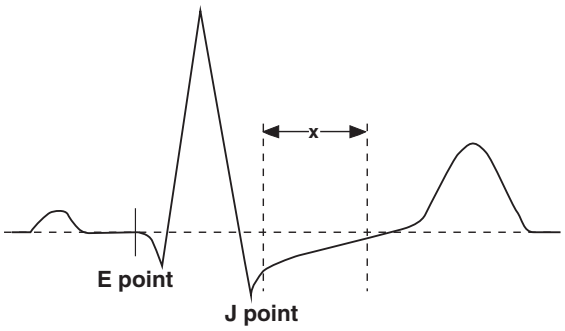


Figure 5.2 GE stress systems measure ST segments by locating an isoelectric reference (E point), the offset of the QRS complex (J point) and the post-J measurement point (J+x point) for measuring the ST segment.

QRS Onset and Offset Detection

QRS onset precedes the first deflection in the used leads, and QRS offset occurs where the last steep slopes of depolarization are replaced by the more or less flat ST segment. The method employed by GE stress systems uses up to 16 leads, determining the earliest onset and latest offset in the leads. The isoelectric point (E point) is placed at 10 milliseconds prior to the earliest QRS onset. This avoids the Q and R waves, yet stays well off the P wave even with decreasing or initially short P-R intervals.

For stress testing two methods for calculation of the E and J points are user selectable. The first method calculates the E and J points before the actual exercise, i.e., in the pre-exercise phase (single calculation). Then, during exercise, the median beat is aligned between these two points. The second method continuously recalculates the E and J points with every incoming beat (continuous calculation). The reasons for using the first method are historical. The second method, which is the factory default method, is the correct one, because it is able to adapt the E and J points when the QRS width changes. In the majority of cases, however, the QRS width will not change significantly during stress testing.

Waveform measurement is relatively straightforward once QRS onset and offset are known. All measurements are taken from the median complexes, providing immunity from noise while at the full diagnostic frequency.

Note

Both the E and J points are user adjustable on most GE stress systems. Consult your operator's manual for details.

ST Level

ST levels are simply the amplitude difference between the isoelectric reference point (E) and the post-J measurement point (J+x point). The operator has the possibility to enter a fixed value, e.g., 60 milliseconds for the distance x, or to select a method for heart-rate adaptive calculation of the distance x. Two methods for heart-rate-adjusted calculation are available:

- x = RR/16
  RR = RR interval. The formula is also used in GE's 12SL resting program
- x = 3/16 ($656/(1 + 0.001 \times HR)$ – 90 ms)
  HR = heart rate. The part of the formula in italics is derived from P.M.Rautaharju et al., Estimation of qt prolongation, *Journal of Electrocardiology, 23:111-117, April 1990*[10]

Instead of using a heart rate adjusted method, the ST level measurements may be adjusted by the user at any time. For example, an ST measurement point of 80 milliseconds post J may be manually swept forward as heart rates increase.

ST Slope

An ST slope is measured over an interval established as 1/8 of the average RR interval to a maximum of 80 milliseconds. The interval starts at the J point. This definition of slope takes into account the correlation between heart rate and repolarization time. Effects of the T wave on ST slope measurement are avoided.

In an algebraic sense, the slope of a given line is defined as the rise divided by the run. Figure 5.3 illustrates the algebraic determination of a slope on an ECG with ST-segment depression. Contrary to visual examination, the slope would be reported as positive.

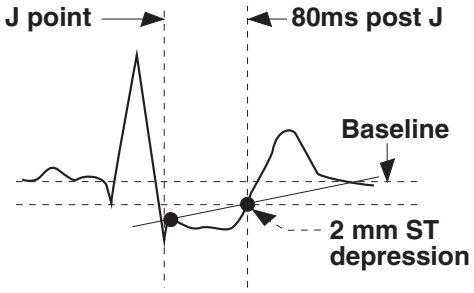


Figure 5.3 The algebraic determination of this ST slope would report it as positive despite the presence of 2 millimeters of ST-segment depression

GE systems employ a least squares fit in order to provide a close match with visual impressions. The actual slope measurement in millivolts per second is the result of a least squares fit of a straight line in 40-millisecond subintervals in the ST interval from J to 1/8 of the average RR interval. (See Figure 5.4) The most negative slope is reported. This provides a close match with visual impressions.

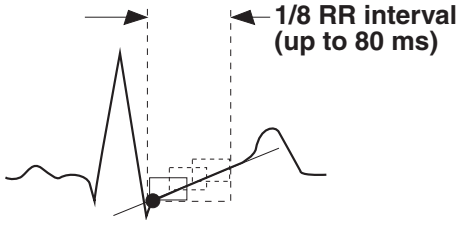


Figure 5.4 By employing a least squares fit for ST slope determination, GE provides a better match with the visual impression

ST Integral

An ST integral is measured over an interval from the QRS offset to the point where the ST segment crosses the isoelectric line, or to the point corresponding to 7/16 of the total ST-T duration, whichever occurs first. An ST integral below the isoelectric line greater than 10 µVs is considered abnormal. Note: One square mm on electrocardiographic paper at standard speed (25 mm/s) and calibration (10 mm/mV) is 4 µVs.[2]

ST Index

An ST index is "1" when the ST depression is 1.0 mm (0.1 mV) or greater, or the sum of ST segment depression in mm plus the ST down slope in mV/s is 1.0 or greater. If the conditions above are not fulfilled, then the ST index is "0". The ST depression is measured in the post J measurement point (J+x point).

R-Wave Amplitude

The R-wave amplitude is the difference in amplitude between QRS onset and the first maximum positive value.

QRS Width

The QRS width is the difference between QRS offset (J point) and QRS onset. During exercise testing, the QRS width is calculated continuously, but two values are the most important ones: QRS width at the beginning of the exercise phase and QRS width at peak exercise. These values are used to detect exercise-induced bundle branch blocks.

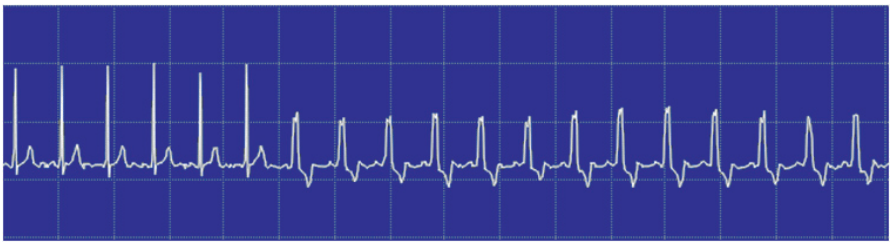


Figure 5.5 Exercise-induced LBBB, induced in the exercise phase, lead V6

Exercise-induced bundle branch blocks are rare, but they have the tendency to become permanent bundle branch blocks.[80]

Continuous calculation of QRS onset and offset is the precondition for detection of exercise-induced bundle branch blocks. Please make sure that the settings are correct (example: see Figure 5.6).

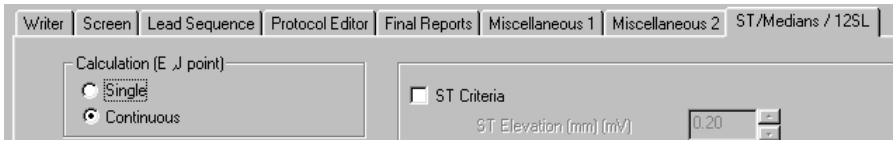


Figure 5.6 "Calculation (E, J point)" setting in CASE/CardioSoft/CS for proper detection of the exercise-induced bundle branch block. J point is the QRS offset, E point is calculated from the QRS onset by subtracting 10ms.

ST/HR Slope

The ST/HR slope was originally developed by Dr. R. J. Linden at the University of Leeds, United Kingdom, in the late 1970s[16]. It is reported to yield more accurate electrocardiographic determination of the presence and severity of coronary heart disease. While originally applied only to bicycle ergometry testing, it has recently been adapted for treadmill exercise by Dr. Paul Kligfield and colleagues at Cornell University.[15,17,18,19,20,21,22,23]

The criteria are based on the near parallel increase of myocardial oxygen demand and heart rate with increasing effort. Essentially, the exercise electrocardiogram is evaluated by linear regression analysis of the rate-related change in ST depression as measured at 60 milliseconds post-J point. Originally, the 12 classical leads and bipolar lead CM5 were evaluated. Changes in leads aVR, aVL, and V1 have been found to be poorly specific and are currently ignored. The addition of lead CM5 improves sensitivity appreciably.

A plot of ST segment depression versus heart rate is drawn for all measured leads. Linear regression analysis is used to best fit a line beginning at peak exercise and extending backward through at least three points until significance is obtained ($p < 0.05$). The points are taken from the ST level and heart rate at the end of each 2-minute exercise stage. The slope of this line is then determined and presented in units of microvolts/beats per minute. The steepest slope of all the leads is reported and graphed, if the ST segment depression is ≥ 50 µV.

The large increments in heart rate between stages of the Bruce protocol were found to yield an inadequate number of points for proper slope evaluation. A modification of the Bruce protocol (half work loads in 2-minute exercise stages) more closely approximate the roughly 10 beats per minute increments found in ergometry testing. This protocol, developed at Cornell University by Okin, et al.[22], is reproduced here and is strongly recommended for the highest predictive accuracy.

Duration of Exercise Stage (min)	Speed (mph)	Grade (%)
2	1.7	0
2	1.7	5
2	1.7	10
2	2.1	11
2	2.5	12
2	3.0	13
2	3.4	14
2	3.8	15
2	4.2	16
2	4.6	17
2	5.0	18
2	5.5	19

Table 5.2 Cornell Treadmill Protocol for ST/HR Slope

Former work[22] established the cut point for normalcy at 2.4 µV/bpm. Patients with three-vessel disease had slopes above 6.0 µV/bpm.

ST/HR Index

The ST/HR index was developed by Dr. Paul Kligfield and colleagues at Cornell University. The ST/HR index is an approximation to the ST/HR slope and therefore comparable results can be achieved[18].

Compared with standard test criteria, simple heart rate (HR) adjustment of ST depression during exercise electrocardiography can improve the identification and assessment of underlying coronary artery disease. Since heart rate during exercise drives progressive ST segment depression in the presence of coronary obstruction that limits flow reserve, the ST/HR index controls for the increasing metabolic severity of ischemia that accompanies exercise. Improvement of exercise test sensitivity with the ST/HR index results from reclassification of otherwise “equivocal” and even “negative” test responses, including increased identification of one and two-vessel disease in men and in women. In addition, in population studies of low and moderate risk subjects, the ST/HR index can increase the prognostic value of the exercise electrocardiogram for prediction of cardiac risk and mortality[24].

In contradiction to ST/HR slope, ST/HR index is much more simpler, is not restricted to special protocols, does not need a significant regression line, and always provides a value. It is simply calculated by dividing the change of the ST depression from the baseline value (exercise start) to maximum exercise by the change in heart rate over the same time period. The leads are scanned for the greatest ST/HR index.

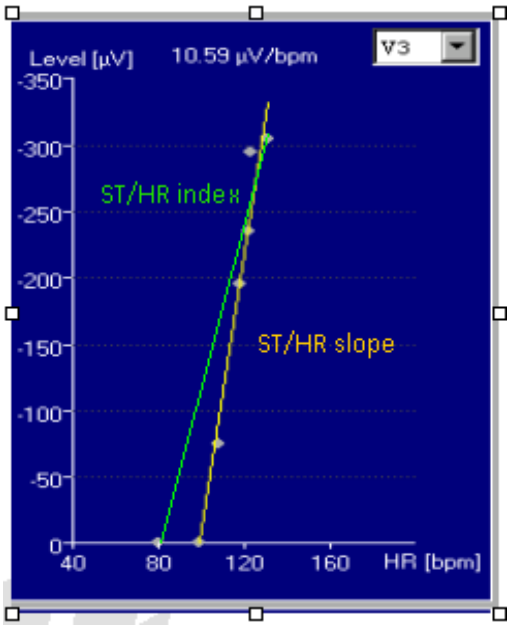


Figure 5.7 ST/HR index and ST/HR slope
ST/HR index is an approximation of the ST/HR slope

Recovery ST Level

The measurements above do not include the recovery phase. In addition to the exercise phase, the recovery phase delivers valuable information. The ST level 0.5 mm at 3 minutes of recovery, for example, is more reliable and precise than the ST level of 1mm at peak exercise (see Figure 5.9).

ST/HR Hysteresis

The ST/HR hysteresis was developed by Dr. Rami Lethinen et al.[37] at Tampere University, Finland, as an extension of the ST/HR loop[25]. It is a highly powerful measurement for identification of coronary artery disease (CAD)[37,90] and prediction of acute myocardial infarction[73]. It is comprehensive, because it takes both, the exercise and the recovery phase in account. Precondition for a proper ST/HR hysteresis measurement is an adequate recovery phase. Proposed are 3 minutes.

ST/HR hysteresis increases the sensitivity and specificity in both men and women, and is a "more competent method in CAD detection in women than ST-segment depression and ST/HR index"[44].

ST/HR hysteresis is calculated by integrating the difference in the ST segment depression between the exercise and recovery phase over the HR (heart rate) for up to 3 min of the recovery phase (see Figure 5.8). After integration, the integral is divided by the HR difference (peak exercise HR – minimum HR during recovery)[37,40,41].

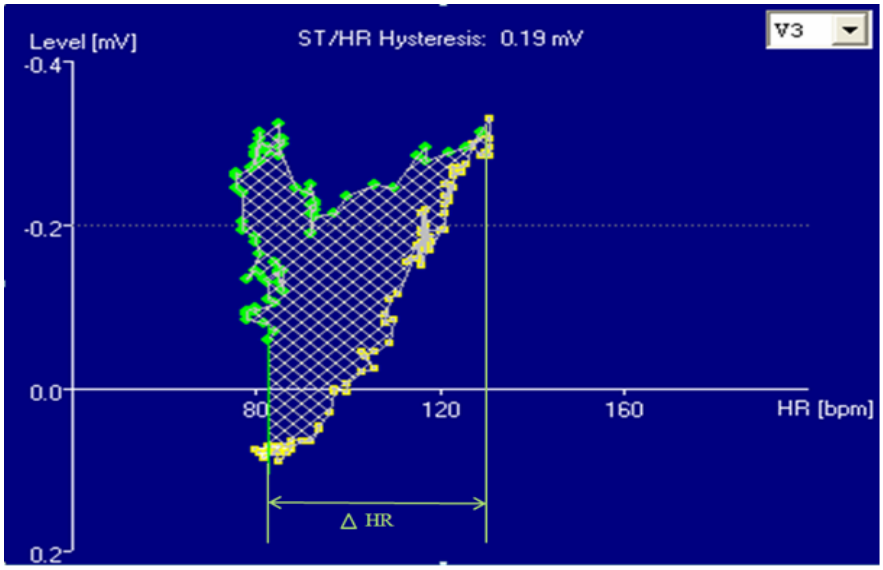


Figure 5.8 Significant ST/HR hysteresis. The area between the lower curve (exercise phase) and the upper curve (recovery phase) divided by the difference of the peak exercise HR and the minimum HR during 3 minutes recovery is the ST/HR hysteresis.
Please note: Negative level values, or ST depression values, are above the zero line. A negative level expressed as a value above the zero line indicates a positive exercise test.

ST/HR hysteresis is an advanced ST depression measurement, because it is the average difference of ST depression between recovery and exercise phase. Consequently the dimension of ST/HR hysteresis is mV (millivolt) or mm (millimeter).

The following Figure 5.9 shows the ischemia detection quality differences of different methods. At a threshold of 0.01 mV, ST/HR hysteresis achieves a sensitivity of 80% and a specificity of more than 80%. The ST depression at peak exercise at the threshold of 0.1 mV (1mm) achieves only a sensitivity of 55% with the same specificity.

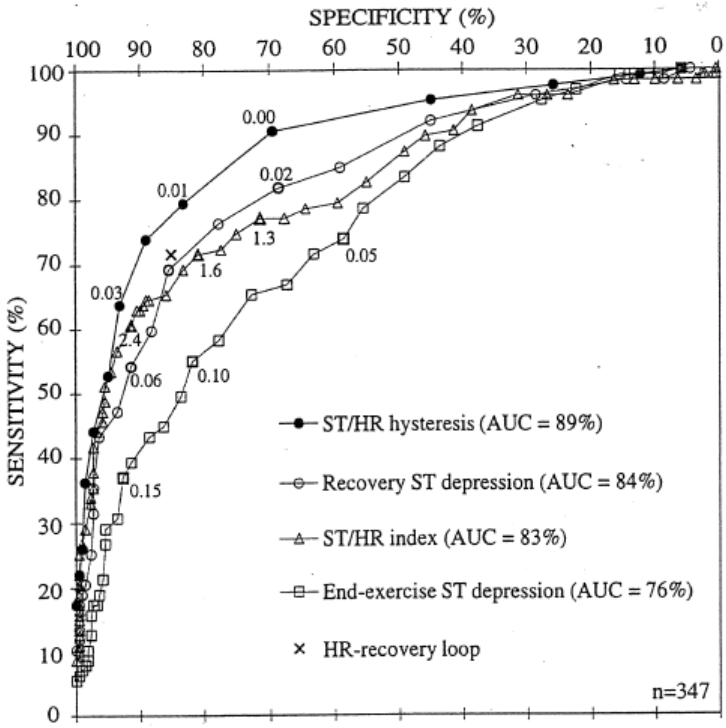


Figure 5.9 Receiver-operating characteristic curves for the continuous diagnostic variables and the operating point for the dichotomous heart rate (HR) recovery loop. The curve symbols refer to the partition values of the variables. Some of these values are specified, expressed in millivolts for the ST/HR hysteresis and ST depressions, and in mV/beat/min for the ST/HR index. AUC = area under the receiver-operating characteristic curve[37]

Sometimes ST/HR hysteresis curves are disturbed. This occurs in patients with pacemaker, atrial fibrillation or exercise induced bundle branch blocks. Responsible for this phenomenon are abrupt changes in the ST segment and/or discontinuous changes in the heart rate. Excessive noise can also disturb the curve.

Arrhythmia Detection

Arrhythmia analysis distinguishes between single-beat events and multi-beat events. Single-beat events are classified by linking characteristics such as the current RR interval, the current QRS morphology, the dominant RR interval, and the dominant QRS morphology with a rule database. An example for a rule type leading to the PVC classification is

If

the current RR interval is shortened

and

the next RR interval is a compensatory pause

and

the morphology is different from the dominant QRS morphology

then

the current beat is a PVC.

Multi-beat events result from multiple, consecutive single-beat events. Two consecutive PVCs, for instance, are a couplet, an alternating sequence of PVC and normal beat is classified as a ventricular bigeminy (see Table 5.3).

In addition, three consecutive 4-second sliding windows are checked for ventricular fibrillation/flutter, rapid ventricular tachycardia and asystole.

	learned QRS complex	QRSL
*	asystole	ASYSTO
*	ventricular fibrillation/flutter	VFIB
*	ventricular tachycardia	VTAC
*	ventricular run (> 2 PVCs)	RUN
*	ventricular couplet (2 PVCs)	CPLT
	atrial fibrillation	AFIB
	pause of 2 missed beats	PAU2
	pause of 1 missed beat	PAU1
	ventricular bigeminy	VBIG
	paroxysmal supraventricular tachycardia	PSVT
	pacer error	PERR
	ventricular escape beat	ESC
	premature ventricular complex	PVC
	premature supraventricular complex	PSVC
	pacemaker capture	PCAP
	artifact	A
	learn phase	L

* event of complex ectopy

Table 5.3 Arrhythmic events with their acronyms. All events, except artifact and learn phase, which are not true events, appear in the event window. An event involving complex ectopy is highlighted. On CASE systems and CardioSoft/CS, for example, these events are shown in red

When the arrhythmia analysis is started, the system needs approximately 5 seconds of ECG data to establish the thresholds for QRS detection. The arrhythmia analysis program will analyze two leads of ECG. These two leads are either selected manually by the user or they are automatically determined by the program. In the latter case, the program scans all available leads to find the two best leads. This takes place at the same time as the determination of the QRS detection thresholds and prolongs the initial process by 1 second. Then, after 10 beats have been collected, the dominant beat (learned QRS complex) will be determined. On the full-disclosure ECG, each of these 10 complexes is labeled with an “L”. The first beat after the end of the learn phase that matches the morphology of the dominant beat, is displayed in the event window and labeled “QRSL”.

The GE arrhythmia analysis algorithm accepts noisy ECGs, allowing for almost uninterrupted monitoring and for a high sensitivity in identifying events. Extremely noisy beats or artifactual beats, however, are rejected or not accepted for event classification. On the full-disclosure ECG, these beats are labeled with an “A”. Ventricular bigeminy is identified as an alternating sequence of normal beats and PVCs. At least two PVCs must be detected. A ventricular escape beat is identified when the current RR interval is prolonged and the morphology differs from that of the dominant beat.

For pacemaker patients (this information should be entered on the patient demographics screen) the arrhythmia analysis algorithm analyzes the temporal relationship of pacer pulse and QRS complex. “Pacemaker capture” is detected when the QRS complex occurs within 300 ms of the pacer pulse. If the QRS complex occurs later than 300 ms after the pacer pulse or not at all, the event is labeled as “pacer error”. Atrial fibrillation is detected on the basis of irregular RR intervals and absence of P-waves. Ventricular fibrillation/flutter is identified by frequency analysis in consecutive 4-second windows.

Detection of ventricular fibrillation/flutter or rapid ventricular tachycardia is based on three consecutive 4-second sliding windows. If the criteria for ventricular fibrillation/flutter or rapid ventricular tachycardia are fulfilled in at least two of the windows, VFIB or VTAC is classified. Asystole is detected in the last 4-second sliding window but only if no fine ventricular fibrillation is detected.

Arrhythmia detection cannot be disabled by the user. Continuous detection is necessary to prevent abnormals from entering into the update process. If arrhythmia detection were disabled and enabled during the stress test, it would be impossible for the system to provide a complete and correct documentation of arrhythmia events.

During the stress test, the event window shows the most recent event with its event label, i.e., the new event overwrites the previous one. However, if events belong to the same category, the first of these events remains displayed. This prevents the screen display from becoming unsteady. All events that can be displayed are listed in Table 5.2. Artifactual QRS complexes (artifact “A”) and QRS complexes from the learn phase (“L”) do not appear in the event window.

Events with complex ectopy (see Table 5.3) such as a ventricular run, will be highlighted in the event window.

The event window continuously displays the ventricular ectopics (VE) per minute. This value is calculated as the sum of all PVCs and ESCs detected in the past 60-second interval, including the PVCs of ventricular tachycardias, runs, couplets, and bigeminy. A new PVC or ESC will thus immediately update the VE/min (ventricular ectopic per minute) value.

During the stress test, the system can save a full-disclosure ECG for review of the arrhythmias at the end of the test procedure. The full-disclosure ECG is sampled at a lower rate sufficient for evaluation of arrhythmias. For more information, please consult your operator’s manual.

Arrhythmia Detection Performance

Evaluation of the accuracy of the algorithms is based on the results from annotated databases. Depending on the intended use of the algorithms, namely for exercise testing, we compiled a set of annotated databases with more than 1000 ECGs, consisting of exercise ECGs from treadmill tests, exercise ECGs from bicycle tests, pacemaker ECGs, the MIT-BIH database and the AHA database[48].

To evaluate the QRS detection and the ventricular ectopic performance we followed the standard *ANSI/AAMI EC57*, *Testing and reporting performance results of arrhythmia and ST segment measurement algorithms*[48].

Database	sensitivity	pos. predictivity
MIT-BIH	99.8%	99.8%
AHA	99.6%	99.8%
Bicycle ECGs	99.9%	99.96%
Treadmill ECGs	99.9%	99.9%

Table 5.4 QRS complex detection performance. (DOC0996283)
sensitivity = true positives / (true positives + false negatives)
pos.predictivity = true positives / (true positives + false positives)

Database	sensitivity	pos. predictivity	false positive rate
MIT-BIH	92%	94%	0.43%
AHA	94%	97%	0.29%
Bicycle ECGs	80%	93%	0.03%
Treadmill ECGs	77%	84%	0.21%

Table 5.5 Ventricular Ectopic Detection Performance (DOC0996283)
sensitivity = true positives / (true positives + false negatives)
pos.predictivity = true positives / (true positives + false positive)
false positive rate = false positives /(correct negatives + false positives)

Exercise-Induced Wide QRS Tachycardia

Exercise-induced wide QRS tachycardias are rare. They are mostly ventricular tachycardias. An exercise-induced wide QRS tachycardia is detected when at least 10 consecutive premature wide complexes with a heart rate (HR) > 140 bpm occur. The tachycardia is analyzed in both, exercise and recovery phase.

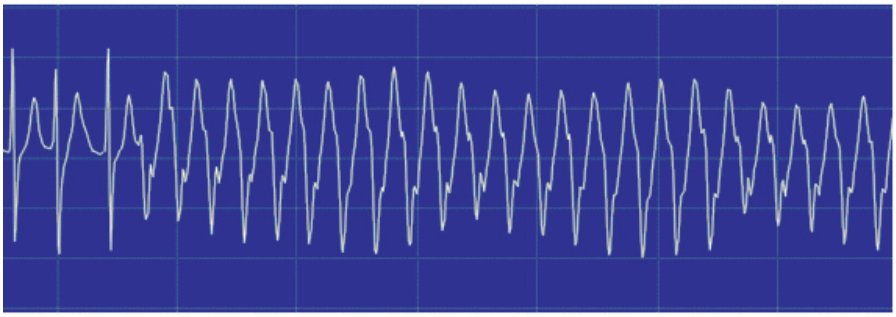


Figure 5.10 Exercise-induced ventricular tachycardia (VT) occurred in recovery, V5

Exercise-Induced Supraventricular Tachycardia

Only the recovery phase is analyzed. The exercise phase is not analyzed, because, from a technical point of view, discriminating between heart rate increase due to exercise versus supraventricular tachycardia is difficult. But according to Maurer et. al[81] : *"tests in patients with known or suspected heart disease; 14 of the 22 cases of exercise-induced SVT were observed during recovery"*. Thus, the majority of exercise-induced SVT can be detected during recovery.

Exercise induced SVT are possibly predictive of atrial fibrillation. *"Risk of development of lone atrial fibrillation during long-term follow-up in subjects with exercise-induced supraventricular tachycardia"*[81].

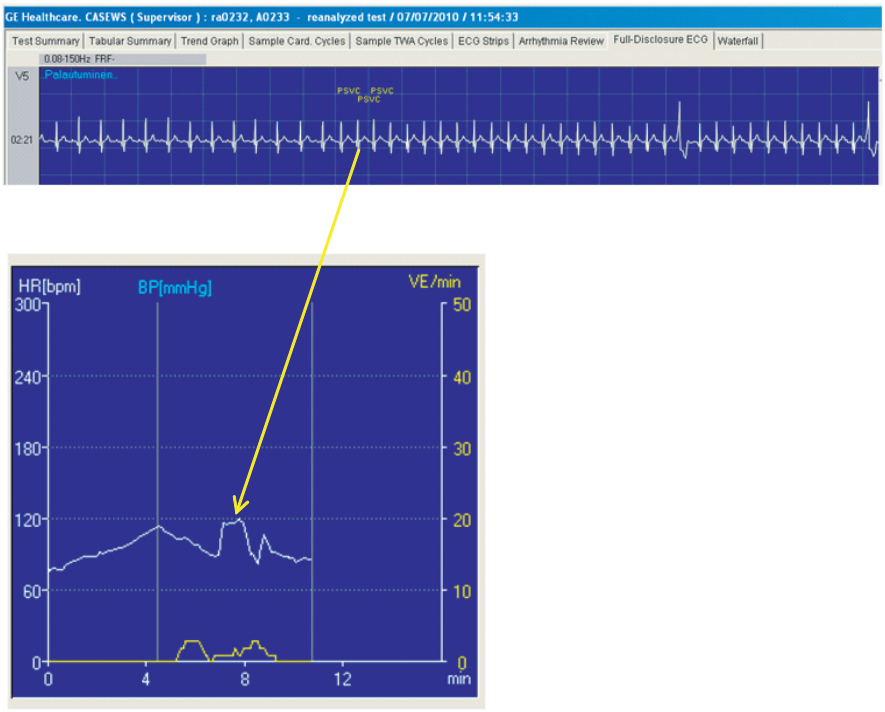


Figure 5.11 Exercise-induced supraventricular tachycardia in recovery phase

Duke Treadmill Score

The Duke Treadmill Score (DTS) is well validated and clinically useful for risk assessment in patients with either established or suspected coronary artery disease for whom the desirability of additional testing must be determined[9,11,12]. One of the major goals of risk assessment is to identify the low-risk patients for whom no additional testing is required. Whereas multiple valid strategies for accomplishing this exists, there is no consensus on the optimal approach. Cost-containment pressures may indicate the use of exercise testing as the preferred initial strategy in patients who are able to exercise and have an interpretable electrocardiogram.

The Duke Treadmill Score is calculated:

DTS = exercise duration – 5 × ST deviation
– 4 × exercise angina index

In the formula, exercise time is in minutes, deviation is mm, and angina index is 0,1, or 2.

The Duke Treadmill Score (DTS) is a predictor for mortality[31,39,41]. It is calculated with the exercise duration in minutes, the maximum exercise-induced ST deviation in mm, and the exercise angina index. The angina index has a value of 0 if the patient experienced no angina during the exercise, 1 if the patient experienced no exercise-limiting angina, and 2 if angina was the reason the patient stopped exercising.

The ST deviation is the amount of exercise-induced ST-segment deviation observed (the largest elevation or depression after resting changes have been subtracted). The ST segment deviation during exercise is the horizontal or downsloping depression or elevation[11]. Leads aVR, aVL and V1 are excluded. If the amount is less than 1 mm, the value is corrected to 0 (ACC/AHA 2002 Guideline Update for Exercise Testing[39]).

The score normally has a range from -25 (indicating the highest risk) to +15 (indicating the lowest risk). For classification the score is divided into three groups: high risk (score < 10), moderate risk (-10 to +4), and low risk (≥ +5). The prognosis of 5 year survival (55–99%) and the average annual mortality (0.2–9%) is calculated on the basis of the Nomogram of the Prognostic Relations, described in “Prognostic value of a treadmill exercise score in outpatients with suspected coronary artery disease”, and on the data from treadmill exercise testing according to the Bruce protocol (or the equivalent in multiples of resting oxygen consumption METS from an alternative protocol).

METS

Exercise capacity can be reported in estimated metabolic equivalents (METS) of exercise. The translation of exercise duration or workload into METS (oxygen uptake expressed in multiples of basal oxygen uptake, 3.5 O_2 ml/kg per minute) has the advantage of providing a common measure of performance regardless of the type of exercise test or protocol used.

MET level or exercise duration achieved on exercise testing is an important predictor of adverse cardiac events after myocardial infarction. This observation appears to hold true for tests performed on the treadmill and the bicycle ergometer. Failure to achieve 5 METS during treadmill exercise is associated with a worse prognosis[39].

The METS calculation for treadmill is applied according to the revised formula presented in the American College of Sports Medicine's *Guidelines for Exercise Prescription and Testing*, 3rd edition, 1986[49]. The equation for Metabolic Equivalents follows:

$$\text{METS} = \frac{\text{speed} \times 26.8 \times (0.1 + 1.8 \times \text{grade}/100) + 3.5}{3.5}$$

where grade is given in percent and speed is given in miles per hour.

If speed is given in km/h the formula is modified to:

$$\text{METS} = \frac{\text{speed} \times 43.1 \times (0.1 + 1.8 \times \text{grade}/100) + 3.5}{3.5}$$

The METS calculation for bicycle ergometers is applied according to the formula presented in the European Heart Journal in 1994[50].

The METS equation for bicycle ergometers follows:

$$\text{METS} = \frac{12.3 \times \text{load} + 3.5 \times \text{weight}}{3.5 \times \text{weight}}$$

where load is given in watts and weight is given in kilograms.

MET levels are extrapolated between stages of exercise. One minute of a stage must be completed to obtain full stage MET values[47,51]. At any point thereafter, full credit is given for the stage.

Depending on age and gender, limits for poor METS, or poor exercise capacity, can be estimated according to see Table 5.6.

Age	Women	Men
< 29	< 7.5	< 8
30–39	< 7	<7.5
40–49	< 6	< 7
50–59	< 5	< 6
60–69	< 4.5	< 5.5
70–79	< 3.5	< 4.5
> 79	< 2.5	< 3.5

Table 5.6 Estimated METS thresholds for poor exercise capacity[36]

The exercise capacity METS is a powerful predictor of mortality. Myers et. al wrote: "Exercise capacity is a more powerful predictor of mortality among men than other established risk factors for cardiovascular disease[89]". Figure 5.12 shows that in case of a high METS value, generally accepted risk factors like hypertension, COPD, diabetes, smoking, BMI, and cholesterol do not cause a higher number of deaths, or, in other words, do not increase the relative risk beyond 1.0.

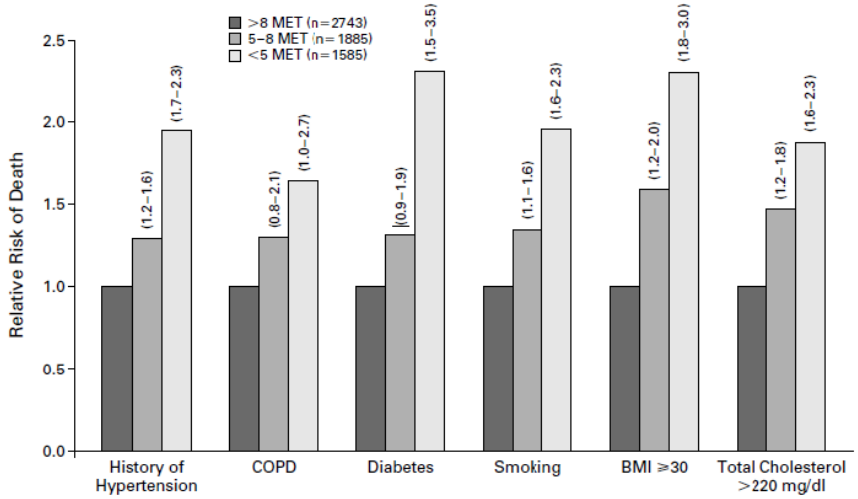


Figure 5.12 Relative Risks of Death from any cause among subjects with various risk factors who achieved a functional capacity of less than 5 METS or 5 to 8 METS, as compared with subjects whose functional capacity was more than 8 METS. Numbers in parentheses are 95 percent confidence intervals for the relative risks. BMI denotes body-mass index, and COPD chronic obstructive pulmonary disease, Myers et. al.[89]

In a treadmill versus bicycle study, Rahimi et.al.[87] found that METS values from treadmill exercise tests differ from those obtained in bicycle exercise tests. Most patients achieve higher METS values on treadmills than on bicycle ergometers.

Actual Load

The actual load is an exercise test outcome when bicycle ergometers are used and it is very similar to bicycle ergometer METS. METS is simply the actual load corrected by the patient's weight.

During a bicycle exercise test the load starts with an initial value of 50 watts, for instance, and then increases gradually by 25 watts every 2 minutes, for instance. Immediately after the change to a new stage, the patient's actual load is lower than the load because the patient has to adapt to the new load.

Actual loads are extrapolated between stages of exercise[52]. One minute of a stage must be completed to obtain the full target load. At any point thereafter, full credit is given for the stage[47,51].

HR Recovery

The HR recovery value is the decrease in heart rate in the first minute of recovery (see Figure 5.13). The change to the recovery phase is initiated by a user action. To avoid a measurement error due to a delayed user action, the program goes back up to two minutes and uses the time point of the maximal heart rate as the beginning of the recovery phase.

HR recovery reflects vagal activity. A low value, or a low decrease, indicates a high risk for overall mortality.[33,39,41]

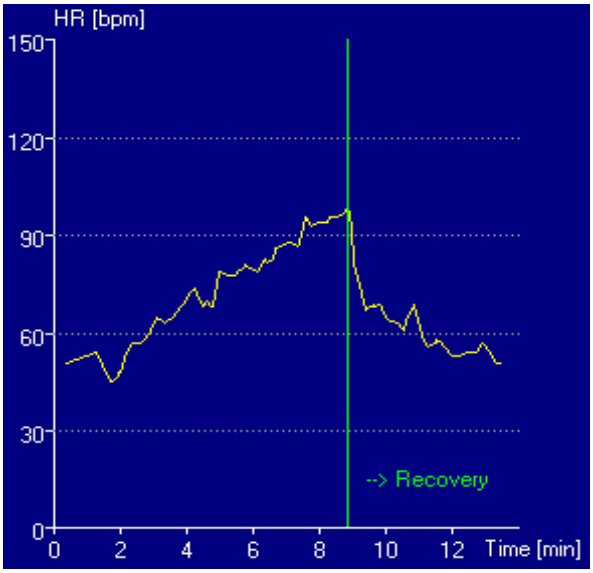


Figure 5.13 Heart rate decrease of more than 25 bpm in the first minute of recovery

The lower the heart rate decrease in the first minute, the higher the risk (see Figure 5.14).

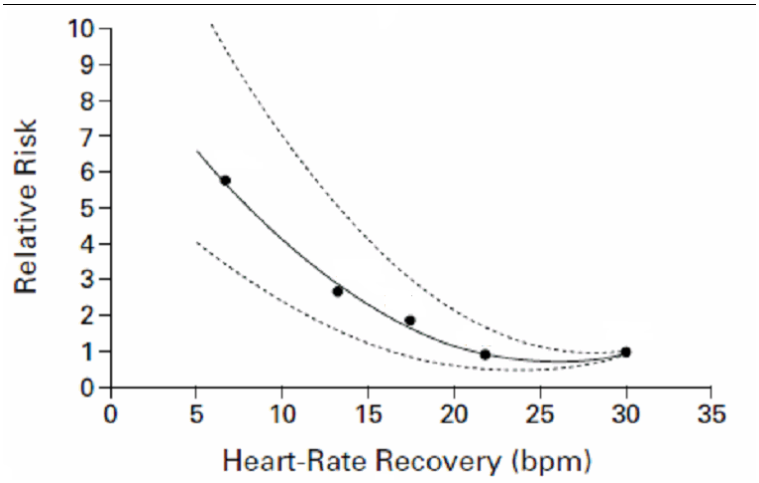


Figure 5.14 Estimates of the Relative Risk of death within six years according to Heart Rate Recovery one minute after peak exercise. Dashed lines represent the 95 percent confidence interval.[33]

FVE Recovery

Frequent ventricular ectopics in the recovery phase of an exercise test (FVE recovery) is a good predictor of mortality. Frequent ventricular ectopy during recovery after exercise is a better predictor of an increased risk of death than ventricular ectopy occurring only during exercise. Frequent ventricular ectopics occur with frequent ventricular premature beats, ventricular couplets, ventricular runs, ventricular bigeminy, and ventricular tachycardia[34].

Figure 5.15 Example of frequent ventricular ectopics

FVE recovery values become questionable in patients having frequent ventricular ectopics in the pretest phase. In those cases the FVE recovery value is followed by a question mark and is excluded from mortality prediction[34].

Note

Ventricular couplets, ventricular runs, ventricular bigeminy and ventricular tachycardia consist of ventricular ectopic beats.

Chronotropic Response

A patient's chronotropic response, or percentage of "HR reserve used", is calculated using the heart rate at rest (HR_{rest}) and at peak exercise (HR_{peak}). The following equation calculates the percentage of HR reserve used during the exercise test.

$$\%HR_{reserve\ used} = 100 \times (HR_{peak} - HR_{rest}) / (220 - age - HR_{rest})^{35}$$

Chronotropic incompetence is identified, when the percentage of HR reserve used is below 80% (or 62% for patients on ß-blockers).[41]

"The HR response to exercise is related to several parameters including age, resting HR, functional capacity, cardiac function, extent of coronary artery disease, and the autonomic nervous system"[79]. HR reserve used is related to the same parameters; however, it has been normalized with respect to the patient's resting heart rate as well as the expected peak heart rate for age. Results presented in figure 5.16 demonstrate a correlation between HR reserve used and coronary artery occlusions greater than 50%. Others have also found that a low HR reserve used value is associated with *"carotid atherosclerosis, independent of the established risk factors in healthy men, which could contribute to the high incidence of cardiovascular diseases in subjects with chronotropic incompetence."*[84] Still others have found it to be a predictor of acute myocardial infarction [75] as well as mortality. [35,38,39,41] Thus, there is significant evidence that HR reserve used is a good indicator of the extent of atherosclerotic disease. The exercise interpretive program uses HR reserve used for improving the specificity for the detection of cardiac ischemia.

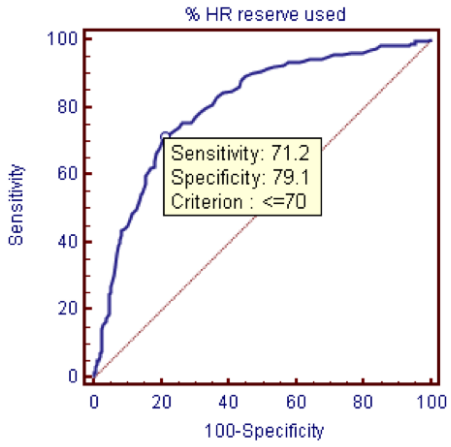


Figure 5.16 HR reserve used and the relation to coronary artery stenosis ≥ 50%. ECG data together with angiographic reference data from FINCAVAS[82] study, Tampere, Finland, 556 patients.

Blood Pressure

Blood pressure values are received from an external blood pressure measurement device or must be entered manually via the key pad.

A blood pressure above 250 mmHg at maximum load is considered abnormal.[39]

Double Product / Rate Pressure Product (RPP)

The Double Product is the product of the heart rate and the systolic blood pressure. Therefore it is also called the Rate Pressure Product (RPP). For normal exercise response RPP should exceed 20,000 mmHg/min[43]. The Double Product correlates with the myocardial oxygen consumption ("Exercise and the Heart", *Froelicher*[2])

Heart Rate Values

Maximal Predicted Heart Rate — Upon entering the patient's age, GE stress systems automatically calculate the Maximal Predicted Heart Rate. The system offers two calculation methods:

1. WHO: Max. Predicted HR = 220 – age in years
2. AHA: Max. Predicted HR = 160 (age < 25 years) or
   115 (age > 75 years) or
   160 – (age – 25) × 45/50 (between 25 and 75 years)

In the event that your laboratory makes use of different predictive criteria, manual entry of specific values is simply completed during the entry of demographic data.

Target Heart Rate — GE systems determine the Target Heart Rate as a user-defined percentage of the Maximal Predicted Heart Rate. While the default value is set at system initialization, a user may elect to alter it on a test-to-test basis.

Dynamic ST Scan

Dynamically scan all leads for the "worst case" ST segment depression. When ST segment depression occurs in another lead that is more severe than the lead currently shown, the display automatically changes to that particular lead. The Leads aVR, aVL, and V1 are excluded.

ST Criteria

The user has the possibility to enable the continuous monitoring of the ST segment. When the selected ST criteria are reached, the program alerts the user and informs of the leads involved. ST criteria can be defined separately for ST depression and for ST elevation.

ST depression (measured in the post-J point J+x) – A combination of level and slope values can be entered:

Level values: off, < -0.05, -0.1, -0.15, -0.2, -0.3 mV

Slope values: off, horizontal and down sloping (< 0.5 mV/s), down sloping (< -1mV/s)

Leads aVR, aVL, and V1 are excluded from monitoring

ST elevation (measured at point J+20 ms) – Only level values can be entered for ST elevation. Slopes are not considered.

Level values: off, > 0.05, 0.1, 0.15, 0.2, 0.3 mV

Lead aVR is excluded from monitoring

PWC Calculation

The Physical Working Capacity (PWC) is calculated by dividing the current load (in Watts, on a bicycle ergometer) by the patient's weight (in kilogram). PWC 130, PWC 150, and PWC 170 are the PWC values at a heart rate of 130, 150, and 170 bpm, respectively. A missing PWC value will be calculated by linear extrapolation when the heart rate has reached the approximate target heart rate (< 10 bpm). For example, at a heart rate of 161 bpm the PWC 170 value is calculated by extrapolation[55].

Target Load

The Target Load (in Watts, for bicycle ergometers) is calculated on the basis of the patient's weight, height, gender and age[52].

For manual calculation use the following procedure:

1. Obtain the patient's height and weight.
2. In Figure 5.17, draw a line from the height value to the weight value.
3. Read the value at the point where this line crosses the body surface line.

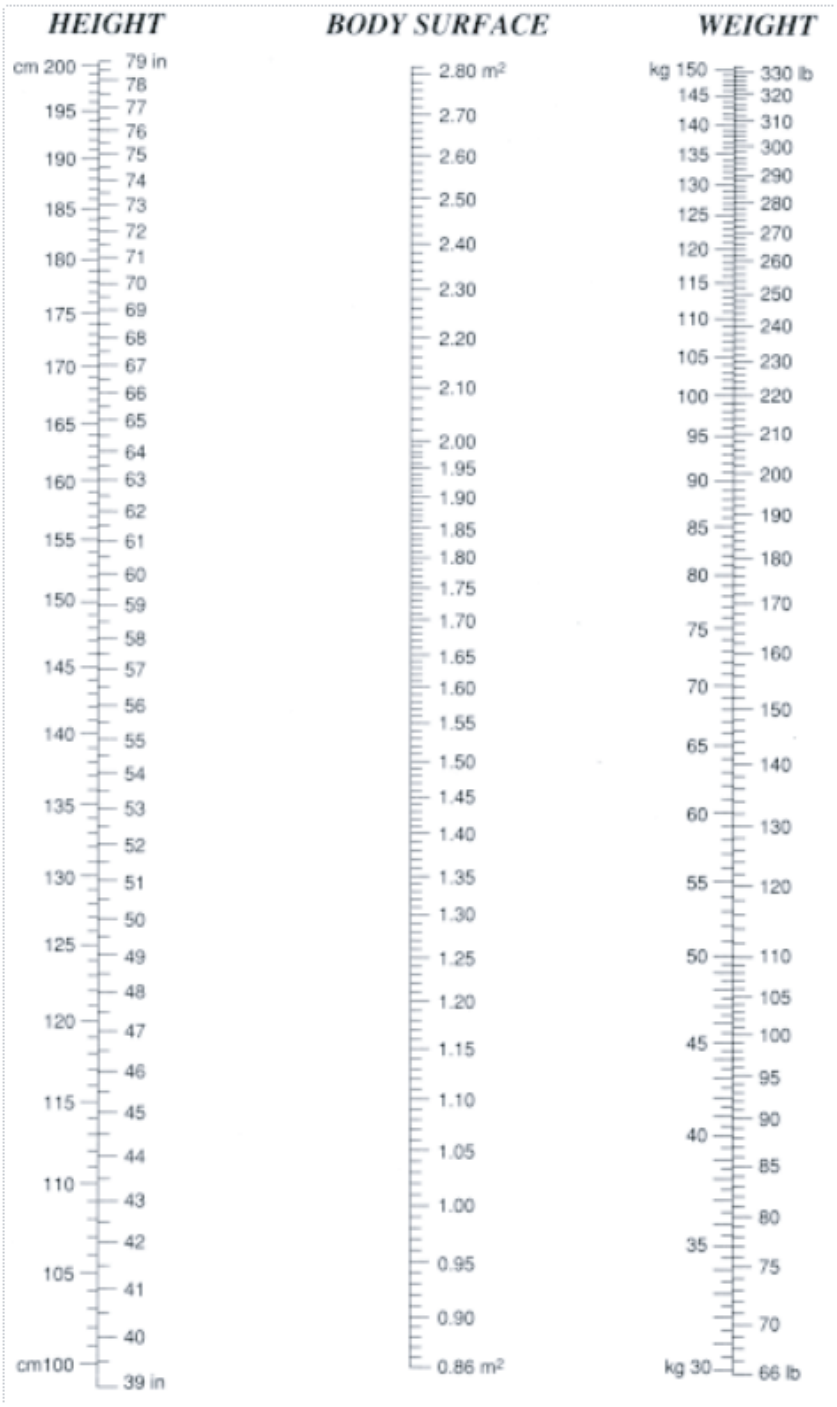


Figure 5.17 Nomogram for the calculation of the body area (according to Du Bois)

4. Together with the patient's age and gender, use this value to read off the target load in the appropriate table below (Table 5.7 for female patients, Table 5.8 for male patients).

20 -24	25 - 29	30 - 34	35 - 39	40 - 44	45 - 49	50 -54	55 - 59	60 - 64	65 - 69	70 - 74	75 - 79	80 - 84	Age / Body surface
100	98	95	93	91	89	87	85	83	81	79	77	75	1.2 - 1.29
108	105	103	101	99	96	94	92	90	87	85	83	81	1.3 - 1.39
116	113	111	108	106	103	101	99	96	94	91	89	86	1.4 - 1.49
124	121	118	116	113	111	108	105	103	100	98	95	92	1.5 - 1.59
131	129	126	123	120	118	115	112	109	107	104	101	98	1.6 - 1.69
139	137	134	131	128	125	122	119	116	113	110	107	104	1.7 - 1.79
147	144	141	138	135	132	129	126	123	119	116	113	110	1.8 - 1.89
155	152	149	146	142	139	136	132	129	126	123	119	116	1.9 - 1.99
163	160	156	153	150	146	143	139	136	132	129	125	122	2.0 - 2.09
171	168	164	160	157	153	150	146	142	139	135	131	128	2.1 - 2.19
179	176	172	168	164	160	156	153	149	145	141	137	134	2.2 - 2.29
187	183	179	175	171	167	163	159	155	151	148	144	140	2.3 - 2.39

Table 5.7 Average expectation values of maximal target load, bicycle, values in Watts, female patients

20 -24	25 - 29	30 - 34	35 - 39	40 - 44	45 - 49	50 -54	55 - 59	60 - 64	65 - 69	70 - 74	75 - 79	80 - 84	Age / Body surface
195	188	181	173	166	159	151	144	137	129	122	115	107	1.6 - 1.69
207	199	191	184	176	168	160	153	145	137	129	121	114	1.7 - 1.79
219	211	202	194	186	178	169	161	153	145	136	128	120	1.8 - 1.89
231	222	213	205	196	187	178	170	161	152	144	135	126	1.9 - 1.99
242	233	224	215	206	197	187	178	169	160	151	142	132	2.0 - 2.09
254	245	235	225	216	206	196	187	177	168	158	148	139	2.1 - 2.19
266	256	246	236	226	216	206	195	185	175	165	155	145	2.2 - 2.29
278	267	257	246	236	225	215	204	193	183	172	162	151	2.3 - 2.39
290	279	268	257	246	235	224	213	202	191	180	169	158	2.4 - 2.49
301	290	278	267	256	244	233	221	210	198	187	175	164	2.5 - 2.59
313	301	289	277	265	254	242	230	218	206	194	182	170	2.6 - 2.69
325	313	300	288	275	263	251	238	226	214	201	189	176	2.7 - 2.79

Table 5.8 Average expectation values of maximal target load, bicycle, values in Watts, male patients

According to: Wonisch M, Berent R, Klicpera M, Laimer H, Marko C, Schwann H, Schmid P. Tabellen zur Berechnung der österreichischen Solllastformel. Praxisleitlinien Ergometrie, *Journal für Kardiologie 2008, 15 (Supplementum A).* Extrapolated for ages > 64 years and higher body surfaces.

For your notes

6 T-Wave Alternans (TWA)

Intended Use

The T-Wave alternans analysis is intended to provide the measurements of the fluctuations of the ST-T-waves. The T-Wave alternans measurements produced by the T-Wave alternans analysis are intended to be used by qualified personnel in evaluating the patient in conjunction with the patient's clinical history, symptoms, other diagnostic tests, as well as the professional's clinical judgment.

CAUTION
Results of the T-Wave alternans program must be reviewed by a qualified physician, and should be used only as an adjunct to clinical history, symptoms, and the results of other non-invasive and/or invasive tests.

Introduction

There is a separate T-Wave Alternans Physician's Guide[32] available, which describes in more detail applications of TWA (Stress and Holter), describes the clinical relevance of TWA analysis, and gives an overview of relevant publications.

Two main methods exist for detection of T-Wave Alternans: the spectal and the time domain method. A consensus guideline[83] on both methods has been published. The time domain method is described here.

Electrical alternans affecting the ST-segment and T-wave is common among patients at increased risk for ventricular arrhythmias. T-wave alternans has been described in research literature as "a fluctuation in T wave morphology occurring on an every-other-beat basis"[27,28,29,77]. Although the electrical alternans affects both the ST-segment and the T-wave, henceforward the alternans is referred to as "T-wave alternans"or TWA. TWA on the electrocardiogram may serve as a noninvasive marker of vulnerability to ventricular tachyarrhythmias, N Engl J Med 1994; 330:235-41[76]. TWA is known as a marker of cardiac electrical instability with the potential for arrhythmia risk stratification. An example of this clinical phenomenon is shown in figure 6.1.

The method for detection of electrical alternans of the ST-segment and T-wave described here was adopted from Harvard Institutes of Medicine, Boston. It was invented by Bruce D. Nearing and Richard L. Verrier and is described in the patent "System and Method for Quantifying Alternation in an Electrocardiogram Signal"[26]. The software is capable of detecting morphology fluctuations in the ST-segment and the T-wave using a method based on current standard computerized ST-T waveform measurements. Furthermore, the method developed by Dr. Nearing and Dr. Verrier directly measures the morphologic fluctuation between odd and even beats in the time domain without mathematical transformation, which allows visual confirmation of measurements by an over-reader. The time domain measurement of TWA is very similar to standard ST measurements, with which clinicians are familiar.

The T-Wave Alternans (TWA) algorithm is to be used in a hospital, doctor's office, or clinic environment by competent health care professionals for recording ST-T wave morphology fluctuations for patients who are undergoing cardiovascular disease testing. The T-Wave alternans analysis only provides the measurements of the fluctuations of the ST-T-waves.

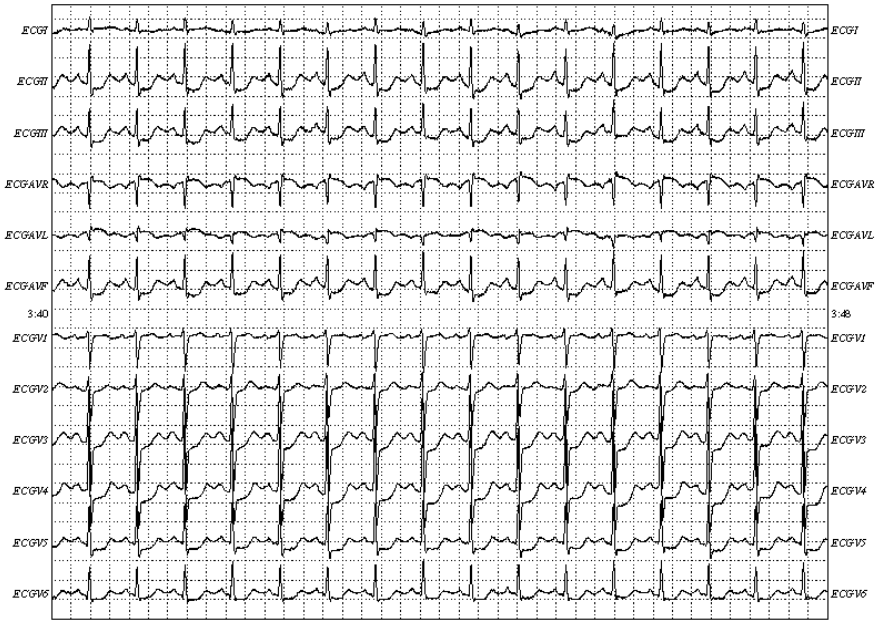


Figure 6.1 12-lead ECG from a bicycle exercise test. The amplitude of the ST-T segment changes from beat to beat in an alternating pattern of higher and lower ST levels. T-wave alternans of 50 µV is visible in lead V4 (ECGV4), 20 µV in lead V5 (ECGV5).

The TWA Algorithm

The basis for measuring TWA in the time domain is the formation of a median PQRST complex for odd and even beats. The median beat complex is formed in a way to minimize the effects random noise and to allow comparison of the alternative beat T wave fluctuations by comparing ST measurements in the ST-T wave on a lead-by-lead basis. The key processes in this method are signal conditioning to reduce noise effects, rejection of ectopic beats, and formation of a median PQRST complex for odd and even beats.

First, the baseline shift of the current PQRST complex of the incoming ECG is corrected using a **cubic spline correction** filter (see Figure 6.2). The cubic spline is calculated on the basis of three points taken from the isoelectric line preceding three consecutive QRS complexes, which is an estimate of the baseline shift and is then subtracted from the ECG. The cubic spline correction has the advantage of not affecting the low frequency content of the signal, and has therefore no negative effect on the T-wave alternans. The signal is then filtered with a **40 Hz low pass filter** to reduce high frequency noise produced by muscle activities.

Additionally, every ECG lead is tested for noisy beats. **Noisy beats are detected/excluded** by analyzing the high and middle frequency content in the ST-T segment, and by analyzing the increase of the variability of the ST-T segments in the odd beats or the increase of the variability in the even beats. Noisy beats are excluded from further processing. Beats excluded due to noise are always excluded in pairs (e.g., noisy beat and an adjacent beat) to keep the even- odd- sequence. The noise value is arbitrarily set to a value of 100 µV when too many beats have been excluded and the measurement is questionable.

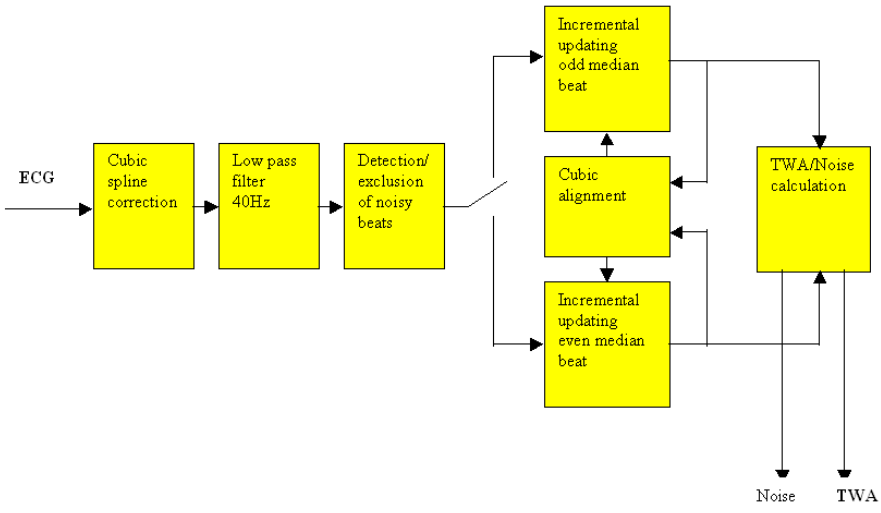


Figure 6.2 Block diagram of the TWA algorithm

Subsequently, the algorithm separates odd and even incoming beats and updates the odd median or the even median beat. The odd and even median beats are updated by either a fixed increment, or a fraction of the difference between the median template and the incoming beat,

whichever is less. The default update factor is 1/8, but other factors (1/4, 1/16, 1/16 or 1/64) are selectable. These factors will affect the rate at which the median templates track changes in the incoming signal. A smaller factor (i.e.,1/64) will track changes slower, but will be more resistant to noise. The update fraction to select will depend on the incoming signal.

Then both the odd and even median beats are aligned to a cubic spline (see section "Cubic Alignment" on page 62). This method has a tremendous effect in reducing the low frequency noise within the PQRST cycle, without disturbing the TWA measurement. It is a highly efficient expansion of the cubic spline correction.

The TWA value is derived by calculating the maximal difference between odd and even beats in the range of QRS end to T-wave end. A nonlinear filter is applied to the TWA measurements to compute the maximal difference in TWA measurements (see section "TWA Calculation" on page 63). The amount of the maximal difference is the TWA value. The noise value is an estimated RMS value, calculated from the differences between even and odd median beat in the isoelectric area before the QRS complex and after the T-wave.

The TWA value is annotated with a question mark if

- the heart rate is above the high heart rate limit (default 125 bpm),
- the noise value is greater than the high noise threshold (default 20 μV), and
- too many noisy beats have been excluded.

TWA values with a question mark are not used for calculation of a maximum TWA value, for instance, and are represented by a gap or as a dashed line in the trend curves.

Ectopic beats can have unpredictable effects on TWA measurements[30]. A premature beat can affect the T-wave of the preceding complex; therefore, premature complexes are detected and excluded together with the preceding beat from incremental updating of odd and even median beats.

Disconnected leads are also excluded from the TWA measurement process.

Cubic Alignment

Correcting the baseline wander only with the cubic spline previously described is not sufficient. Since only points in the isoelectric area preceding the QRS complexes are used, the baseline wander can be removed only to a limited extent. To further reduce baseline wander, additional points which are located after the T-end are used for cubic spline correction. This helps compensate for the differences between the isoelectric areas in front of the QRS complex and the isoelectric area between the T-wave and P-wave. The isoelectric area before the QRS complex is influenced by atrial repolarization of the P-wave. Other reasons for different amplitudes in both “isoelectric areas” could be a short PR interval or a merging of P and T-waves. Applying the cubic spline correction algorithm to points before the QRS complex and also to points after the T-wave will further enhance removal of artificial baseline wander, thus improving the measurement quality of T-wave alternans values.

The cubic alignment algorithm aligns both the even and the odd median beat to a cubic spline (see Figures 6.3 and 6.4). This cubic spline is calculated on the basis of three points located exactly between the odd and even median beats before the P-wave (1), before the QRS complex (2), and after the T-wave (3). The algorithm is very tolerant to the location of the points. Its yields very good results, even when atrial repolarization or a short PR interval hides the isoelectric line before the QRS complex, or a merging T-wave and P-wave in the other two points hides the isoelectric T-P-interval.

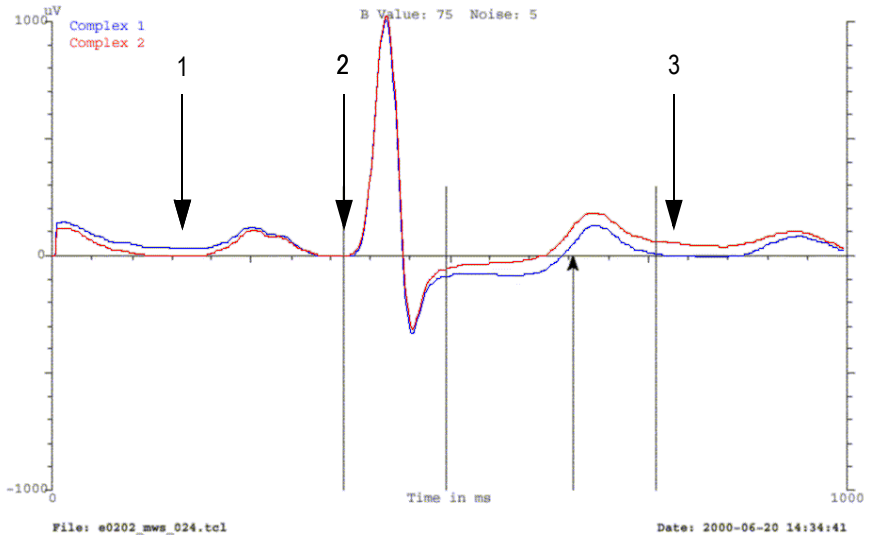


Figure 6.3 Example of insufficient baseline wander correction. Odd and even median beats (superimposed) after cubic spline correction. The value of 75 does not represent T-wave alternans.

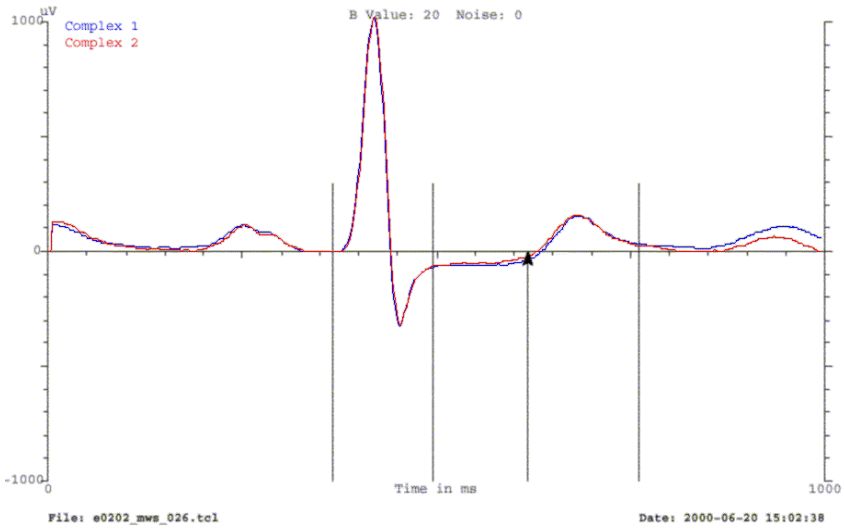


Figure 6.4 Same odd and even median beats as in figure 6.3, but with alignment to a cubic spline

TWA Calculation

After the odd and even median beats have been formed, the TWA value is measured as the maximum difference between the ST-T wave amplitudes in the two medians. The ST-T wave amplitude used for comparison is the amplitude in the area between the end of the QRS and the end of the T wave. When calculating the maximum difference between odd and even beat in the area between QRS end and T-end, there is still a possibility that high frequency noise can cause inaccurate measurement of the TWA value. Therefore, a nonlinear filter is used to further minimize the effects of high frequency noise. The filter uses a 20 ms window, one each in both the odd and the even median beats, both starting at QRS end. The minimal difference between the windows is selected and stored, and then the windows are moved one step towards the end of the T-wave. Again, the minimal difference is selected and stored and the windows are moved once more. The procedure is repeated until the windows reach T-end. Then the maximum of the stored values is considered the TWA value. The values are stored every 10 s and are, therefore, available for the TWA trend, for instance.

Interpreting/Correcting TWA Results

The higher the noise and artifact level of the ECG, the more difficult it is to measure the TWA accurately. Noisy ECG can cause false positive TWA values even in healthy patients. To assure maximum performance of the algorithms, follow all the recommended guidelines for operation, including skin preparation, electrode selection and placement.

Please note that electrode and leadwire movement can cause artifacts similar to the frequency content of TWA. Securing the leadwires is strongly recommended.

A positive T-wave alternans is defined when the TWA value reaches/ exceeds an amplitude threshold of 65 µV (for update factor 1/8)[42].

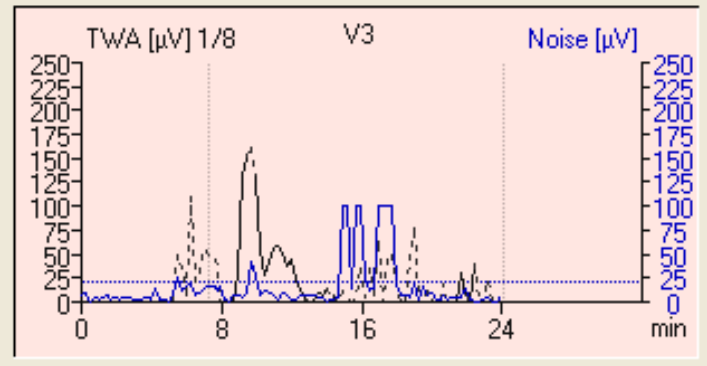


Figure 6.5 TWA and Noise trend. The peak shortly after 8 minutes is a TWA episode. Dashed curve segments identify unreliable TWA values. Noise values of 100 µV indicate that too many beats have been excluded.

The user has the possibility to exclude leads with poor quality. In the TWA quantitative study[45] it is recommended to use only the precordial leads for TWA detection. Limb leads should be excluded because of their high noise levels, which are usually much higher than the noise levels of the precordial leads. But in the precordial leads only the horizontal plane can be examined.

From the limb leads, lead II is the best and it is orthogonal to lead V2. It has on average the highest QRS peak to valley amplitude of all limb leads (II = 1 mV, I = 0.6 mV, III = 0.7 mV). Lead -aVR is close to II. With including limb leads II and aVR also the vertical plane can be examined sufficiently, without the disadvantage of increasing the noise level by the leads aVL, I, aVF and III. **General proposal: exclude leads aVL, I, aVF and III.**

The TWA algorithm does not exclude atrial fibrillation because it is assumed that TWA in atrial fibrillation patients is highly predictive. But atrial fibrillation waves can falsify TWA values. When disturbing fibrillation waves exist, they are mostly apparent in lead V1. For those cases it is proposed to exclude lead V1.

During treadmill testing it can happen that, due to the patient's left arm movement, the electrode V6 is touched continuously. This causes artifacts, disturbing the TWA measurement. For those cases it is proposed to exclude lead V6.

The user interface, see Figure 6.6, helps the ECG reader to identify incorrect TWA episodes. Since the TWA algorithm is a time domain method, TWA can be visually confirmed, by clicking the TWA value of interest in the trend curve, shortly before a peak. Therewith the according odd and even TWA median beats (one upon the other) pop up and the original ECG is shown for this time point. Based on this information the reader is able to identify TWA values as erroneous, by identifying confounding artifacts that are visible in the median beats and/or original ECG on the same page. In addition the user interface provides the necessary means for correcting erroneous TWA values.

Figure 6.6 User interface for TWA examination and correction. ECG from the Finnish Cardiovascular Study (FINCAVAS)[82], from Tampere University, Tampere, Finland.

Note

Ischemia induced TWA[28] might be achieved at lower heart rates and, therefore, at lower noise levels during supine bicycle exercise tests. The assumption is based on the GE Healthcare stress database: The same mean ST depression is achieved with upright bicycle exercise tests at a heart rate of 139 bpm and with supine bicycle exercise tests at a heart rate of 113 bpm. Besides, Wetherbee et.al.[88] compared treadmill upright and bicycle supine and found higher ST depressions in supine bicycle exercise tests.

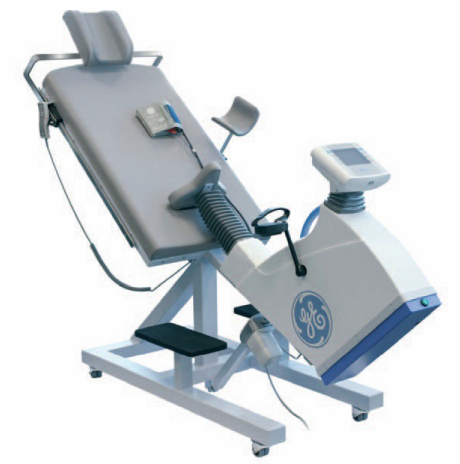


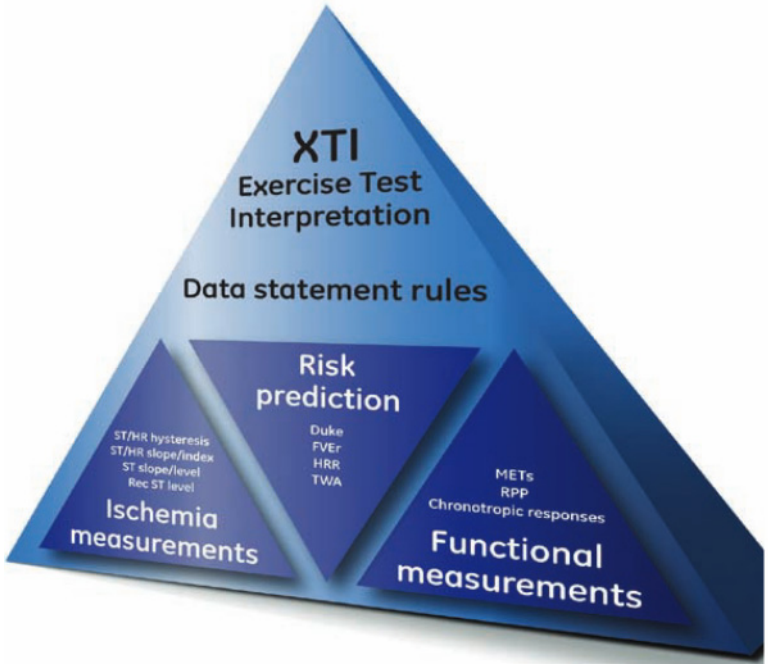
Figure 6.7 GE bicycle ergometer adjustable for supine exercise tests

TWA Settings

Even though the following settings can be changed, it is advised that you leave them at their default factory settings.

- Factor for incremental updating. The factor will affect the rate at which the median templates track changes in the incoming signal. **1/8** is the default factor, but other factors are available: 1/4, 1/8, 1/16, and 1/64. With the factor 1/8, the algorithm will track TWA faster, but will be more susceptible to the effects of noise. A smaller factor (i.e., 1/64) will track changes slower, but will be more resistant to noise. Factor 1/8 is the better choice, because therewith the transient and short TWA episodes can be detected.
- Heart rate limit (default **125 bpm**). Setting the heart rate limit to a lower value can help avoid false measurements at high exercise, but it also reduces the sensitivity of TWA detection.
- Noise limit (default **20 µV**). Setting the noise limit to lower values can help to avoid false TWA measurements due to muscle tremor, for instance. Only high frequency noise can be controlled by this limit. A lower limit also reduces the sensitivity of TWA detection.

7 Exercise Test Interpretation (XTI)



Description of the Exercise Test Interpretation Program

An exercise test on a treadmill or a bicycle delivers a large number of measurements that are valuable in predicting morbidity/mortality, in detecting coronary artery disease and in describing the functional exercise response of a patient. The ideal user would take all available measurements, compare them with known thresholds, and come to a complete assessment of the exercise test. However, it is very difficult to have a comprehensive knowledge of all measurements and their thresholds, especially of the new ones, namely HR recovery, FVE recovery, ST/HR hysteresis, and HR reserve used.

The Exercise Test Interpretation (XTI) program compares the exercise measurements against established thresholds and provides statements and reasoning texts (explanation of the statements) when thresholds are

exceeded.[85] Following is an example of a statement with the accompanying reasoning text:

ST/T changes indicative of ischemia

because ST/HR hysteresis > 0.02 mV in [V5 V6] and

HR reserve used < 70%

The XTI program consists of rules and a rule interpreter. The rule interpreter receives the input data, combines them with the rules, and creates statements and reasoning texts.

The intention of the statements and reasoning texts is to provide a short, clear, and accurate overview of the results of an exercise test. If the user needs detailed information, GE Healthcare stress systems also offer access to ECG strips, trend curves, median beats, etc.

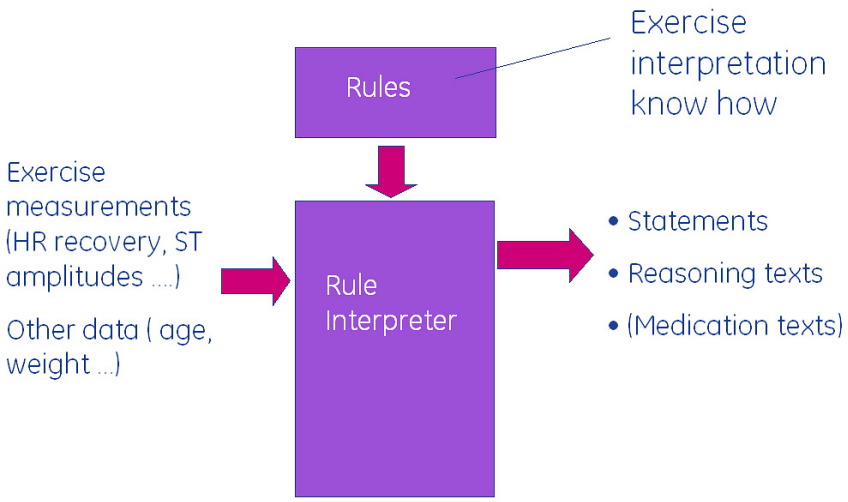


Figure 7.1 Program structure of the exercise test interpretation. The exercise measurements and other data are combined with the rules. Then statements and reasoning texts are created.

The input data are exercise measurements (ST level, ST slope, ST/HR hysteresis, ST/HR slope, ST/HR index, T-wave alternans value, heart rate, ventricular ectopic beats per minute, METS, systolic blood pressure, etc.) and other data (age, gender, medication, angina score, lead descriptors, stress test device [treadmill or bicycle], etc.). Measurements are available from the pretest phase, exercise phase, recovery phase (1 min), recovery phase (3 min), and/or different leads. ST levels are from all leads and all phases.

Based on the input data and the rules, the rule interpreter creates

- statements on risk prediction,
- statements on functional response,
- statements on ischemia (coronary artery disease), and
- technical statements.

In addition, an overall statement is created, namely:

- normal exercise test response, or
- borderline exercise test response, or
- abnormal exercise test response
- undefined exercise test response

Apart from the overall statements, a statement is accompanied by a reasoning text. In general, the reasoning texts conform to the rules.

Example:

Probably increased risk of malignant arrhythmias .. statement

because T-wave alternans ≥ 65 µV in [V3] .. reasoning text

Medication texts are additional reasoning texts. They appear only with medication sensitive statements when the according medicament name was entered.

Example:

Reduced heart rate response .. statement

because HR reserve used < 65% .. reasoning text

Possible cause: Medication beta-blocker .. medication text

A statement does not appear when it is not significant. This means, a statement is created only if the corresponding rule is true. The statement “Probably increased risk of malignant arrhythmias,” for example, appears only when the T-wave alternans value is greater than or equal to 65 µV.

Technical statements are created to alert the user when the standard leads are incomplete, when the exercise test is too short, and when the patient’s age is below 18 years.

The statements and reasoning texts are available in 19 languages: English, French, German, Italian, Spanish, Portuguese, Swedish, Hungarian, Polish, Norwegian, Danish, Dutch, Czech, Japanese, Chinese, Russian, Korean, Finnish and Turkish. If a language is not available, the texts appear in English.

Limitations of the Exercise Test Interpretation (XTI) Program

XTI was developed for the main indications for exercise testing. These indications are diagnosis of coronary artery disease, testing vulnerability to arrhythmia during exercise and recovery, evaluating exercise capacity, and assessment of a patient's risk for mortality and morbidity. The most appropriate test method for XTI is a standard exercise test up to the patient's maximal capacity during exercise with a 3-minute recovery phase at a low work load (see figure 7.2).

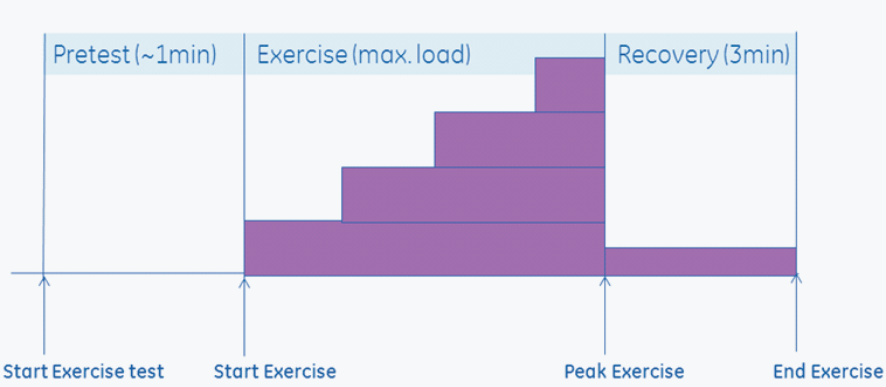


Figure 7.2 Standard exercise test

Submaximal exercise tests (for post MI patients), a patient's physical impairment or poor motivation may reduce sensitivity in ischemia detection or risk assessment.

If a patient is not motivated, statements, such as "Reduced heart rate response to exercise" or "Insufficient exercise capacity" might be presented.

XTI was developed for treadmill and bicycle testing. When performing pharmacological testing or pharmacological testing combined with exercise, low METS values occur. A low METS value might suppress statements on heart rate response and exercise capacity, for instance.

Warning
The results of the Exercise Test Interpretation must be confirmed by a qualified physician or cardiologist and should be used only as an adjunct to clinical history, symptoms, and the results of other non-invasive or invasive tests.

Examples for complete interpretation

Example 1

Probably increased risk of cardiovascular event

because HR recovery ≤ 12 per minute

Reduced heart rate response to exercise

because HR reserve used < 65%

Insufficient exercise capacity

because metabolic equivalent (METS) < 6

ST/T changes indicative for ischemia

because ST/HR hysteresis > 0.02 mV in [V5] and HR reserve used < 70%

Abnormal exercise test response

Example 2

ST/T changes may be clinically significant

because horizontal or downsloping ST ≤ -0.1 mV in [V5]

Borderline exercise test response

Example 3

Cannot rule out clinically significant ST/T changes

because horizontal or downsloping ST ≤ -0.05 mV in [V5]

Borderline exercise test response

Example 4

Probably normal exercise response

Rules

The rules of the Exercise Test Interpretation determine when a certain interpretive statement is displayed. The rules contain the threshold values which, when exceeded, trigger the display of the respective interpretive statement (identified in the following sections in bold).

Most rules combine different measurements. METS is often used for such combinations. For example, a low METS value with a large TWA value has been shown to be more predictive of malignant arrhythmias.[46]

Rules for risk assessment

Probably increased risk of cardiovascular event:

- HR recovery ≤ 12 per minute
  Excluded: PVCs in recovery > 3 per minute, age ≤ 20 years
- Bicycle: Duke treadmill score (DTS) < -11
  Treadmill: Duke treadmill score (DTS) < -10
  Excluded: METs ≤ 1.8, age < 40 years

Probably risk of cardiovascular event:

- PVCs in recovery ≥ 7 per minute
  Bicycle: excluded peak HR ≤ 120

Probably increased risk of malignant arrhythmias:

- Incremental update factor 1/4:
  T-wave alternans ≥ 85µV
- Incremental update factor 1/8:
  T-wave alternans ≥ 65µV
- Incremental update factor 1/16:
  T-wave alternans ≥ 32µV
- Incremental update factor 1/32:
  T-wave alternans ≥ 16µV
- Incremental update factor 1/64:
  T-wave alternans ≥ 10µV

Excluded: Leads I, III, aVF, aVL, age ≤ 30

Probably increased risk of stroke/cardiovascular event:

- Atrial fibrillation in pretest or exercise phase

Excluded: Age ≤ 50

Exercise-induced bundle branch block:

- QRS width at peak exercise > 130 ms and
  QRS width at start exercise > 120 ms and
  Difference of QRS widths > 30 ms

Exercise-induced wide QRS tachycardia:

- Wide QRS tachycardia in exercise phase, but not in pretest phase

  or

- Wide QRS tachycardia in recovery phase, but not in pretest and exercise phase

Exercise-induced supraventricular tachycardia:

- Supraventricular tachycardia in recovery phase

Cannot compute risk:

- No rules above are true and METS $\leq$ 1.8 and METS $\geq$ 1.0

Rules for functional response assessment

Significantly reduced heart rate response to exercise:

- Treadmill: HR reserve used < 65%
- Bicycle upright: HR reserve used < 42%
- Bicycle semi supine: HR reserve used < 35%
- Bicycle supine: HR reserve used < 27%

- if beta-blocker, output info text
  "Possible cause: medication beta-blocker"

Reduced heart rate response to exercise:

- Treadmill: HR reserve used < 80%
- Bicycle upright: HR reserve used < 60%
- Bicycle semi supine: HR reserve used < 50%
- Bicycle supine: HR reserve used < 37%
- HR reserve used < 65% and METS > 2

- if beta-blocker, output info text
  "Possible cause: medication beta-blocker"

The heart rate response rules above are excluded when METS is between $\leq$ 1.8 and $\geq$ 1.0.

Insufficient exercise capacity:

Treadmill:

Female:

- METS < 7.5, age $\leq$ 29 years
- METS < 7.0, 30 $\geq$ age $\leq$ 39 years
- METS < 6.0, 40 $\geq$ age $\leq$ 49 years
- METS < 5.0, 50 $\geq$ age $\leq$ 59 years
- METS < 4.5, 60 $\geq$ age $\leq$ 69 years

- METS < 3.5, 70 ≥ age ≤ 79 years
- METS < 2.5, age > 79 years

Male:

- METS < 8.0, age ≤ 29 years
- METS < 7.5, 30 ≥ age ≤ 39 years
- METS < 7.0, 40 ≥ age ≤ 49 years
- METS < 6.0, 50 ≥ age ≤ 59 years
- METS < 5.5, 60 ≥ age ≤ 69 years
- METS < 4.5, 70 ≥ age ≤ 79 years
- METS < 3.5, age > 79 years

Bicycle:

Female:

- METS < 6.0, age ≤ 29 years
- METS < 5.6, 30 ≥ age ≤ 39 years
- METS < 4.8, 40 ≥ age ≤ 49 years
- METS < 4.0, 50 ≥ age ≤ 59 years
- METS < 3.6, 60 ≥ age ≤ 69 years
- METS < 2.8, 70 ≥ age ≤ 79 years
- METS < 2.0, age > 79 years

Male:

- METS < 6.4, age ≤ 29 years
- METS < 6.0, 30 ≥ age ≤ 39 years
- METS < 5.6, 40 ≥ age ≤ 49 years
- METS < 4.8, 50 ≥ age ≤ 59 years
- METS < 4.4, 60 ≥ age ≤ 69 years
- METS < 3.6, 70 ≥ age ≤ 79 years
- METS < 2.8, age > 79 years

Reduced exercise capacity:

Treadmill:

Female:

- METS < 10.0,age ≤ 29 years
- METS < 9.0, 30 ≥ age ≤ 39 years
- METS < 8.0, 40 ≥ age ≤ 49 years
- METS < 7.0, 50 ≥ age ≤ 59 years
- METS < 6.0, 60 ≥ age ≤ 69 years
- METS < 4.5, 70 ≥ age ≤ 79 years
- METS < 4, age > 79 years

Male:

- METS < 11.0, age ≤ 29 years

- METS < 10.0,30 ≥ age ≤ 39 years
- METS < 8.5, 40 ≥ age ≤ 49 years
- METS < 8.0, 50 ≥ age ≤ 59 years
- METS < 7.0, 60 ≥ age ≤ 69 years
- METS < 5.5, 70 ≥ age ≤ 79 years
- METS < 4.5, age > 79 years

Bicycle:

Female:

- METS < 8.0, age ≤ 29 years
- METS < 7.2, 30 ≥ age ≤ 39 years
- METS < 6.4, 40 ≥ age ≤ 49 years
- METS < 5.6, 50 ≥ age ≤ 59 years
- METS < 4.8, 60 ≥ age ≤ 69 years
- METS < 3.6, 70 ≥ age ≤ 79 years
- METS < 3.2, age > 79 years

Male:

- METS < 8.8, age ≤ 29 years
- METS < 8.0, 30 ≥ age ≤ 39 years
- METS < 6.8, 40 ≥ age ≤ 49 years
- METS < 6.4, 50 ≥ age ≤ 59 years
- METS < 5.6, 60 ≥ age ≤ 69 years
- METS < 4.4, 70 ≥ age ≤ 79 years
- METS < 3.6, age > 79 years

The exercise capacity rules above are excluded in case of METS ≤ 1.8.

Abnormal blood pressure response:

- Max.syst.blood pressure > 250 mmHg
  or
- Max. syst. blood pressure > 33.3 kPa

Insufficient rate pressure response:

Bicycle:

- Max. Rate Pressure Product (RPP) < 16,000 mmHg per min
  or
- Max. Rate Pressure Product (RPP) < 2,133 kPa per min

Treadmill:

- Max. Rate Pressure Product (RPP) < 20,000 mmHg per min
  or
- Max. Rate Pressure Product (RPP) < 2,666 kPa per min

The rate pressure rules above are excluded in case of METS ≤ 2 and METS ≥ 1.0.

Cannot compute functional response:

- No functional response rules above are true and METS ≤ 1.8 and METS > 1.0.

Rules for ischemia assessment (coronary artery disease)

The following ischemia rules are applied to leads I, II, III, aVF, V2-V6. Leads aVR, aVL and V1 are generally excluded. In case of peak exercise LBBB and LBBB shaped pacemaker stimulation, the rules are also excluded.

ST/T changes indicative of ischemia:

- ST/HR hysteresis > 0.05 mV

The following rules are suppressed when the preceding ischemia rules is true.

Bicycle:

- ST/HR hysteresis > 0.02 mV and METSs > 2.0 and HR reserve used < 70%

Treadmill:

- ST/HR hysteresis > 0.02 mV and METSs > 2.0 and HR reserve used < 85%

Others:

- ST/HR hysteresis > 0.02 mV and METSs ≤ 2.0 and HR reserve used > 8%

Excluded for the above ischemia rules: Recovery time ≤ 60 s; Leads V2, V3, and V4 in case of RBBB at peak exercise or 3 min recovery.

The following rules are suppressed when at least one of the preceding ischemia rules is true.

Bicycle:

- ST/HR index ≥ 1.6 mV/bpm and HR reserve used < 70%

Treadmill:

- ST/HR index ≥ 1.6 mV/bpm and HR reserve used < 85%

Excluded: Leads V2, V3, and V4 in case of RBBB at peak exercise.

ST/T changes may be clinically significant:

ST = ST amplitude at peak exercise

The following rule is suppressed when at least one of the preceding ischemia rules is true.

- ST level ≤ -0.1 mV and ST slope < 0.05 mV/s

Excluded: Leads V2, V3, and V4 in case of RBBB at peak exercise. All leads in case of LBBB and LBBB shaped pacemaker stimulation at peak exercise.

The following rule is suppressed when at least one of the preceding ST segment changes rules is true.

- recovery ST ≤ -0.05 mV and recovery ST slope < 0.05 mV/s

Excluded: Leads V2, V3, and V4 in case of RBBB at 3 min recovery. All leads in case of LBBB and LBBB shaped pacemaker stimulation at 3 min recovery.

Cannot rule out clinically significant ST/T changes:

ST = ST amplitude at peak exercise

The following rules are suppressed when at least one of the ischemia rules above is true.

- ST ≤ -0.05 mV and ST slope < 0.05 mV/s (horizontal)
- ST < -0.15 mV and ST slope ≤ 1 mV/s (slightly ascending)

Excluded: Leads V2, V3, and V4 in case of RBBB at peak exercise

The rules above are excluded in case of peak exercise LBBB and LBBB shaped pacemaker stimulation

Rules for overall statements

Probably normal exercise response:

None of the preceding rules was true.

Borderline exercise response:

The “ST/T changes may be clinically significant”, the “Cannot rule out clinically significant ST/T changes”, the “Reduced exercise capacity”, and/or the “Reduced heart rate response to exercise” rules have been true.

Abnormal exercise response:

At least one of the preceding rules was true, except the rules for the borderline exercise response

Undefined exercise response:

None of the preceding rules was true and METS ≤ 1.8.

Technical Rules

No ECG

Inhibits all other rules

Standard leads incomplete:

One or more missed leads: I, II, III, aVR, aVL, aVF, V1 – V6

Warning! Results are questionable:

Age < 18 years,

or

Exercise_time < 1 min,

or

Recovery time < 1 min,

or

Undefined start exercise.

Caution: Age unknown (45 years assumed)

Age outside range of 0 ... 200 years.

Caution: Gender unknown (male assumed)

Not male or female.

Graphical XTI output

The graphical XTI output is an easy-to-understand and comprehensive display of the results of an exercise test. It translates the XTI statements into positions on a 4x4 matrix. The matrix consists of four categories

- Risk
- Functional response
- Ischemia (CAD)
- Overall

and four exercise response columns, namely:

- undefined (grey)
- normal (green)
- borderline (yellow)
- abnormal (red)

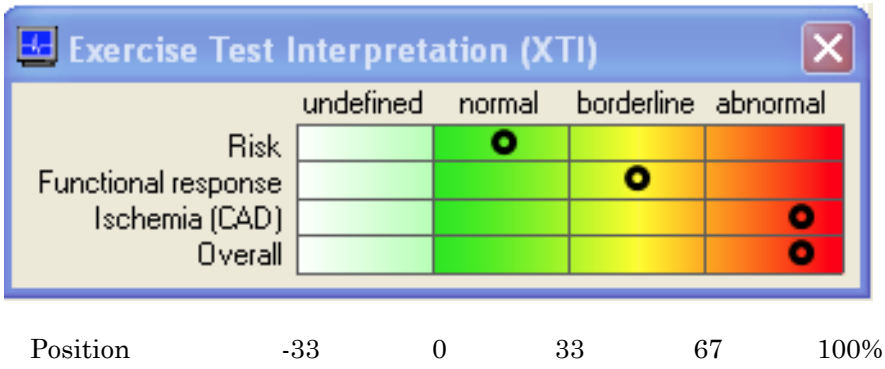


Figure 7.3 Graphical display of XTI results. Categories are Risk, Functional response, Ischemia (CAD) and Overall. Exercise test response columns are undefined, normal, borderline and abnormal.

First the statements are assigned to the 4 categories “Risk”, “Functional Response”, ”Ischemia (CAD)” and “Overall”. Then the positions of the corresponding statements are calculated for each category to provide marker positions. The positions are based on the quality of the statements in a category. The quality is assessed by the specificity and reliability of the measurements used in the statement (see Table 7.1). If more than one statement is true in one category, the statement with the highest quality defines the final position. If no statement in a category is true, the marker is positioned in the middle of the green area in this category or in the middle of grey in case of no ECG or undefined exercise response (METs value too small).

The main contributor for “Risk” is HR recovery, for “Functional response” it is METS, and for “Ischemia (CAD)” it is ST/HR hysteresis.

The marker for the “Overall” category row is normally copied from the category above whose marker is farthest to the right.

Examples:

The statement “Increased risk of cardiovascular death” is translated according to its CVD detection quality to the marker position at the beginning of the red area of the “Risk” row.

The statement “Insufficient exercise capacity” is translated according to its specificity for overall mortality detection to the marker position in the middle of the red area of the “Functional response” row.

The statement “ST/T changes indicative of ischemia” with ST/HR hysteresis > 0.05 mV is translated according to its CAD detection quality to the marker position in the upper part of the red area of the “Ischemia (CAD)” row.

Statement	Position in %
Risk	
Probably increased risk of cardiovascular event	86
Probably risk of cardiovascular event (FVE recovery)	45
Probably increased risk of malignant arrhythmias	75
Probably increased risk of stroke/cardiovascular event	80
Exercise induced bundle branch block	58
Exercise induced wide QRS tachycardia	55
Exercise induced atrial fibrillation	49
Exercise induced supraventricular tachycardia	52
Undefined risk	-17
Probably normal	17
Functional response	
Significantly reduced heart rate response to exercise	81
Reduced heart rate response to exercise	50
Insufficient exercise capacity	85
Reduced exercise capacity	55
Abnormal blood pressure response	77
Insufficient rate pressure response	75
Undefined functional response	-17
Probably normal	17
Ischemia (CAD)	
ST/T changes indicative of ischemia (ST/HR hysteresis)	96
ST/T changes indicative of ischemia (ST/HR hysteresis + HR reserve used)	90
ST/T changes indicative of ischemia (ST/HR index + HR reserve used)	88
ST/T changes may be clinically significant (ST peak)	50
ST/T changes may be clinically significant (ST recovery)	45
Cannot rule out clinically significant ST/T changes	40
Probably normal	17
Others	
Probably normal exercise response	17
Undefined exercise response	-17
No ECG	-20

Table 7.1 Statements and their positions

- By positioning the cursor on a marker, the corresponding statement and reasoning text are displayed (Figure 7.4). By positioning the

cursor in the “Functional response” category, for instance, all corresponding statements and reasoning texts of this category are displayed (Figure 7.5). By positioning the cursor in the “Overall” category, all statements and reasoning texts are displayed (Figure 7.6).

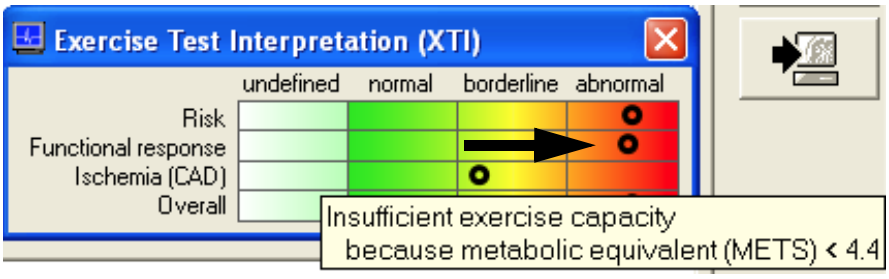


Figure 7.4 Example: Statement and reasoning texts when cursor is at marker position "abnormal functional response".

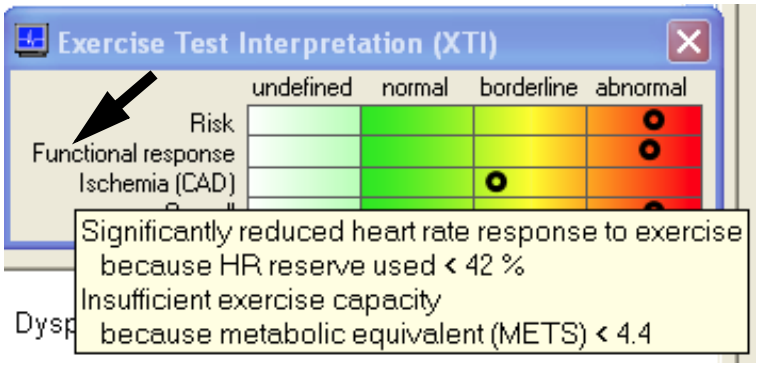


Figure 7.5 Example: Statement and reasoning texts when cursor is in the "Functional response" position.

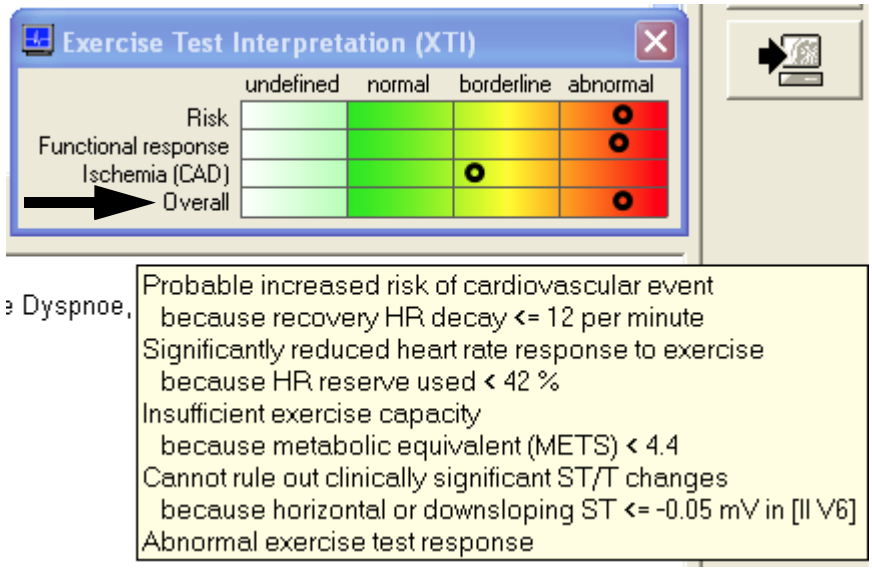


Figure 7.6 Example: Statement and reasoning texts when cursor is in the "Overall" position.

For your notes

8 Audio Assessment of Exercise Tests

An audio replay gives a fast overview of an exercise test and provides a highly sensible demonstration of all kind of discontinuities, for instance, arrhythmias like atrial fibrillation, intermitted supraventricular tachycardias and intermitted branch bundle blocks. Audio assessment is intended to be an addition to the visual assessment at the end of an exercise test. It might help not to overlook important ECG phenomena.

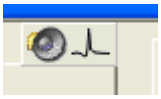


Figure 8.1 Button on CardioSoft/CS for starting and stopping replay of an audio ECG. During replay all other exercise results can also be examined visually

Fast Assessment

The ECG is reproduced 60 times faster. Therefore an exercise test of 10 min, has a duration of 10 sec, for instance.

The increasing of the frequency corresponds to the exercise phase, relative to the increasing of the heart rate during exercise. The subsequent decreasing of the heart rate corresponds to the recovery phase.

The reproduction is in stereo. The right channel represents lead V2 and the left channel lead V5.

Based on the recent knowledge about audible ECG, following abnormalities/discontinuities are assessable:

- Absolute arrhythmia (atrial fibrillation)
- No HR response to new stage
- No steady increasing of HR during exercise
- No significant HR increase from rest to peak exercise
- No steady decreasing of HR during recovery
- No significant decrease of HR during recovery
- PVCs in recovery phase
- V2 is significantly louder than V5

Examples

To listen to an audio ECG please click on the loudspeaker symbol. The ECGs and clinical data, are from the Finnish Cardiovascular Study (FINCAVAS)[82], from Tampere University, Tampere, Finland.

ra0001 (A0001)

Normal exercise response (patient 67 y, f, 154 cm, 61 kg)

During exercise the heart rate increases normally. The changes of the stages are clearly audible. A few supraventricular premature beats are audible during exercise and recovery.

The loudness of V2 is similar to the loudness of V5.

ra1016 (D0018)

Atrial fibrillation. From the beginning there is a grumbling sound, typical for atrial fibrillation. The sound continues during the whole exercise test.

The patient (73 y, m, 186 cm, 86 kg) died 3 months after the exercise test, because of artereosclerotic heart disease (WHO-ICD, I25.1[54]).

The loudness of V2 is higher than the one of V5, reason left bundle branch block (LBBB).

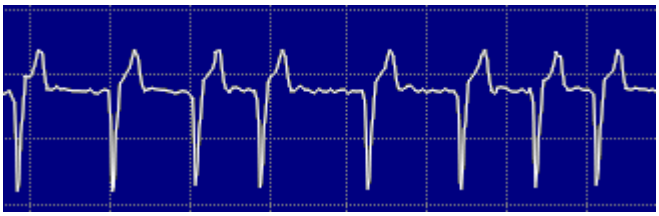


Figure 8.2 Atrial fibrillation in pretest phase, lead V1

ra0232 (A0233)

Abnormal exercise response. The patient (67 y, m, 161 cm, 68 kg) died 3 months after the exercise test, because of an acute anterior myocardial infarction (WHO-ICD, I21.0[54]).

During the recovery phase frequent ventricular ectopics and a sudden increase of heart rate are audible.

The loudness of V2 is higher than the one of V5, due to an old anterior myocardial infarct.

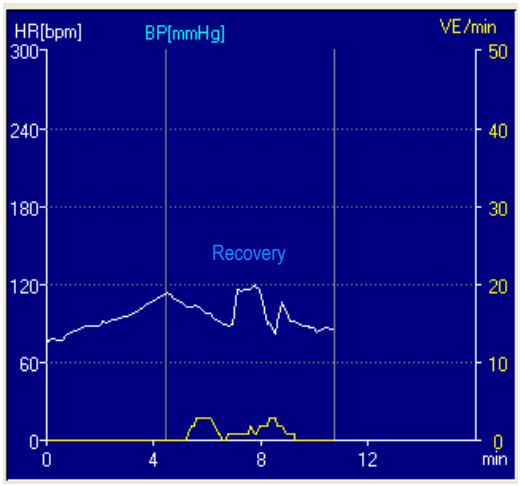


Figure 8.3 Increase of the heart rate and ventricular ectopics(VE/min) in recovery phase.

For more details on audio assessment of exercise tests, see the *Audio-ECG Physician's Guide*.[86]

For your notes

9 Resting ECG Interpretation and Pre Test Risk Assessment

With their exercise test systems CASE and CardioSoft/CS, for instance, GE Healthcare offer tools to support the planning of a patient's exercise test procedure. These tools are the 12 SL Resting ECG Interpretation program, see Physician's Guide[53], and the AHA (American Heart Association) Coronary Heart Disease Risk and Stroke Risk Prediction program (see below).

AHA Coronary Heart Disease Risk and Stroke Risk Prediction

A number of risk factors have been found to be associated with a distinctly enhanced risk of coronary heart disease, including sudden coronary death, myocardial infarction, and angina pectoris. Framingham and other epidemiological studies have shown that a prediction of the incidence rate of coronary heart disease can be made for groups of persons well in advance of the appearance of symptoms. Among the risk factors identified are: gender, age, cigarette smoking, elevated blood pressure, high levels of serum cholesterol, low HDL-cholesterol (High Density Lipoprotein cholesterol), diabetes, and ECG abnormalities. These factors are not the only risk factors which might logically be considered in assessing risk of coronary heart disease, but they are a set of proven merit which can be readily measured by an office nurse or a technician without hazard or trauma to the patient.

Coronary Heart Disease Risk Prediction

GE's Coronary Heart Disease Risk Prediction program is an implementation of an update of an earlier risk handbook (American Heart Association. *Coronary Risk Handbook. Estimation of Coronary Heart Disease in Daily Practice*, Dallas 1973). It is based on more recent analysis of the Framingham Heart Study which adds HDL-cholesterol to the risk profile (Anderson KM, Wilson PDF, Odell PM, Kannell WB. "*An updated Coronary Risk Profile*", Circulation. 1990). In general, the more risk factors present or the greater the degree of abnormality of any

factor, the greater the risk. The program combines factors and facilitates assessment of risk for persons whose blood pressure or lipid values may not reach some arbitrary value set as “abnormal”. By using the program, fewer persons will be misclassified because they have borderline values for blood pressure and lipids.

The program provides a synthesis of the information expressed as the probability of a coronary event within five or ten years of risk factor assessment. It allows pre-symptomatic assessment of coronary vulnerability from a coronary risk profile. These results do not necessarily apply to persons who already have coronary heart disease.

Stroke Risk Prediction

Probability of stroke risk is directly related to the level of risk factor abnormality, in the case of age and systolic blood pressure, and to the number of risk factors present, i.e., diabetes mellitus, cigarette smoking, cardiovascular disease, or electrocardiographic abnormality – left ventricular hypertrophy or atrial fibrillation. GE’s program combines the risk factors and makes a quantitative assessment of risk even though the systolic blood pressure is not high enough to be classified as definitely in the hypertensive range. Since most hypertensives are in the borderline category, and this level of blood pressure elevation is clearly important in stroke incidence, the program takes such intermediate levels into account.

Stroke risk is somewhat greater for men than women, and the risk profiles are gender-specific. For men and women a certain systolic blood pressure level on treatment has a higher risk than the untreated level; consequently anti-hypertensive treatment is taken into account. For women an additional interaction adjustment is needed. The relationship between blood lipids and stroke is clearly different from their key role in the pathogenesis of coronary heart disease. Total cholesterol and HDL-cholesterol are important risk factors influencing coronary heart disease but not stroke.

GE’s program provides a synthesis of the risk factor information for each gender expressed as the probability of a stroke event in a specified ten year period. This probability of stroke in a pre-symptomatic individual does not necessarily apply to persons with prior cerebral infarction or hemorrhage.

Definitions of Terms and Measurements

Risk factors in the program and their method of measurement are defined in the following list. If other measurement techniques are used to determine any of the values, they should be adjusted to those defined.

HDL-Cholesterol	High density lipoprotein cholesterol determined after heparin-manganese precipitation.
Fasting Total Cholesterol	The physician is advised that the cholesterol values in the program are based on the Abell-Kendall method. If your laboratory uses another method, you should determine from the laboratory director the correction factor necessary to convert to the Abell-Kendall values. The correction factor varies among laboratories and must be determined by each laboratory. Most direct and automated cholesterol determinations give values five percent to 15 percent above those stated in the tables. Use of corrected values will affect the precision of risk estimates made from these tables. Plasma cholesterol measurements used here are 3 to 4.7 percent lower than serum (Cloey T, Bachorik PS, Becker D, Finney C, Lowry D, Sigmund W. "Reevalution of serum-plasma differences in total cholestrol concentration". *JAMA 1990; 253:2788-2789.).*
Systolic Blood Pressure, BP sys (mmHg)	Casual pressure taken with the subject seated and resting for five minutes. An average of two measurements is preferred.
Cigarette Smoking	Refers to whether or not an individual is a cigarette smoker or has quit only within the last 12 months. The program does not take into account the intensity of the smoking habit and contrasts only smokers and non-smokers.
Anti-Hypertensensive Therapy	Currently on anti-hypertensive medication.
Cardiovascular Disease	History of myocardial infarction, angina pectoris, coronary insufficiency, intermittent claudication or congestive failure.
Atrial fibrillation/flutter	History of atrial fibrillation/flutter.
Left Ventricular Hypertrophy by ECG	LVH by ECG consists of finding tall R waves in leads reflecting potentials from the left ventricle accompanied by ST segment depression or T wave inversion.

For your notes

10 Exercise Testing

General

Typically an exercise test consists of three phases: the pretest, the exercise and the recovery phase. Exercise and recovery phase are important for calculation of the ST/HR hysteresis, for instance. An exercise test should comprise a pretest phase of one minute or more, started after successful applied electrodes, an exercise phase, and a recovery phase of three or more minutes.

In their Exercise Test Systems, GE Healthcare offers tools to support the planning of the test procedure for a patient. These tools are the 12 SL Resting ECG Interpretation program, see Physician's guide[53], and the AHA Coronary Heart Disease Risk and Stroke Risk Prediction program, discussed in chapter 9.

Good electrode application and preparation is essential to receive good results. A lack of diligence in applying the electrodes causes high noise and multiple artifacts in the ECG and leads to difficulties in evaluating an exercise test and their measurements, especially measurements relating to ST segment and to T-wave alternans. Good skin preparation, electrode quality, and good placement are important factors for achieving reliable ECG measurements from the ST/T segment, for instance, and a reliable Exercise Test Interpretation. To assure maximum performance, follow all the recommended guidelines for operation, including skin preparation, electrode selection, and placement. Please note that electrode and leadwire movement can cause artifacts similar to the frequency content of the ST/T segment of the ECG. Securing the leadwires is strongly recommended.

Role of Stress Testing in Reducing Cost of Healthcare

Unnecessary Cath Lab interventions have been identified as one of the most wasteful expenditures in all of healthcare, worldwide.[91,92] Even Consumer Reports* has qualified it as being in the top 10.

Fortunately, the stress test is an effective tool that can be used to curb this waste. Below are a few quotes from the scientific literature that make this point:

- The appropriateness of PCI (percutaneous catheter intervention) has been challenged because many patients undergoing PCI lack documentation of ischemia (lack of oxygen) by non-invasive testing (that is, stress testing) prior to the procedure…"[92]
- On the basis of the evidence, PCI is considered formally appropriate only if the patient has (1) ischemic symptoms that might be improved by revascularization, (2) objective evidence of ischemia by stress testing, and (3) failed a trial of optimal medical management because the ischemia is intractable to maximally tolerated doses of antiischemic medications."[91]

One of the root causes for this waste is the erroneous but, unfortunately, widespread belief that plaque which significantly narrows a coronary artery will lead to a heart attack. This belief has resulted in a preoccupation with these obstructions,[93]causing clinicians to invasively treat patients , even when they are asymptomatic, by mechanically dilating these areas and inserting a stent to keep them dilated. This is despite the preponderance of evidence that heart attacks are caused by clots which result from plaque rupture (that is, where the plaque loses its fibrous cap and leaks clot activating factors into the blood that flows by it).[94] In fact, most heart attacks result from a rupture of a plaque that is so small it does not elicit any symptoms[95] and is often invisible on the X-ray images obtained via the Cath Lab.[96-98]

Nevertheless, it took the results of the COURAGE trial to put care providers on notice[99] that mechanical treatments of these obstructions, even when the narrowing of the coronary artery exceeds 70%, is of little benefit unless the patient is symptomatic and has been found to have objective evidence of myocardial ischemia.[100]

Given the controversy raised by the COURAGE trial, more investigations were launched. Meta-analysis of similar trials has also generated a similar conclusion: "initial stent implantation for stable CAD shows no evidence of benefit compared with initial medical therapy for prevention of death, nonfatal MI, unplanned revascularization, or angina."[101,102]

The cost of this inappropriate treatment has been found to be substantial. Indeed, without documented evidence of ischemia, "the added cost of PCI was approximately $10,000, without significant gain in life-years or quality-adjusted life-years. The incremental cost-effectiveness ratio varied from just over $168,000 to just under $300,000

* Source: http://www.consumerreports.org/cro/2012/08/treatment-traps-to-avoid/index.htm (Accessed February 13, 2013)

per life-year or quality-adjusted life-year with PCI. A large minority of the distributions found that medical therapy alone offered better outcome at lower cost. The costs per patient for a significant improvement in angina frequency, physical limitation, and quality of life were $154,580, $112,876, and $124,233, respectively."[103]

Estimates of the number of inappropriate treatments are derived from several sources, which need to be interpreted in relation to the different reasons for performing PCI. For instance, PCI is also used for treating heart attacks due to plaque rupture and clotting. However, emergency Cath Lab procedures (which often include stents) are appropriate. In fact, these emergency procedures have been found to be very effective versus the other treatment for a heart attack, namely thrombolytic therapy. [104-107] Therefore, it is important to separate out procedures related to emergency PCI (also called primary, direct or immediate) versus those related to an elective PCI due to stable plaque.

According to the most recent statistics available from the AHA, [95] it is estimated that 1,133,000 PCI procedures are performed per year in the United States. In addition, it is estimated that another 1,072,000 inpatient diagnostic cardiac catheterizations were performed. Diagnostic CATH procedures are also relevant to this issue since it may be done as an extra step to confirm the presence of a narrowing before the PCI is actually performed. Nevertheless, it is not evident from these AHA statistics which of these procedures are due to an elective versus emergency condition. Instead, we need to turn to cohort studies to estimate the level of inappropriate treatment.

For example, in the United States, "a retrospective, observational cohort study using claims data from a 20% random sample of 2004 Medicare fee-for-service beneficiaries aged 65 years or older who had an elective PCI (N=23 887)"[108] found that only 44.5% (n=10 629) of these patients underwent stress testing within the 90 days prior to the elective PCI. Moreover, "there was wide regional variation among the hospital referral regions with stress test rates ranging from 22.1% to 70.6% (national mean, 44.5%; interquartile range, 39.0%-50.9%)."[108] "These numbers are remarkably similar to those in the United Kingdom, where 43% of patients have stress testing before elective PCI. Furthermore, revascularization rates also vary widely, with an 83% higher rate in Florida than in Oregon. Revascularization rates depend on race (28% variation) and cardiac catheterization rates (68% variation), which in turn depends on hospital admission rates for CAD as well as the number of cardiac surgeons and interventionalists in the local population." [109]

In a larger, "multicenter, prospective study of patients within the US National Cardiovascular Data Registry undergoing PCI between July 1, 2009, and September 30, 2010, at 1,091 US hospitals",[110] it was found that of the "500,154 procedures classified", 144,737 (28.9%) were elective PCIs.[110] For emergency situations, almost all of the procedures were appropriate. However, in the non-acute setting, "only 50% of procedures were classified as appropriate, 38% as uncertain, and 12% as inappropriate." Moreover, the majority of these inappropriate procedures were performed in patients with little to no angina or with low-risk ischemia on stress testing. The study also found "substantial hospital variation in the rate of inappropriate PCI".[110] This led the authors to conclude that "a better understanding of the clinical settings in which inappropriate PCIs occur and reduction in their variation across hospitals should be targets for quality improvement."[110]

A Clinical Approach to Exercise Testing

Note

This chapter is taken unchanged from the preceding physician's guides. It is not completely state of art, especially in risk assessment and new exercise measurements, but it remains valuable in a lot of aspects of exercise testing.

Note

The following material in this chapter 10 has been adapted from *The Clinical Approach to Exercise Testing* by Stephen P. Glasser, M. D., F. A. C. P., F. A. C. C. and Pamela I. Clark.
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Multistage exercise testing allows the physician to observe a subject's physiological adaptation to exercise and, as such, is a valuable extension of a standard history and physical examination. Exercise testing may be used to evaluate symptoms such as chest pain, palpitations, dyspnea, or easy fatigability; estimate the severity of coronary artery disease; appraise the effects of therapeutic interventions (e.g., surgery, drugs, physical training). In addition, exercise testing may be an aid in objectively evaluating an individual's functional capacity and tolerance for stress and may help in choosing an appropriate program of physical conditioning. Finally, recent work suggests that the exercise response is of considerable predictive value.[56,57,58,59,60] An abnormal ST segment response alone results in 10 to 15 fold greater likelihood of developing some coronary event over the ensuing 3 to 5 years, when compared with a normal ST response. (See Table 10.1)

1.	Evaluate symptoms
2.	Estimate severity of disease
3.	Appraise therapy
4.	Determine exercise tolerance
5.	Choose a program of physical conditioning
6.	Predict future cardiac events

Table 10.1 Applications of Exercise Testing

It is apparent that the most significant contributions to the safety of exercise testing are (1) selecting which patients can be safely tested and (2) deciding when a test should be terminated (that is, the point at which sufficient diagnostic information has been obtained, but beyond which further exercise might result in unnecessary risk to the patient). Both of these require knowledge of the condition of the patient and of the exercise procedure and is the reason that most clinical laboratories require that a physician be present to supervise all exercise tests. Two basic questions must be answered before exercise testing is initiated.

1. Will the results of testing change future medical management?
2. Do the benefits of testing outweigh the possible risks?

Concepts Useful in Interpreting Exercise Tests

Percentage of Predicted Maximal Heart Rate (MHR) Achieved

Figures for maximal predicted heart rate, age-adjusted, have been compiled as "target" heart rates towards which the subject works. (See Table 10.2[61]) Because the exercise heart rate is a good indicator of heart work, the percent of MHR at which symptoms of electrocardiographic changes occur is helpful in assessing a person's degree of disability. Also, the percent of maximal predicted heart rate that a patient achieves at peak exercise can provide an estimate of the efficacy of the test. If a patient must terminate exercise because of limiting noncardiac factors, the percent of maximum heart rate achieved may help the examiner to decide if the cardiovascular system was sufficiently stressed for valid interpretation of the electrocardiographic response to exercise. Thus, a test in which the maximal heart rate achieved is less than 85 percent of predicted, in which no abnormal signs or symptoms occur, cannot be called a normal test but, instead, must be termed an inconclusive test.

Age	20-29	30-39	40-49	50-59	60-69
Heart Rate	190	182	179	171	164
(Proceedings of the National Workshop on Exercise in the Prevention, in the Evaluation, and in the Treatment of Heart Disease. S. C. Med. Assoc., 65:1, 1969)					

Table 10.2 Predicted Maximal Heart Rates*

Total Exercise Time

The total time a subject spends on the treadmill can be used as an indicator of functional capacity by comparing that performance with age and gender-matched individuals. If the protocol is kept constant, serial studies of an individual patient can be of value in detecting decreasing tolerance to exercise or in evaluating the effects of treatment.

Total METS

Resting oxygen consumption is approximately 3.5 mm/kg/min, or 1 MET. If a subject is tested to his maximum physiological capacity, he is presumed to have reached his maximum oxygen consumption (VO2 max). Increasing physical work loads require increasing amounts of oxygen or multiples of resting oxygen consumption (eg, 2 METS, 3 METS). Because it is known what number of METS are required for each stage of a particular protocol, the total METS achieved can be an indicator of work capacity without the use of more sophisticated equipment to measure expired gases. The usual work capacities of different clinical subsets are listed in table 10.3.[62]

* Average maximal rates published by 10 investigators.

6 METS or less	limited patients
7 to 11 METS	asymptomatic patients
12 to 15 METS	healthy, active men
16 to 20 METS	endurance athletes

Table 10.3 Work Capacities as they Relate to Clinical Subsets.

Functional Aerobic Impairment

Functional aerobic impairment (FAI) is the difference between the estimated VO_2 max and that predicted for age and sex[63] and can be calculated from the equation:

$$FAI = \frac{(\text{predicted } VO_2\text{max} - \text{observed } VO_2\text{max}) \times 100}{\text{predicted } VO_2\text{max}}$$

If the Bruce protocol is used and the subject is not allowed to bear any weight on the handrails, his treadmill duration time can be plotted against his age on a standard nomogram and his functional aerobic impairment estimated without actually measuring oxygen uptake (see Figure 10.1). It must be emphasized that the nomograms shown here are valid only when used with the Bruce protocol, and the treadmill duration time must be calculated beginning with stage 1 (not including the lesser stages, zero or one-half).

Percent of Predicted O_2 Consumption Achieved

Maximum oxygen consumption (VO_2 max) is the highest level of oxygen uptake that an exercising subject can achieve; that is, if physical work is further increased, oxygen consumption will fail to increase, having reached physiologic limits. Oxygen consumption is limited by cardiac output and by extraction of O_2 by the peripheral tissues (arterio-venous difference). Predicted VO_2 max for a healthy subject is influenced by age, gender, body weight, and level of habitual physical activity. The percent of predicted oxygen consumption that an individual achieves at peak exercise can be estimated without complicated analysis of expired air. Since the FAI is the percent reduction in predicted oxygen uptake, the percent of normal predicted VO_2 max achieved can be estimated by subtracting the FAI from 100 percent[63]. Thus, an individual with 30 percent FAI would have achieved approximately 70 percent of the VO_2 max predicted for his age, gender, and level of physical activity. A person with 0 percent FAI is estimated to have reached 100 percent of his predicted VO_2 max.

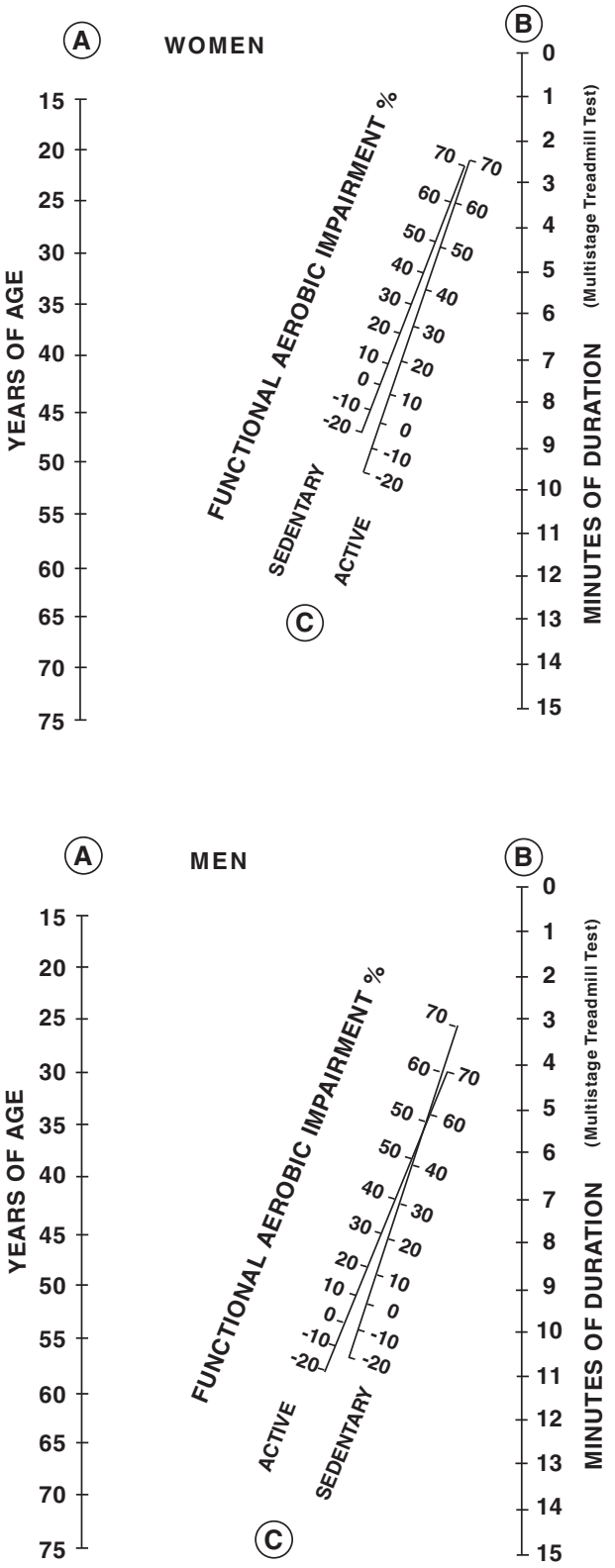


Figure 10.1 Nomograms for Assessment of Physiologic Impairment

Symptoms and Signs

The healthy individual should be free of symptoms during submaximal effort; however, at peak exercise, fatigue, leg weakness, or exhaustion is expected and may be accompanied by mild dizziness or nausea. Chest pain, claudication, and extreme dyspnea are abnormal responses.

During dynamic exercise, the working muscle groups generate heat (muscle temperatures as high as 109 °F (43 °C) have been recorded), which is dissipated through the skin. Therefore, the normal response to exercise is increased skin temperature and diaphoresis. Healthy individuals may develop cool, clammy skin at peak exercise, often associated with a drop in blood pressure. A similar reaction at less than maximal exercise is abnormal.

Electrocardiographic Response to Exercise

Peaking of the P wave, shortening of the PR segment, downward displacement of the PR (PQ) junction, shortening of the QT interval, decrease in R-wave amplitude, and downward displacement of the J point are all normal responses to exercise. The duration of normal J-point depression is generally about 40 milliseconds; significant ST depression that persists beyond that is abnormal. Elevation of the ST segment at rest owing to the early repolarization phenomenon that returns to baseline with exercise is a normal response.

The accepted electrocardiogram baseline for use in the evaluation of changes in the ST segment is the PR (or PQ) junction, which is somewhat lower than the usual isoelectric line of a resting ECG tracing.

Heart Rate and Blood Pressure

The expected response of the heart rate to exercise is an increasing rate with increasing workloads and leveling off at maximal or near maximal performance. The average change in heart rate from resting to peak exercise (chronotropic reserve) for the healthy subjects participating in the Seattle Heart Watch was 108 ±14 beats per minute (bpm) for 2532 men and 94 ±15 bpm for 244 women[64]. Lesser responses of heart rate can be found in highly trained athletes and infrequently in normal individuals. In occasional subjects, anxiety at the onset of testing will cause an initially rapid heart rate that should normalize within the first 3 minutes of exercise, and rise steadily with each increasing workload thereafter.

Average changes in systolic blood pressure from rest to exercise (intropic reverse) in the Seattle Heart Watch group was 61 ±19 mmHg for the healthy men and 42 ±18 mmHg for the healthy women[64]. Some individuals will show a slight drop in systolic pressure during the first stage of exercise, again most likely in response to lessening of anxiety that has produced hypertension at rest. At maximal effort many subjects show a drop in systolic pressure, which comes up again when exercise is terminated, then drops slowly toward resting levels during recovery. Immediately after maximal or near maximal exercise, a drop in blood pressure is almost uniformly seen and about 10 percent of subjects have

a significant drop with resultant dizziness. This is due to cutaneous vasodilatation and venous pooling and to a decrease in cardiac output. Following the immediate drop, blood pressure again rises and, then, gradually declines toward baseline values.

In response to decreasing systemic vascular resistance with exercise, a small decrease in diastolic blood pressure (further widening the pulse pressure) is expected in healthy individuals. Elevation of diastolic blood pressure greater than 10 mmHg during exercise is considered an abnormal response.

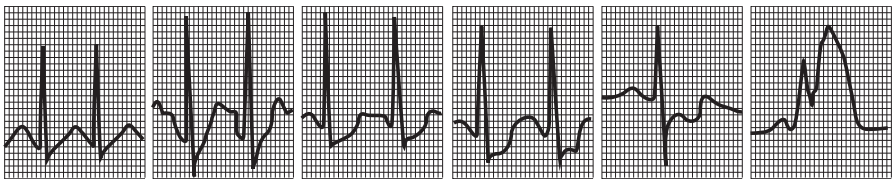
The heart rate blood pressure product ("double product") can also be used as a measure of myocardial oxygen demand. It has been shown that the "triple product" (heart rate x systolic blood pressure x left ventricular ejection time) correlated closely with VO_2 max, which is not surprising since these factors are the major determinants of myocardial oxygen demand. By eliminating left ventricular ejection time, a fair correlation with VO2 max still exists and eliminates the need for the additional difficult measurement.

Exercise Test Interpretation

When interpreting an exercise test, the ST segment response remains the most important exercise variable. However, abnormalities in the other exercise variables should be considered, as well. These include: the presence or absence of chest pain during testing, the responses of heart rate and blood pressure, changes in the R-wave amplitude, exercise duration, exercise-induced cardiac murmurs, gallops, rales, etc, and exercise arrhythmias. A detailed discussion of all these variables is, obviously, beyond the scope of this reference guide, and the interested reader is referred to *The Clinical Approach to Exercise Testing*[65] or another text on exercise testing. However, several of these variables, including the ST segment response to exercise, will be briefly discussed.

The ST Segment Response

Four types of ST segment responses have been associated with coronary disease (see Figure 10.2). ST segment elevation, slowly upsloping ST depression, horizontal ST depression, and downsloping ST depression. For maximal (and most submaximal) exercise tests, ischemic ST depression of 1.0 millimeter or more at 80 milliseconds after the J point, in a horizontal or downsloping configuration, is required to call a test abnormal.



A B C D E F

A Minimal J-point depression, isoelectric at 80 milliseconds.

B More marked J-point depression, but also isoelectric at 80 milliseconds.

C Slowly upsloping ST depression, remaining depressed more than 1 millimeter at 80 milliseconds.

D Horizontal ST depression.

E Downsloping ST depression.

F ST elevation.

Figure 10.2 The ST Segment Response to Exercise.

However, most authorities agree that the abnormal ST segment response is actually a continuum. The least abnormal is the marked J-junction depression, with the ST segment crossing the baseline at 60 to 80 milliseconds. The next is the slowly upsloping, with J-junction depression and an upsloping ST segment which is still at least 1 millimeter below the baseline at 80 milliseconds. More abnormal still is frank ST depression, greater than 1 millimeter depressed at 80 milliseconds with a horizontal configuration. And, most markedly abnormal is the pattern of ST depression with downsloping configuration. Each pattern has been associated with coronary disease to some degree and, generally, the likelihood of disease can be estimated by the severity of the pattern, the time of its onset, and the double product at

which it occurs. A subject who develops slowly upsloping ST depression at maximum exercise is less likely to have significant disease than is the person who develops marked downsloping ST depression at a low workload. It has become the custom in many laboratories to not label a test as positive or negative, but to judge it as normal or abnormal and to relate the test results to the likelihood of the presence or absence of coronary disease and the severity of that disease. A typical test interpretation might read: abnormal test, manifest by 3 millimeters downsloping ST depression at 65 percent of predicted maximal heart rate, associated with typical angina and a new S3 gallop. The likelihood of coronary disease is high, and the likelihood of extensive disease is high.

It should be noted that upsloping ST depression may be seen in one lead, while horizontal or downsloping depression is present in another lead, so that multiple lead systems may be valuable in increasing the sensitivity of this response.

Problems in the Interpretation of ST Segment Responses to Exercise

Many clinical variables affect the diagnostic reliability of exercise ST segment responses. Some causes of "false positive" ST changes are: female gender and left bundle branch block (both discussed below), preexcitation syndromes, mitral valve prolapse, digitalis, diuretics, and some psychotropic drugs. Sometimes masking "true positive" ST responses are: right bundle branch block (also discussed below), left axis deviation, previous myocardial infarction, and, again, some psychotropic drugs. The clinician must be familiar with these modifiers of the ST segment before attempting to interpret the exercise response of any individual patient.

Women have a higher frequency of "false positive" ST segment responses for a number of reasons. Foremost is that in the younger age groups the likelihood of coronary disease in females is low regardless of the presenting clinical syndrome. This low prevalence of disease suggests results in a high false-positive rate, in accordance with Bayes' Theorem. Then, too, mitral valve prolapse and vasoregulatory asthenia, both causes of false-positive ST changes, are common in women. Finally, it must be emphasized that most of the data thus far accumulated about exercise variables has been gathered from male subjects, and much more needs to be learned about the responses of women to exercise.

Most investigators agree that left bundle branch block on resting electrocardiogram totally precludes the reliable assessment of ST changes with exercise. Orzan et al[66], for instance, evaluated 57 symptomatic subjects with left bundle branch block, who had multilead treadmill testing and cardiac catheterization. Exercise-induced ST changes occurred equally in subjects with and without coronary disease, irrespective of the criteria chosen. In contrast, Tanaka et al[67] showed no increase in false-positive ST segment responses in patients with right bundle branch block, as long as analysis was confined to the lateral precordial leads (V4, V5, and V6). If ST segment depression occurred in V1, V2, or V3 only, however, the false-positive rate was high. On the other hand, there may be a mild reduction in sensitivity when right bundle branch is present. An additional technical problem may be encountered when analyzing the ST segment response to exercise in

subjects with right bundle branch block. The wide terminal S wave seen in right bundle branch block may obscure the location of the J point, rendering quantification of ST segment shifts difficult.

Sensitivity, Specificity, Predictive Value, and Pretest Likelihood

In order to obtain the full benefit of each exercise test, one must have a thorough knowledge of what is meant by the concepts of sensitivity, specificity, predictive accuracy (value), and pretest likelihood. The term "sensitivity" relates to the question: "Given a population with a particular disease, what percent of patients will have an abnormal test response?" Specificity relates to the question: "Given a population free from a particular disease, what percent of patients will have a normal test response?" Four possibilities exist when a test is performed, dependent upon whether the individual tested has or does not have the disease for which he is being tested:

	Abnormal Test	Normal Test
Disease present	true positive	false negative
Disease absent	false positive	true negative

The formulas for calculating the sensitivity and specificity of exercise-induced depression of the ST segment in subjects with and without angiographic coronary disease are:

$$\text{sensitivity} = \frac{\text{true positive}}{\text{true positive} + \text{false negative}}$$

$$\text{specificity} = \frac{\text{true negative}}{\text{true negative} + \text{false positive}}$$

Although useful concepts, these terms are limited clinically by the fact that they approach the problem in reverse; thus, if we already know that disease exists, there is little need to perform a diagnostic test.

The real clinical question to be asked is: "Given an ST segment response, what is the probability that an individual has coronary artery disease?" This question is addressed by the predictive accuracy (or predictive value) of a test:

$$\text{predicted value of an abnormal test} = \frac{\text{true positive}}{\text{true positive} + \text{false positive}}$$

$$\text{predicted value of a normal test} = \frac{\text{true negative}}{\text{true negative} + \text{false negative}}$$

An estimation of the probability of coronary artery disease prior to exercise stress testing in patients with different chest pain syndromes is listed in Table 10.4. It shows that the likelihood of obstructive coronary artery disease in someone with atypical angina is about 50 percent. This figure is of course subject to modification by the gender, age, associated risk factors, and the degree to which the angina is atypical. Table 10.4 also shows that a normal exercise test in a patient with atypical chest

pain results in a post-test likelihood of coronary disease of 25 percent. Conversely, an abnormal ST segment response to exercise in such a patient results in a post-test probability of coronary disease of 88 percent. The calculations in table 10.5 use only the ST segment response to exercise testing. The occurrence of chest pain during exercise—even though atypical in nature—or any other abnormal signs and symptoms would, of course, influence the figures. These figures are derived from Bayes' Theorem, which permits calculation of the post-test probability as it relates to the sensitivity and specificity of the particular test. Thus, the theorem is useful in assessing the possibility that the test result represents a false-negative or false-positive finding.

Clinical Presentation	Pretest Odds/Prob	Positive Test Post-Test Odds/Prob	Negative Test Post-Test Odds/Prob
Typical angina	9:1/90%	63:1/98%	9:3/75%
Atypical angina	1:1/50%	7:1/88%	1:3/25%
Asymptomatic	1:9/10%	7:9/44%	1:27/4%

Table 10.4 Post-Test Odds and Probabilities of Disease as Related to Pretest Odds and Probabilities

Other Exercise Variables

Of the many exercise variables, one of the most important responses to monitor is blood pressure. The normal response of both systolic and diastolic pressure has been discussed briefly in a previous section.

A small but significant number of patients undergoing exercise develop hypotension either as an isolated abnormal finding or associated with other exercise abnormalities. Recognition of this response is important not only for the safe conduct of the test, but because of the value of the sign as a predictor of critical narrowing of the coronary arteries. Morris and McHenry[68] reported exercise-related hypotension in 21 of 272 patients with coronary artery disease. Eighty-eight of the 272 patients had single vessel disease, none of whom had exercise hypotension. However, 6 of 96 with double vessel disease and 15 of 88 with triple vessel disease had the abnormal response. Thus, exercise hypotension becomes more common as coronary disease increases in severity.

A number of investigators began studying R-wave amplitude changes during treadmill testing after Bonoris et al[69] reported that a group of patients with decreased R-wave amplitude after exercising had less severe coronary artery disease and fewer wall motion abnormalities when compared to a group of patients who had an increase or no change in R-wave amplitude. Preliminary studies are conflicting, and it remains to be seen whether R-wave amplitude changes will prove to be of value in improving the sensitivity, specificity, or predictive value of the exercise ECG.

Finally, signs of exercise left ventricular dysfunction (S3 gallop, rales) or the appearance of ischemic events other than ST segment changes (new mitral regurgitation murmur, anginal chest pain) during or post-exercise are valuable in assessing the presence and extent of coronary disease, and should be sought with each exercise test.

Computer Processing of the Exercise ECG

The interpretation of an exercise test has expanded beyond the categorization of analysis of the ST segment response using a positive-negative classification. Despite this fact, the ST segment remains the most important exercise variable. There are several reasons why computer-assisted analysis of the exercise ECG is becoming more important in stress testing. Distortion of the electrocardiographic signal during maximal exercise due to muscle and respiratory artifact frequently prevents accurate interpretation of the ST segment response. The potential that computer processing has for the removal of such distortions is great (see Figure 10.3). Also, inter- and intra-observer variations in the interpretation of the ST segment response have been documented, and computer interpretation removes observer bias from analysis. Important also is the degree of precision that can be achieved by computer analysis of the ST segment slope. Classification of normal and abnormal ECG responses during exercise depend on the accuracy of the measurements used (that is, ST or J amplitude, ST slope or ST area). Simoons et al[70] have noted that the reliability of such measurements depends on the algorithms for location of the baseline and of the ST segment itself, usually accomplished by utilizing the QRS complex in some manner as a fiducial (or reference) point. Comparisons of the results of different algorithms for detecting the onset and end of the QRS complex, however, have shown that various programs differ considerably. Therefore, one should always check the computer determined QRS onset and offset points before reviewing the ST segment measurements.

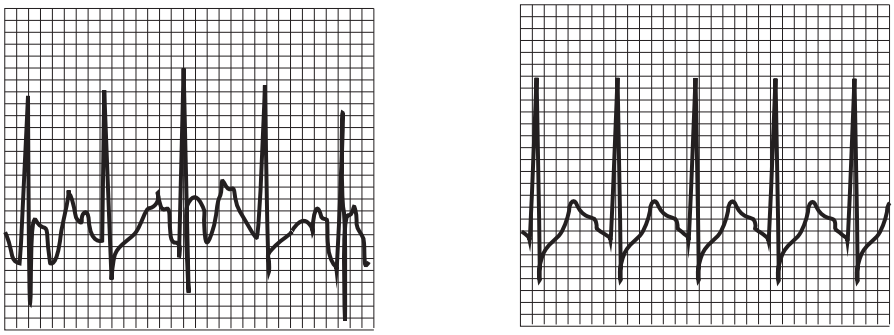


Figure 10.3 Exercise ECG Tracings of a Patient at Maximal Exertion

Simoons et al[71] have also recently presented a set of recommendations for the application of computers to diagnostic electrocardiography. (Refer to Table 10.5) They suggest that the adoption of these guidelines can result in an increase in sensitivity of 10 to 45 percent with only a small loss of specificity (3 to 10 percent). Finally, future computer applications will allow the assessment of other exercise variables and pretest and post-test probabilities with a greater reliability than is now available.

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
- Definitions of onset and end of 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 fiducial points from which the measurements have been taken
- Graphic or numerical output of the measurements should be available in addition to diagnostic statements

Table 10.5 Recommendations for Computer-Assisted Interpretation of the Exercise Electrocardiogram

For your notes

11 Reports

In-Test and Final Reports

GE systems offer a multitude of reports during (in-test reports) and at the end (final reports) of the stress test. These reports are the rhythm report, the comparative medians report, the 4 x 2.5 format 12-lead report, etc. For descriptions of the reports, consult your operator's manual. For two of these reports, some brief additional information follows:

Linked Medians report – consists of joined or "linked" median complexes for each lead. The medians are linked to match the current heart rate. The result is a noise-free and clean ECG strip, readable as usual. Since the ECG is artificially sequenced with median beats, rhythm changes, and ectopic beats, for example, are not visible. Therefore a real-time, one-channel rhythm strip is also provided.

Vector Loops report – Report showing X,Y,Z lead plots and three-plane vector loops of horizontal, frontal, and sagittal planes using the Frank X, Y, Z lead set. If the Frank lead set is not applied, GE's stress systems derive the X,Y,Z leads from the standard leads using the Inverse Dower Matrix described in "Vectorcardiogram synthesized from a 12-lead ECG: Superiority of the inverse dower matrix".[78]

For your notes

12 Glossary

Abbreviations and Definitions

12SL

An acronym for GE's 12 simultaneous lead resting ECG analysis program.

Acquisition module

The unit which serves as the interface between the patient and the stress system. Electrodes from the patient connect to the acquisition module, and a cable connects the unit to the system.

Actual load

The patient's effort to achieve the target load.

AFIB

Atrial fibrillation.

Algorithm

A step-by-step set of instructions for processing data.

Alignment

The purpose of alignment is to adjust the incoming beat to fit with the median template with respect to the slope characteristics of the waveform.

Arithmetic averaging

A signal-processing technique that aligns a set number of consecutive beats and divides them by the number of beats included in the alignment array yielding a mean QRS.

Artifact

Locally restricted noise or artificial complex not originated by the heart activity.

Audio assessment

Possibility of GE exercise systems to replay ECG for audible assessment of exercise tests.

Auto relearn

The process whereby GE stress systems detect a significant change in QRS morphology and relearn both the median complex and the ST segment measurement points.

BBB

Bundle branch block

Band pass filter

A filter that permits the passage of a specific frequency range (band). For example, a 5 to 30-Hz band-pass filter would eliminate all frequencies below 5 Hz and greater than 30 Hz.

Baseline roll filter

Filters on the low end of the ECG frequency spectrum (less than 1 Hz) whose purpose is to eliminate extraneous baseline drift. AHA requirements for diagnostic ECG equipment dictate that this filter be no more aggressive than a 0.05 Hz high-pass filter.

BP

Here, systolic blood pressure.

Bpm

Beats per minute.

Common mode noise

ECG interference generated from environmental equipment that is common to all leads.

Common mode rejection ratio

A proportion indicating the system's ability to ward off the effects of environmental electrical noise.

Correlation

Correlation matches the shape (slope characteristics) of the incoming beat to the median template. Where there is a sufficient correlation, the incremental update of the median template proceeds.

Chronotropic response

See "HR reserve used".

Cubic spline

A third-order polynomial technique for control of baseline drift employed as an alternative to aggressive, potentially distorting filterings.

Cyclic artifacts

Artifacts caused by footfalls during treadmill testing or pedaling during bicycle testing.

Double Product

The product of heart rate and systolic blood pressure, also called Rate Pressure Product (RPP).

DTS

Duke Treadmill Score, calculated with test time, ST deviation, and angina. Risk predictor.

Dominant template

See "Median complex".

Dynamic ST scan

The leads are scanned dynamically for the worst case ST depression.

E point

The isoelectric reference point set in the PR segment.

ESC

Ventricular escape beat.

Exercise capacity

Ability of a patient to exercise.

Exercise test

Application of physical stress to a patient using treadmill, bicycle, drugs, etc.

Exercise Test Interpretation

Part of HEART-Exercise software package. Translates measurements, thresholds, and patient data to interpretation and reasoning texts.

Fiducial point

A landmark or reference point.

Filtering

With respect to electrocardiography, filtering refers to the extraction and elimination of certain frequencies from the raw signal.

FRF algorithm

Algorithm for reducing the artifacts in the ECG with much less distortion of the QRS complexes.

FVE recovery

Ventricular ectopics per minute in recovery phase.

Graphical XTI output

Graphical expression of exercise test results.

Hertz (Hz)

The labeling unit of a frequency in terms of cycles per second. Also abbreviated as cps.

HEART-Exercise

The name for GE's 12 simultaneous lead exercise ECG analysis program. Contains the functionality described in this physician's guide.

HR reserve used

Patient's heart rate response to exercise calculated as $(HR_{peak} - HR_{resting})/(220 - age - HR_{resting})$.

HR recovery

Decrease of the heart rate in first minute of recovery.

High-pass filter

A filter that permits the passage of frequencies above a specific value. For example, a 0.01 Hz high-pass filter allows the passage of all frequencies above 0.01 Hz while removing all those below.

Incremental updating

Signal-processing technique used by GE stress systems resulting in a median complex. Successfully correlated incoming beats update the median template by the smaller fixed increment or a fraction of the difference between the template and the incoming beat.

Intelligent Lead Switch

Automatic selection of the best leads for QRS detection.

J point

The end of the QRS complex as delineated by the location where the last steep slopes of depolarization are replaced by the more or less flat ST segment.

LBBB

Left Bundle Branch Block.

Low-end filter

The high-pass filter that works on the lower end of the frequency spectrum.

Low-pass filter

A filter that permits the passage of frequencies below a specific value. For example, a 40-Hz low-pass filter allows the passage of all frequencies below 40 Hz while removing all those above.

Mean complex

The resultant complex from the arithmetic averaging technique of signal processing.

Median complex

The resultant complex from the incremental updating technique of signal processing.

Median template

See “Median complex”.

Median update

See “Incremental updating”.

MET

Metabolic equivalent or exercise capacity. METS is the plural.

Multi-beat event

Consecutive single-beat events. For example, a bigeminy, consisting of pairs of PVCs and normal beats.

Noise

All kinds of signal, disturbing the ECG, mostly caused by muscle activities.

Noise filter

A user-selectable low-pass filter that can be set at either 20, 40 or 100 Hz.

Pace enhance

Improved display of pace pulses.

Post-J measurement point (J+x)

Point for measurement of the ST level.

PSVC

Premature Supraventricular Complex.

PVC

Premature ventricular complex

PWC

Physical working capacity. Load in watts devided by patient’s weight.

PWC 130, PWC 150, PWC 170

Physical working capacity at heart rate 130 bpm, 150 bpm, or 170 bpm.

QRS detection

The purpose of this step is to detect electrical impulses associated with a heart beat of sinus or ectopic origin.

QRS offset

See “J point”.

QRS onset

First deflection of the QRS complex of all leads.

Relearn

If GE stress systems detect a significant change in QRS morphology or a specific user command, then the incoming complex is established as the dominant template and the ST segment measurement points are recalculated.

Risk prediction

Prediction of morbidity, overall mortality, cardiovascular death, acute myocardial infarction and/or malignant arrhythmias, based on data obtained by exercise testing.

RPP (Rate Pressure Product)

See "Double Product".

RR interval

Time distance to precedent beat.

Rule

Provides an interpretation by combining terms, consisting of measurements and thresholds.

Single-beat event

Events dedicated to single complexes. Such events are PVC or SVPC, for instance.

Signal acquisition

The process of obtaining the analog ECG signal from the patient and converting it into a digital format. In GE systems this process is performed in the acquisition module.

ST depression or ST segment depression

ST segment which is below the isoelectric line.

SVT

Supraventricular tachycardia

Signal conditioning

An enhancement of the ECG signal whose purpose is to present clean waveform data by improving the signal-to-noise ratio. See also "Filtering" and "Signal processing".

Signal processing

The employment of mathematical algorithms to improve the ECG presentation. See also "Incremental updating" and "Arithmetic averaging".

Signal-to-noise ratio

The amplitude of the ECG signal in proportion to the amplitude of the noise in the signal.

Stress test

See “Exercise test”.

ST criteria

Possibility to set ST criteria for continuous monitoring of the ST segment.

ST/HR hysteresis

Value derived from ST levels from exercise and recovery phase.

ST/HR index

Calculated by dividing the change of the ST depression from baseline to maximum exercise by the change in heart rate over the same time period.

ST/HR slope

Slope of a regression line through ST/HR points, beginning at peak exercise and extending backward through at least three points until significance is obtained.

ST Index

Value calculated with ST depression and ST down slope.

ST Integral

Area of ST segment.

ST level

Difference between an amplitude in the ST segment and the amplitude before the QRS onset.

ST segment

ECG segment from QRS offset to T-wave onset.

ST slope

Slope of the ST segment.

Template

See “Median complex”.

Target load

Load in Watts the patient should achieve on bicycle.

TWA

T-wave alternans. Alternating shapes of the ST/T segments.

VE

Ventricular Ectopic (PVC and ESC).

VT

Ventricular tachycardia

XTI (e**X**ercise **T**est **I**nterpretation)

See "Exercise Test Interpretation".

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