COMPUTERS AND BIOMEDICAL RESEARCH 22, 339–348 (1989)

An Algorithm for the Quantification of ST-T Segment Variability

SAUL E. GREENHUT, BENJAMIN H. CHADI, JONG W. LEE, JANICE M. JENKINS, AND JOHN M. NICKLAS*,†

Departments of Internal Medicine, Electrical Engineering, and Computer Science, University of Michigan, Ann Arbor, Michigan 48109

Received June 9, 1988

A template boundary algorithm which quantitatively determines repolarization (ST-T segment) variability in a normal population has been developed. The algorithm defines an initial ST-T template for comparison with successive beats. Variability is quantified using boundary limits around the template which are widened, when necessary, to included incoming ST-T segments. The boundaries at the end of each hour are stored and the collection of boundaries over a set of normal subjects quantifies the normal variation over the entire ST-T segment. The algorithm can be used to determine prospectively normal ST-T variability based on a regression analysis of R-wave or T-wave amplitude, and QT interval. Application of these boundary predictions should be useful in distinguishing repolarization changes secondary to ischemia from normal variability.

INTRODUCTION

Myocardial ischemia produces characteristic changes in electrocardiographic (ECG) repolarization which are commonly used to differentiate cardiac from noncardiac symptoms and to detect asymptomatic ischemia. Continuous monitoring of cardiac repolarization has been advocated as a diagnostic alarm for ischemic events allowing early effective therapeutic interventions. However, no attempt has been made to distinguish repolarization changes secondary to ischemia from random normal variability. Therefore, to improve the specificity of ECG ischemic alarms, an algorithm has been developed which can continuously monitor and quantify repolarization (ST-T segment) variability in a normal population.

Variability is quantified using boundary limits around an ST-T template. The template is patient specific, redefined hourly, and updated continuously. The initial boundary is widened to include incoming ST-T segments which would have otherwise crossed these boundary limits. The boundary at the end of each

* To whom reprint requests should be addressed at 3910 Taubman Center, 1500 E. Medical Center Drive, Ann Arbor, MI 48109-0366.

† Dr. Nicklas is supported by the NIH Clinical Investigator Award HL 01170.

0010-4809/89 $3.00

hour is stored and the collection of boundaries over a set of normal subjects can be used to quantify normal variation over the entire ST-T segment.

METHODS

Data Acquisition

The algorithm is implemented in C programming language for the IBM PC/AT microcomputer. Three-channel ECG data (leads I, II, and V_2) are recorded on magnetic tape (Hewlett–Packard Model 3968A) in FM mode with a frequency range of DC to 156 Hz. The ECG data are acquired from a multilead monitoring system (Marquette Electronics Model 7010) through the use of an in-house fabricated module which captures the analog data at the necessary low end frequency cut-off of 0.05 Hz for accurate ST-T segment analysis. The complete frequency range of the incoming ECG data is 0.05 to 60 Hz.

The ECG data are analyzed off-line using a Tecmar Lab Master (Scientific Solutions, Inc., Solon, OH) analog to digital converter. The signal is sampled at an effective rate of 250 Hz and quantized using 12 bits of resolution. The program allows data to be sampled and analyzed at different rates. A 1-V square-wave calibration signal is recorded on each of the tape channels used for ECG recording.

Fiducial Markers

The algorithm is dependent upon consistent temporal location of the R wave, J point, and T-wave peak. The R wave is found by the use of a convexity operator which indicates the sharpness of a waveform. The J point (and baseline between P and Q waves) is identified through the use of a tangent operator which indicates the angle of waveform portions. The T-wave peak is located by comparing maxima/minima positions in the three leads within a time-varying region using a variance operator. The ST-T segment is divided into six segments by these fiducial marks. Four segments between the J point and T-wave peak are divided as equally as possible, given the 250 Hz digitization rate. Each of the two segments following the T-wave peak are equal to MIN (size of existing segment, 40 msec).

R-wave peak. A portion of the waveform is determined to be an R wave if its convexity value in lead I exceeds the current convexity threshold. The operator is defined as

$$\text{convexity} = |(2 * \text{ecg}[i]) - \text{ecg}[i - 12\ \text{msec}] - \text{ecg}[i + 12\ \text{msec}]|, \quad [1]$$

where ecg[i] is the ECG signal amplitude in mV at time i msec and the vertical bars indicate absolute value. Thus, the convexity operator is large for sharp and high amplitude waveforms, while it is smaller for slowly changing and low amplitude waveforms. The convexity threshold is defined as a fraction of maximum convexity values and is updated continuously.

Baseline and J point. The tangent operator is used to find the first level portion of the PR segment (baseline) progressing backward from the R wave.

Tangents are computed until a value >1 or <-1 is found within a fixed temporal window. If an appropriate tangent cannot be located within a specified temporal window, the position of baseline is estimated from the R-wave location and the previous baseline position.

The J point is determined using a method similar to that for finding the PR segment baseline position. Beginning after the R wave, tangents of successive segments are calculated within a temporal window until a tangent >1 or <-1 is found. If the J point is not located within the window, it is estimated based on R-wave location and the previous J-point position. The baseline and J point are determined on the moving average of beats.

T-wave peak. The peak of the T wave is found, in averaged beats, using a variance operator within a variable temporal window. The window is defined by the average RR interval and is searched for maximum and minimum locations. In order to smooth the variability in position of the minima/maxima from one beat to the next, the peak values are found through a moving average of five data points and compared to a reference value preceding each search interval. The minimum must be less than the value at the reference location and the maximum above this number. Thus, biphasic T waves can yield multiple potential T-wave peaks. A single T-wave peak fiducial marker is determined by assuming that the T-wave position will not vary significantly with lead position. The locations of the maxima and minima in the three leads are compared using statistical variance over the potential combinations of T-wave peaks. The maxima/minima combination with the smallest variance defines the T-wave position for all leads. Subsequent physiologic changes in T-wave peak location are determined within a small, rate variable window. The window is biased in the direction of the rate change. If the rate increases, the window expands in the direction of the current R wave. If the rate decreases, the window expands toward the next P wave.

Noise Reduction

Beat averaging. A moving average of 20 beats (40 during template generation) is updated with each incoming ECG waveform. The R-wave peak serves as the reference point from which beats are summed. This averaging reduces random noise in the signal and only averaged beats are examined for ST-T variability.

Premature beat elimination. Premature beats, and other large amplitude premature noise, are eliminated from analysis through the definition and continual updating of a temporal window surrounding the RR interval moving average. If a convexity value exceeds the convexity threshold, but is outside of this window, the wave is treated as noise or an ectopic beat and neither the current or the immediately subsequent beat is analyzed.

Baseline wander correction. Baseline wander, which is seen as a varying DC offset, is corrected on all incoming beats. Consecutive PR segments are sampled and a linear slope between them determined. For all slopes not equal to 0, baseline wander is assumed and the waveform adjusted by extrapolating the

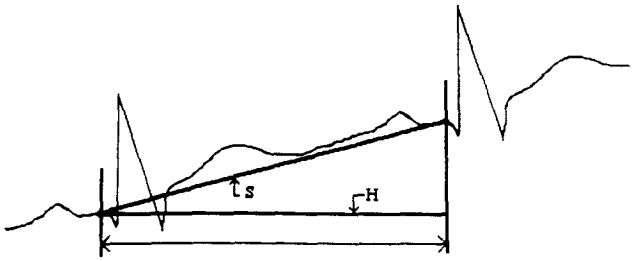


FIG. 1. Schematic showing how baseline wander is corrected on a portion of ECG waveform. The vertical distance from line H to line S is subtracted from the ECG waveform, on a point-by-point basis, to yield the baseline corrected signal.

slope between PR segments to the entire waveform and adding or subtracting the distance from the horizontal line (H) to the slope line (S) on a point-by-point basis (Fig. 1).

ST-T and PR segment noise windows. To eliminate noise in the ST-T and PR segments, incoming waveforms are compared to a running average of 20 beats. Incoming segments with values differing by more than ±0.3 mV are discarded and not further analyzed (Fig. 2).

Rate segregation. This window detects sudden changes in the RR interval which may produce ST-T segment changes. To avoid averaging significantly different QT intervals, producing artifactual widening or flattening of the T wave, groups of beats at different rates are averaged separately. Two consecutive beats falling outside of this window cause the discarding of the current moving average. A new moving average begins calculation and the rate window is moved appropriately.

Template and ST-T Boundary Construction

During the first 75 sec of each successive hour a new template is defined and stored. Each successive averaged ST-T segment is compared to the previous

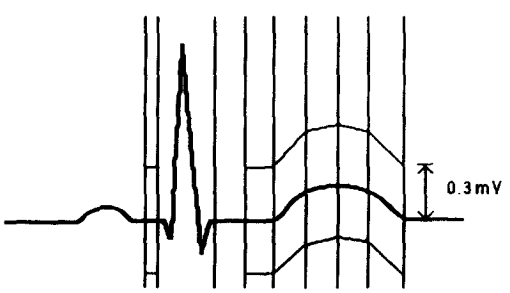
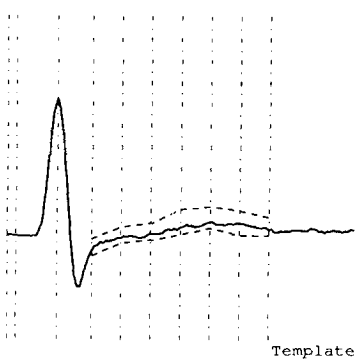


FIG. 2. Schematic showing the height and position of the PR and ST-T segment noise windows on an ECG waveform. The vertical bars represent the PR and ST-T segment fiducial markers. The boundary lines represent the ±0.3 mV amplitude noise windows over the two segments.

ST-T boundary for the particular lead. The previous boundaries represent the cumulative variability in the ST-T segment for each lead over all analyzed beats. If the current ST-T segment intersects the previous boundary, then a new boundary is created which encloses the current ST-T segment. If at least one of the three boundaries is updated then all three leads are stored, along with the updated boundaries, and beat parameters. This information can later be viewed off-line (Figs. 3–5). If the current ST-T segment is completely contained within the previous boundary, then no updating of the boundary occurs and the process continues with the next averaged beat. At the end of an hour, the original template can then be compared with the final boundary and the range of an individual's ST-T segment over 1 hr calculated.

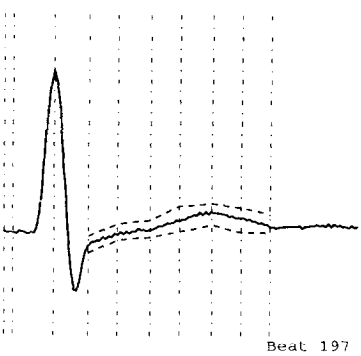


197> Lead I
73 Beats Outside Boundary
Hour:Min:Sec - 1: 0: 0

# Beats To Pass Criteria		
R Amplitude	:	5342
R-R Interval	:	5049
Baseline (2 in row)	:	4880
ST-T and PR Noise	:	4834

Distance From Template to ST-T Boundary [uV]

Pnt	Max	Min	Total
A	55.8	25.1	80.9
B	53.0	23.7	76.7
C	50.2	30.7	80.9
D	85.1	36.3	121.3
E	71.1	32.1	103.2
F	62.8	55.8	118.5
G	58.6	29.3	87.9



	Template	Beat 197	
R-Height:	665	795	uV
QRS Period:	104	104	mSec
Mean ST:	3	8	uV
ST-Depress:	29	31	uV
ST-Slope:	721	789	uV/mSec
+ ST-Area:	156	536	uV-mSec
- ST-Area:	-1289	-1138	uV-mSec
T-Height:	89	120	uV
+ T-Area:	7749	11275	uV-mSec
- T-Area:	67	67	uV-mSec
QT Interv1:	344	352	mSec
Heart Rate:	102	94	beats/min

Date: 05/06/88
File Name: test1800

FIG. 3. Lead I output display, following 1 hr of analysis, showing the final boundary revision around the ST-T segment of the original template and the 197th stored beat. The vertical dotted lines represent the 10 fiducial marker positions and the horizontal dashed lines are the final ST-T segment boundary. On the right are listed the number of beats to pass the noise reduction criteria, the ST-T template boundary distances, and numerous template and current beat parameters described in the text. Note that the heart rate has slowed from 102 to 94 beats/min prolonging the QT interval.

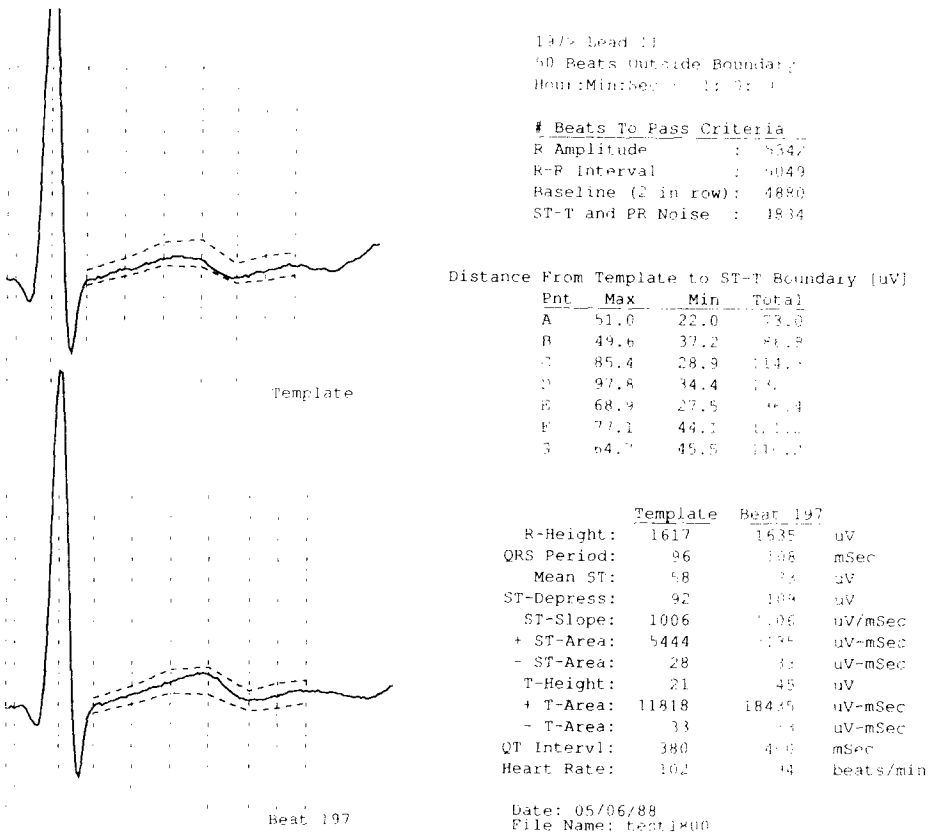


FIG. 4. Lead II output display following 1 hr of analysis. This figure is ordered as in Fig. 3.

Program Output

Information is stored whenever an averaged beat exceeds the ST-T boundary limits (Figs. 3–5). Each of the three leads is stored and can be displayed, along with the original template from that hour, and the current ST-T boundary. Many parameters are also displayed for the current beat and the template. (Fiducial markers are numbered from left to right, 1 through 10, respectively, in the following description.)

These are:

—Distance from the template to the current ST-T boundary at the seven ST-T fiducial markers (μV).

—Number of beats outside the ST-T boundary for that lead.

—Time of beat occurrence (hr:min:sec). To the nearest 1 min 30 sec.

—R-wave amplitude (μV). Relative to baseline.

—QRS duration (msec). Duration from the baseline (second fiducial marker) to the J point.

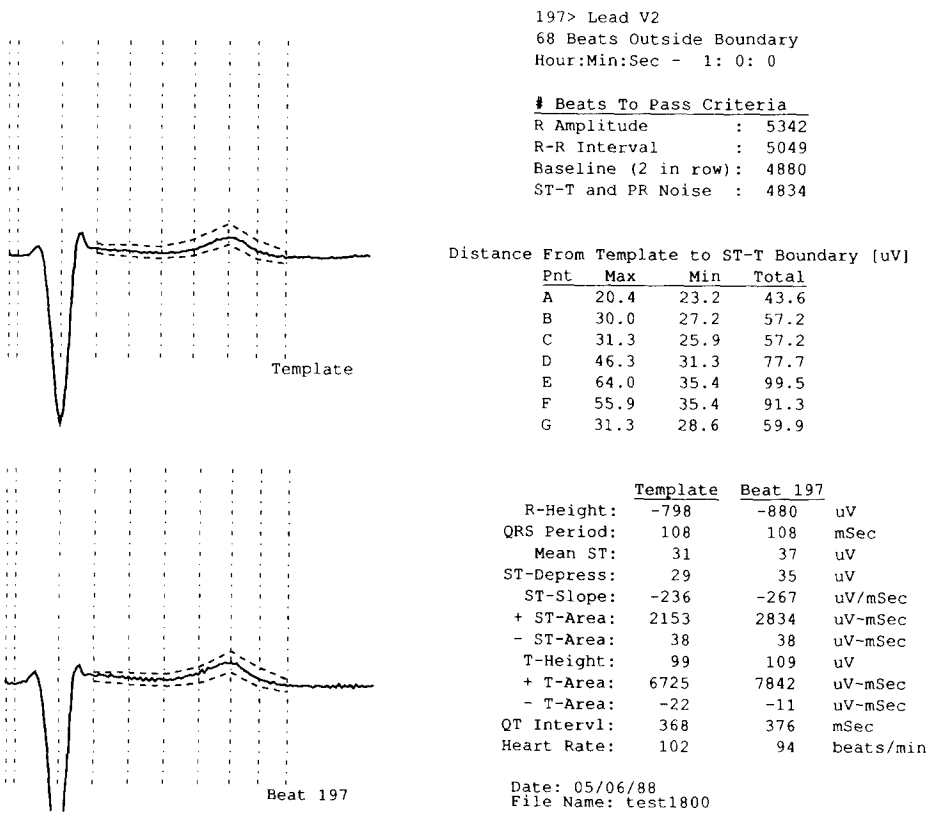


FIG. 5. Lead V_2 output display following 1 hr of analysis. This figure is ordered as in Fig. 3.

—Mean ST value (μV). Average ST value from the J point to the sixth fiducial marker.

—Level of ST depression (μV). Value of the ST segment 80 msec following the J point.

—ST slope (μV/msec). ST slope from the J point to the sixth fiducial marker.

—Positive ST area (μV-msec). Area above baseline between the J point and the sixth fiducial marker.

—Negative ST area (μV-msec). Area below baseline between the J point and the sixth fiducial marker.

—Amplitude of the T-wave peak (μV). Relative to baseline.

—Positive T-wave area (μV-msec). Area above baseline between the sixth and tenth fiducial markers.

—Negative T-wave area (μV-msec). Area below baseline between the sixth and tenth fiducial markers.

—QT interval (msec). Duration from the baseline (second marker) to the tenth marker.

—Heart rate (beats/min). Based on the current moving average RR interval.

—ST band areas (μV-msec). Area between each of the ST fiducial markers from the template to the current boundary level. Values are not currently displayed, although they are calculated and stored.

RESULTS

Representative output displays from 1 hr of ECG data for leads I, II, and V_2 are shown in Figs. 3, 4, and 5, respectively. The fiducial markers have been located correctly in all leads. In lead II, the algorithm chose the later, inverted peak due to its temporal proximity to the combination of peaks chosen in leads I and V_2. The data in Figs. 3 through 5 show that lead I had 73 beats which caused the boundary to be updated during the hour, while lead II had 50, and lead V_2 had 68.

Ninety percent of the beats for this hour were analyzed for ST-T segment variability. The remaining 10% were excluded because of the automatic noise reduction techniques. For example, 5342 beats passed the convexity threshold value and were therefore called R waves. Of these, 293 were discarded as possible ectopic beats or noise due to the RR interval criteria. The baseline wander adjustment requires that 2 consecutive beats be accepted to continue processing; 4880 passed this criteria. Forty-six additional beats failed to pass the ST-T and PR segment noise amplitude boundaries and were therefore not analyzed further.

The amplitude of the final ST-T boundaries are also displayed in Figs. 3–5. Point A refers to the J-point fiducial marker, point E to the T-wave peak, point G to the final fiducial marker, and the remaining letters to the various interpolated markers. The total indicates the range from the minimum boundary to the maximum boundary in μV at the particular fiducial marker. These values are fairly consistent over the ST segment and tend to expand slightly over the T-wave region for all three leads.

To the right of the template boundary display are shown features comparing the current beat and the original template. The final item listed here is heart rate and decreased from 102 to 94 beats/min since template generation. Careful inspection shows that the T-wave peaks have moved outward from the R-wave position and, likewise, the T-wave peak fiducial markers have moved in this direction. Thus, the decrease in heart rate also coincided with an increase in the QT interval.

DISCUSSION

The template boundary algorithm for ST-T segment analysis described here provides the first method for quantifying normal variability in repolarization. Although ECG changes characteristic of ischemia have been well described in the past (*1–6*), their specificity has been difficult to document. ST segment depression during exercise has been extensively correlated with angiographic

coronary artery disease (*7–18*), but the specificity of that relationship has been limited (65%–97%) (*9–12, 15–18*) and dependent upon the selected patient population. Higher values for specificity often caused low sensitivity values due to movement of the ischemic threshold. Little data are available on more direct correlations with ischemia (*19*). If continuous monitoring of cardiac repolarization is to be employed as an effective diagnostic tool on which important therapeutic decisions are based, then its specificity for distinguishing ischemia must be high and well documented. This algorithm provides the foundation for such specificity by quantifying and describing nonischemic, normal ST-T segment variability.

This algorithm is designed to be operator-independent without producing excessive signal elimination. The extensive series of noise reduction filters excluded only 10% of the incoming beats, most of these secondary to ectopy or ectopic-like noise. Those beats which were analyzed for ST-T segment variability could be adequately compared, despite physiologic rate changes, because of the reproducible placement of the fiducial marks from beat-to-beat. This feature of the algorithm is robust because it utilizes multiple leads in selecting fiducial locations. For example, the T-wave peak, because of its low frequency, is the most difficult fiducial marker to locate on a beat-by-beat basis for individual leads. This method, based on electrophysiologic principles, takes advantage of the three available leads of information to yield reproducible fiducial placement.

The present algorithm widens the ST-T segment boundaries to include all incoming segments. This method, although indicating the range of variability, does not measure the variance. However, the algorithm is easily modified to determine confidence intervals for normal ST-T segment variability. Boundaries can be defined initially and the percentage of beats falling outside the limits recorded. Thus boundary limits including 90, 95, or 99% of normal ST-T segments can be retrospectively determined.

Finally, the algorithm can be used to determine prospectively normal ST-T boundaries based on a regression analysis of R-wave or T-wave amplitude, QT interval, etc. A clinical study, gathering 24-h ECGs from 100 normal subjects, is currently in progress and will be used to quantify normal variability over the entire ST-T segment. A goal of this study is to determine a relationship between a waveform feature and the normal ST-T segment boundary width. Application of these boundary predictions should be useful in distinguishing repolarization changes secondary to ischemia from normal variability.

REFERENCES

1. HOLLENBERG, M., BUDGE, W. R., WISNESKI, J. A., AND GERTS, E. W. Treadmill score quantifies electrocardiographic response to exercise and improves test accuracy and reproducibility. *Circulation* **61,** 276 (1980).
2. RIFKIN, R. D., AND HOOD, W. B., JR. Bayesian analysis of electrocardiographic exercise stress testing. *N. Engl. J. Med.* **297,** 681 (1977).

3. KURITA, A., CHAITMAN, B. R., AND BOURASSA, M. G. Significance of exercise-induced junctional S-T depression in evaluation of coronary artery disease. *Amer. J. Cardiol.* **40,** 492 (1977).
4. FORLINI, F. J., COHN, K., AND LANGSTON, M. F. ST-segment isolation and quantification as a means of improving diagnostic accuracy in treadmill stress testing. *Amer. Heart J.* **90,** 431 (1975).
5. SHEFFIELD, L. T., HOLT, J. H., LESTER, F. M., CONROY, D. V., AND REEVES, T. J. On-line analysis of the exercise electrocardiogram. *Circulation* **40,** 935 (1969).
6. MCHENRY, P. L., STOWE, D. E., AND LANCASTER, M. C. Computer quantitation of the ST-segment response during maximal treadmill exercise. *Circulation* **38,** 691 (1968).
7. HOLLENBERG, M., ZOLTICK, J. M., GO, M., *et al.* Comparison of a quantitative treadmill exercise score with standard electrocardiographic criteria in screening asymptomatic young men for coronary artery disease. *N. Engl. J. Med.* **313,** 600 (1985).
8. UHL, G. S., HOPKIRK, J. A. C., HICKMAN, J. R., FISCHER, J., AND MEDINA, A. Predictive implications of clinical and exercise variables in detecting significant coronary artery disease in asymptomatic men. *J. Cardiac Rehabil.* **4,** 245 (1984).
9. BERMAN, J. A., WYNNE, J., MALLIS, G., AND COHN P. F. Improving diagnostic accuracy of the exercise test by combining R-wave changes with duration of ST segment depression in a simplified index. *Amer. Heart J.* **105,** 60 (1983).
10. KANSAL, S., ROITMAN, D., BRADLEY, E. L., JR., AND SHEFFIELD, L. T. Enhanced evaluation of treadmill tests by means of scoring based on multivariate analysis and its clinical application: A study of 608 patients. *Amer. J. Cardiol.* **52,** 1155 (1983).
11. RIJNEKE, R. D., ASCOOP, C. A., AND TALMON, J. L. Clinical significance of upsloping ST segments in exercise electrocardiography. *Circulation* **61,** 671 (1980).
12. COHN, K., KAMM, B., FETEIH, N., BRAND, R., AND GOLDSCHLAGER, N. Use of treadmill score to quantify ischemic response and predict extent of coronary disease. *Circulation* **59,** 286 (1979).
13. BERMAN, J. L., WYNNE, J., AND COHN, P. F. A multivariate approach for interpreting treadmill exercise tests in coronary artery disease. *Circulation* **58,** 505 (1978).
14. FROELICHER, V. F., JR., THOMPSON, A. J., WOLTHUIS, R., *et al.* Angiographic findings in asymptomatic aircrewmen with electrocardiographic abnormalities. *Amer. J. Cardiol.* **39,** 32 (1977).
15. FORTUIN, N. J., AND WEISS, J. L. Exercise stress testing. *Circulation* **56,** 699 (1977).
16. ERIKSSEN, J., ENGE, I., FORFANG, K., AND STORSTEIN, O. False positive diagnostic tests and coronary angiographic findings in 105 presumably healthy males. *Circulation* **54,** 371 (1976).
17. GOLDSCHLAGER, N., SELZER, A., AND COHN, K. Treadmill stress tests as indicators of presence and severity of coronary artery disease. *Ann. Intern. Med.* **85,** 277 (1976).
18. BORER, J. S., BRENSIKE, J. F., REDWOOD, D. R., *et al.* Limitations of the electrocardiographic response to exercise in predicting coronary-artery disease. *N. Engl. J. Med.* **293,** 367 (1975).
19. DEANFIELD, J. E., SHEA, M., RIBIERO, P., *et al.* Transient ST-segment depression as a marker of myocardial ischemia during daily life. *Amer. J. Cardiol.* **54,** 1195 (1984).