The Predictive Value of Exercise QRS Duration Changes for Post-PTCA Coronary Events

Shai Efrati, M.D., Angel Cantor, M.D., Benjamin Goldfarb, M.D.,
and Reuben Ilia, M.D.

From the Exercise Testing Unit, Cardiology Department, Soroka University Medical Center, Faculty of Health Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

Background: The sensitivity and predictive values of exercise ECG testing using ST-T criteria after percutaneous transluminal coronary angioplasty (PTCA) are low, precluding its routine use for screening for restenosis. The predictive value of QRS duration criteria during exercise testing (ET) ECG after PTCA for future coronary events has not been reported. The aim of the study was to compare QRS duration changes with ST-T criteria during ET, as a predictor of coronary events after PTCA.

Methods: A prospective study of 206 consecutive patients who underwent ET at a mean of 34 ± 14 days after their first PTCA, and were followed for a mean of 23 ± 9 months. Patients were divided by QRS duration into two groups—Q1: ischemic response (QRS duration prolongation of more than 3 ms relative to the resting duration), and Q2: normal response (QRS duration shortening or without change from resting duration). Patients were also divided by their ST-T response, S1: ischemic response, and S2: normal response.

Results: During follow-up 52 patients (58%) experienced restenosis or MI, or underwent CABG—Q1: 44 (85%), Q2: 8 (15%) ($P < 0.0002$), S1: 8 (15%), S2: 44 (85%), ($P < 0.641$), two patients died—Q1: 1 (1%) and Q2: 1 (1%). For QRS and ST-T, the relative risk of having at least one of the coronary events was 4.02 (CI 2.1–9.9) versus 1.13 (CI 0.8–2.9), respectively. The sensitivity for future coronary events was 85% and 52% and the specificity was 48% and 98% for the QRS and ST-T criteria, respectively.

Conclusion: QRS prolongation during peak ET ECG after PTCA is a more sensitive marker than ST-T criteria for detection of patients at risk for later coronary events. **A.N.E. 2003;8(1):60–67**

exercise QRS; post-PTCA coronary events

The exercise test (ET) electrocardiogram (ECG) using ST-T criteria is a simple, accessible, safe, and low-cost tool for detecting ischemic heart disease. ECG markers for ischemia are either elevation, horizontal, or downsloping depression of the ST segments, but these criteria have low sensitivity and specificity, especially in the presence of an abnormal resting ECG due to a previous MI or to the use of antiischemic drugs such as β -blockers.¹ In attempts to improve the diagnostic accuracy of the test, other ECG variables have been proposed, such as ST-segment heart rate index, ST-segment heart rate slope, and QRS complex amplitude, duration, and frequency.^{1,2}

In our previous studies^{3–6} we investigated rest and exercise QRS duration in patients with ischemic heart disease using a computerized optic

scanner, and found significant differences between these patients and normal controls. Those with ischemic heart disease had significant QRS prolongation during exercise, whereas normal controls had either no change or shortening of this interval. Using this technique, the diagnostic value of the test was improved in a group of 165 subjects. Similar results were obtained using assessment of exercise QRS prolongation as a means to detect ischemia in a group of post-MI patients. Furthermore, this method was more useful than classical ST-T changes to detect ischemia in a group of 101 women, for whom the standard exercise stress test has a low predictive value. These studies compared QRS prolongation results with those of thallium stress testing and cardiac catheterization that were the "gold standards." Similar results were

found in a group of 51 patients in whom the QRS width changes were recorded during PTCA. QRS prolongation was a marker for ischemia in most patients during PTCA, and was found to be more sensitive than chest pain or ST-T changes. QRS duration was found to be more prolonged with occlusion of the proximal or middle segments of major arteries. The criterion for diagnosis of ischemia in all these studies was QRS prolongation of more than 3 ms relative to QRS duration at rest.

PTCA is a widely used therapeutic procedure in patients with ischemic heart disease. ET performed after PTCA is an effective method for assessing functional capacity and serves as a point of reference for future examinations. A single ET performed after PTCA, using standard ST-T changes for detecting ischemia, had no prognostic value for future coronary events.⁷⁻¹⁴ The predictive value of ET for future coronary events using QRS duration criteria has not yet been described. The aim of the present study was to conduct a prospective comparison of QRS duration criteria with ST-T criteria for the detection of an ischemic response in post-PTCA patients who were followed for coronary events for approximately 2 years.

METHODS

Study Population

During the prospective study period (August 1995 to May 1998), 273 consecutive patients underwent ET 10 to 60 days after their first PTCA. Sixty-seven patients were excluded because they achieved less than 70% of the age-determined target heart rate, or because they had an intraventricular conduction defect. Thus, the final study population consisted of 206 patients, 82% men, with a mean age of 58 ± 11 years (range 25-90), who underwent ET a mean of 34 ± 14 days after PTCA, with a mean follow-up period of 23 ± 9 months. Patients were divided into two groups according to changes in QRS duration and ST-T criteria for ischemia; Q1: QRS prolongation during exercise greater than 3 ms relative to QRS duration at rest was considered an ischemic response; Q2: no change or a shortening of the QRS duration during exercise relative to the QRS duration at rest was considered the normal response. S1 was defined as the ischemic ST-T response during ET, and S2 was defined as the nonischemic response using ST-T criteria. The coronary event endpoints of our study were symptomatic

restenosis (defined as a new narrowing of more than 50% at the site of the previous dilation), MI, CABG, and/or death. Only symptomatic patients underwent a second coronary angiography.

Exercise Testing

Standard Bruce Protocol exercise testing was performed on a computerized treadmill system (Quinton 5000). Patients receiving medication were instructed to taper the doses and stop the drug 4 days (β -adrenergic blocking agents), 48 hours (calcium blockers), or 12 hours (nitrates) before the test. None of the patients was receiving antiarrhythmic drugs or other drugs that might influence QRS duration.

Exercise was continued until the target heart rate was achieved or until the development of limiting symptoms (angina, dyspnea, fatigue, or claudication), abnormalities of rhythm such as a run of supraventricular arrhythmia, three or more consecutive premature ventricular beats, or significant ST-T segment displacement. Horizontal or downsloping ST-T depression greater than 0.1 mV relative to the baseline at 0.08 seconds after the J point occurring during exercise or during the recovery period in at least three consecutive complexes and in at least two consecutive leads was considered positive for ischemia. The test was considered negative when the patient reached more than 70% of the predicted maximal heart rate without demonstrating significant ST-T changes. All the tests were reviewed by one of the investigators.

Optical Scanner Measurements

The computerized technique for QRS duration measurement using an optical scanner has been described in detail.³ Briefly, the ECGs were scanned by a Logitech optical scanner, and the images stored in GIF format (graphic image file). Measurements were made off-line by two observers using a zoom technique such that the line width of the ECG on the computer was 2-3 mm, thus permitting precise delineation of the junction of PR segment and Q wave and the junction of S and ST segments.

The measurements were made at peak exercise on lead V₅ (which usually most clearly delineates the onset and termination of the QRS complex), using an averaged complex of 20 beats as produced by the Quinton 5000.

Figure 1. Measurement of QRS duration interval.

The following formula was used: $D = T (x_r - x_l) / (X_r - X_l)$ where $D = \text{QRS duration}$, T is a factor depending on the ECG paper speed and the reference segment length, X_r and X_l are the x-coordinates of the points defining the reference line segment, and x_r and x_l are the x-coordinates of the initial and endpoints of the QRS complex. The corresponding Y_r , Y_l , y_r , and y_l (Fig. 1) denote the y-coordinates of these points, but their values are not significant for correction purposes. This formula corrects possible linear and angular errors (α) introduced by the optical scanning process.¹⁵

All tests were reviewed by two of the investigators (S.E., A.C.) who were blinded to patient characteristics.

Statistical Analysis

The data were analyzed with the SPSS statistical software. Continuous data were expressed as mean $\pm$ SD. Categorical data were expressed as frequencies and percentages. Pearson's χ^2 test was used to compare categorical data, and one-way ANOVA was used for comparison of continuous data. Groups defined by diagnostic test criteria were compared using survival method analysis with the Wilcoxon (Gehan) log rank test, and Kaplan-Meier curves were plotted. The association between the diagnostic test criteria and coronary events was analyzed by use of the Cox propor-

tional hazards regression model. Multivariate Cox modeling statistical analysis was performed to determine the independent association between the diagnostic criteria and other baseline covariates. The following covariates were used in the modeling process: age, sex, cigarette smoking, diabetes mellitus, hyperlipidemia, hypertension, history of CABG, the number of coronary arteries with significant stenosis, stent use, and postprocedural stenosis diameter. Hazard rate ratios (relative risk) were calculated as the antilogarithm of the coefficient of the Cox proportional hazards regression of the outcome event with all covariates entered into the model. The relative risk is reported with 95% confidence intervals. A P value of <0.05 was considered statistically significant.

RESULTS

Baseline patient characteristics are shown in Table 1. All 206 patients had significant coronary artery disease defined as obstruction of more than 70% of at least one artery. One hundred and eight patients (52%) had single-vessel disease, 68 (33%) had two-vessel disease, and 30 patients (15%) had three-vessel disease. The PTCA was related to MI in 87 patients (42%): 14 patients (7%) underwent rescue PTCA, 20 (10%) underwent primary PTCA, and 53 (26%) underwent PTCA after post-MI risk stratification.

ET was performed at a mean of 34 ± 14 days after the PTCA. Table 2 shows that the mean ET time duration was 6.94 ± 2.8 minutes, the mean maximal heart rate was 134 ± 21 beats per minute, and the mean percentage of the maximal predicted heart rate (according to age) was 82.8 ± 10 . There were no significant statistical differences among the ET parameters and time duration from the performance of the PTCA to the performance of ET among the various groups. Figure 2 shows a histogram depicting changes in QRS duration in our study cohort. The mean QRS duration change was 10.7 ± 17.6 (ms); 124 patients (60.2%) had a QRS duration prolongation of more than 3 ms.

Table 3 reveals coronary events that occurred during the follow-up period (23 ± 9 months) by study groups. In the entire study group of 206 patients, 52 (25%) experienced at least one coronary event. Of these 52 patients, 44 (85%) were from the Q1 group (35% of the Q1 group), as compared to eight (15%) from group Q2 (10% of the Q2 group) ($P < 0.0002$). Of the same 52 patients with at least

Table 1. Baseline Patient Characteristics (Mean $\pm$ SD or Percentage)

	All (n = 206)	Q1 ^a (n = 124)	Q2 ^a (n = 82)	S1 ^a (n = 30)	S2 ^a (n = 176)
Age (years)	58 $\pm$ 11	58 $\pm$ 11	57 $\pm$ 11	58 $\pm$ 11	57 $\pm$ 11
Male gender	82%	83%	80%	93%	78%
Diabetes mellitus	22%	19%	27%	23%	22%
Hyperlipidemia	48%	52%	43%	47%	47%
Smoking history	44%	44%	44%	40%	40%
Hypertension	40%	40%	40%	43%	43%
Diseased vessels					
1	52%	54%	50%	55%	55%
2	33%	31%	37%	32%	32%
3	15%	16%	13%	14%	13%
PTCA indication					
MI (rescue)	7%	7%	6%	8%	0%
MI (primary)	10%	11%	9%	10%	10%
Post-MI assessment	26%	24%	28%	27%	17%
Angina pectoris	57%	58%	57%	55%	73%
Follow-up (months)	23 $\pm$ 9	24 $\pm$ 9	22 $\pm$ 8	23 $\pm$ 8	23 $\pm$ 8

^a Q1 = QRS ischemic response; Q2 = QRS normal response; S1 = ST-T ischemic response; S2 = ST-T normal response. MI = myocardial infarction; PTCA = percutaneous transluminal coronary angioplasty.

one coronary event, eight (15%) were from the S1 group (27% of the S1 group) and 44 (85%) from the S2 group (25% of the S2 group) ($P < 0.641$).

Restenosis was found in 31 of the 206 study patients (15%). Of these, 25 (81%) were from the Q1 group (20% of the Q1 group), and six (19%) were from the Q2 group (7% of the Q2 group) ($P < 0.014$); 7 (23%) were from the S1 group (23% of the S1 group), and 24 (77%) from the S2 group (14% of the S2 group) ($P < 0.09$).

Ten patients from the entire study group underwent CABG (5%). Of these, nine were from the Q1 group (7% of the Q1 group) and one from the Q2 group ($P < 0.055$), whereas one was from the S1 group (3% of the S1 group) and nine were from the S2 group (5% of the S2 group) ($P < 0.752$).

From the entire study group, eight patients (4%) had MI during follow-up. Of these, seven (88%) were in the Q1 group (6% of the Q1 group) and one from the Q2 group (1% of the Q2 group) ($P < 0.236$), whereas one was from the S1 group (3% of the S1 group) and seven were from the S2 group (4% of the S2 group) ($P < 0.441$). During the follow-up period, two of the 206 patients died (1%), one was from the Q1 group and the other from the Q2 group; one from the S1 group and the other from the S2 group.

The cumulative survival during follow-up with no coronary event was 75%. The Kaplan-Meier curves in Figures 3 and 4 show this differentially for the various study groups. The relative risk when comparing groups Q1 and Q2 for restenosis was

Table 2. ET Parameters (Mean $\pm$ SD or Percentage)

	All (n = 206)	Q1 ^a (n = 124)	Q2 ^a (n = 82)	S1 ^a (n = 30)	S2 ^a (n = 176)
ET duration	6.94 $\pm$ 2.8	6.95 $\pm$ 2.8	6.92 $\pm$ 2.8	6.9 $\pm$ 2.4	6.95 $\pm$ 2.9
Maximal heart rate	134 $\pm$ 22	134.1 $\pm$ 21	134.6 $\pm$ 22	135.3 $\pm$ 16	134.1 $\pm$ 23
Maximal heart rate (% of predicted, mean $\pm$ SD)	82.8 $\pm$ 11	82.9 $\pm$ 11	82.5 $\pm$ 10	84.1 $\pm$ 9	82.9 $\pm$ 11
Chest pain during ET	8%	7%	6%	20%	7%

^a Q1 = QRS ischemic response; Q2 = QRS normal response; S1 = ST-T ischemic response; S2 = ST-T normal response.

Figure 2. Histogram depicting QRS duration changes in the entire study population.

2.9 (CI 1.6–5.2); for CABG 5.9(CI 1.3–14.7); for MI 4.1 (CI 2.2–9.1); and for at least one of the four events was 4.0 (CI 2.1–9.9). Relative risk when comparing groups S1 and S2 for restenosis was 1.9 (CI 0.8–4.9); for CABG 0.7 (CI 0.3–2.4); for MI 0.8 (CI 0.3–2.3); and for at least one of the four events was 1.1 (CI 0.8–2.9) (Fig. 5). The sensitivity of the test for prediction of future coronary events was 52% and 85% and the specificity was 98% and 48% for the ST-T and the QRS criteria, respectively (Fig. 6). When the QRS and ST-T parameters were combined the following results were obtained: for 23 patients with ischemic QRS and ST-T changes the specificity was 98% and the sensitivity was 51%; for 131 patients with at least one ischemic parameter (ischemic QRS or ischemic ST-T changes) or both, the specificity was 47% and the sensitivity was 96% (Fig. 6).

Figure 3. Percent of patients with no cardiac event (restenosis, CABG, and MI) during follow-up in the QRS duration groups. The dotted lines represent patients with ischemic QRS response. The solid line represents patients with nonischemic QRS response.

DISCUSSION

The normal QRS duration response to exercise is either no change or slight shortening.^{16,17} The exact mechanism for this response remains unclear, as does the mechanism of the exercise-induced lengthening of the QRS duration in subjects with IHD. In experimental animal models, varying effects of coronary artery ligation on the transmembrane action potential have been described with an initial slight lengthening followed by a subsequent shortening mainly due to shortening of the plateau phase.^{18,19} There is a parallel decrease in resting membrane potential, action potential magnitude, and upstroke velocity. Postulated reasons for these changes are ischemia-induced increased outward potassium currents with increased extracellular potassium concentration, as well as increased inward sodium and calcium currents

Table 3. Coronary Events During Follow-up, by Study Groups (n (%))

	All (n = 206)	Q1 ^a (n = 124)	Q2 ^a (n = 82)	P	S1 ^a (n = 30)	S2 ^a (n = 176)	P
CE	52 (25)	44 (35)	8 (10)	0.0002	8 (27)	44 (25)	0.641
Restenosis	31 (15)	25 (20)	6 (7)	0.014	7 (23)	24 (14)	0.09
CABG	10 (5)	9 (7)	1 (1)	0.055	1 (3)	9 (5)	0.752
MI	8 (4)	7 (6)	1 (1)	0.236	1 (3)	7 (4)	0.441
Mortality	2 (1)	1 (0.8)	1 (1)		1 (3)	1 (0.6)	

Q1 = QRS ischemic response; Q2 = QRS normal response; S1 = ST-T ischemic response; S2 = ST-T normal response. CABG = coronary artery bypass graft; CE = Coronary Event (Restenosis, MI or CABG); MI = myocardial infarction.

Figure 4. Percent of patients with no cardiac event (restenosis, CABG, and MI) during follow-up in the ST-T criteria groups. The dotted lines represent patients with ischemic ST-T response. The solid line represents patients with nonischemic ST-T response.

and the concomitant increase in the intracellular sodium and calcium concentrations.¹⁹

More recently, several investigators have studied electrophysiological phenomena in the human ischemia model during PTCA. Wagner et al.,²⁰ who studied PTCA of the left anterior descending artery, found conduction disturbances in several patients and used the term "periischemic block." This study was more concerned with changes in QRS vector direction than QRS duration. Spekhorst et al.²¹ used body surface potential mapping to demonstrate changes in voltage amplitude and temporal information, which were thought to be due to conduction slowing in the ischemic area.

Our group³⁻⁶ studied rest and exercise QRS duration in patients with ischemic heart disease using a computerized optic scanner and found significant differences between these patients and normal controls. Those with ischemic heart disease had significant QRS prolongation with exercise, whereas normal controls had either no change or shortening of

Figure 5. Relative risk for coronary events relative to an ischemic QRS or ischemic ST-T response. MI = myocardial infarction, CABG = coronary artery bypass grafting, CE = coronary event (restenosis, MI or CABG).

Figure 6. Predictive value of the test. Sensitivity and specificity using the ischemic criteria for ST-T changes, QRS changes, or combination of the two criteria: Patients with both ischemic responses and patients with at least one ischemic response.

this interval. Using this technique, it was shown that in a population of young, old, ischemic, and control patients of both sexes, the diagnostic value of the test was improved in a group of 165 subjects. Similar results were obtained using assessment of exercise QRS prolongation as a means to detect ischemia in a group of post-MI patients. Furthermore, this method was found more effective than classical ST-T changes for the detection of ischemia in a group of 101 women, in whom the standard ST-T exercise stress test has a high false-positive rate. In those studies, QRS prolongation was compared with the results of thallium stress testing and cardiac catheterization, which served as the "gold standard." Similar results were found when QRS width changes were recorded before, during, and after the first inflation in a group of patients who underwent PTCA. QRS prolongation was a marker for ischemia in most patients during PTCA, and ischemic QRS was found to be more sensitive than chest pain or ST-T changes. QRS duration was more prolonged with occlusion of the proximal or middle segments of major arteries. The criterion for diagnosis of ischemia in all these studies was QRS prolongation of more than 3 ms compared with QRS duration at rest.

In the present study, exercise testing performed after PTCA was found to be useful in the assessment of the functional result, and served as a point of reference for future examinations. However, a single ET performed 1 month after the PTCA using the classical standard ST-T criteria could not be used as a prognostic parameter, nor did it diagnose restenosis.⁷⁻¹⁴ Honan et al.¹⁰ have shown that chest pain and positive ET results following PTCA do not necessarily indicate restenosis. They found that ischemic ST-segment changes have a

sensitivity of only 24% with a specificity of 88% in predicting restenosis. Several studies have examined the value of stress tests using exercise-dipyridamole echocardiography or nuclear imaging after PTCA and found that the positive predictive value of stress thallium-201 myocardial perfusion scintigraphy for predicting restenosis is 53% to 82% with a negative predictive value of 75% to 95%,^{13,22,23} whereas the positive predictive value of stress-induced wall motion abnormalities is 69% to 80% with a negative predictive value of 76%.^{8,12,13} These tests are more expensive and less readily available than standard treadmill exercise testing. Our study population represents a select group of post-PTCA patients. Patients with limiting factors such as peripheral or cerebrovascular disease, orthopedic disease, severe valvular disease, or congestive heart failure were not evaluated by ET. Patients who could not reach the target heart rate were excluded from the study. Thus, our study patients have less diffuse atherosclerosis disease than the general population undergoing PTCA (52% of the patients had a single artery disease).

Our present study demonstrates that, in patients who underwent their first PTCA, ET using QRS duration criteria is a good marker for the prediction of future coronary events. There were significant differences ($P < 0.0002$) between QRS duration with ischemic response and nonischemic response in predicting at least one coronary event (Fig. 3), but no significant difference between ischemic ST-T changes versus normal ST-T responses in this regard (Fig. 4). There was also a statistically significant difference between ischemic and nonischemic QRS duration for restenosis, which was not seen in patients with ischemic or nonischemic ST-T changes. Patients with an ischemic QRS prolongation are at increased risk for future coronary events with a relative risk of 4.02 for having at least one event as opposed to the only mildly elevated relative risk of 1.13 for patients with an ischemic ST-T response (Fig. 5). ET ECG using the QRS is more sensitive than ST-T criteria in predicting future coronary events with a sensitivity of 85% compared to 52%, respectively (Fig. 6). To improve the diagnostic value of the test we analyzed the combination of QRS duration and ST-T changes. This new strategy did not improve the diagnostic value of the test. The low sensitivity and high specificity were similar to those obtained using the ST-T criteria alone. The combination of at least one ischemic criterion (patients with ischemic QRS or ischemic

ST-T) or both criteria improved the sensitivity of QRS criteria from 85% to 96%, but reduced the specificity from 52% to 47%.

Although the optimal timing for ETs to identify restenosis is 6 months after PTCA, scheduling the test as early as 1 month after PTCA provides an opportunity to detect patients at high risk for future coronary events. The high sensitivity of QRS criteria and the high specificity of ST-T criteria provide the physician with important information that can guide decisions relating to further evaluation and treatment of these patients.

In this study, the specificity of the test using the QRS criteria was only 48%. It has been previously reported that up to 59% of patients with restenosis are asymptomatic.²⁴⁻²⁸ Because only symptomatic patients had a second angiography, we may have missed instances of restenosis in asymptomatic patients. Another factor that may have contributed to this difference in findings may be post-PTCA endothelial dysfunction and stress-induced myocardial ischemia. It is possible that the coronary flow response to exercise may be temporarily blunted at the angioplasty site or in the distal artery,²⁹ explaining why 25-50% of patients undergoing stress-echocardiographic study or scintigraphic stress testing within 6 weeks of PTCA have an ischemic response and nonocclusive disease at angiography.¹³

CONCLUSION

ST-T criteria at exercise testing have a relatively low predictive value for risk of ischemia and cardiac events after PTCA. We compared QRS prolongation with ST-T criteria during ET, and found highly significant differences between these two measures. QRS prolongation was a much better predictor of post-PTCA patients at risk for future cardiac events.

This technique can be used as a prognostic tool, providing a new means to predict future cardiac events in this patient population. Computerized measurement of QRS duration is simple and inexpensive, and can easily be introduced into most ECG stress exercise laboratories. Further studies are warranted to establish the optimal risk stratification for post-PTCA patients.

REFERENCES

1. Kligfield P, Okin PM. Evolution of the exercise electrocardiogram. *Am J Cardiol* 1994;73:1209-1210.

2. Parrents E, Duard H, Couffinal T, et al. The exercise-recovery loop and exercise slope of ST-segment changes/heart rate in the diagnosis of coronary disease and restenosis after angioplasty. *Arch Mal Coeur Vaiss* 1994;87:1283-1288.
3. Cantor A, Goldfarb B, Aszodi A, et al. QRS prolongation measured by a new computerized method: A sensitive marker for detecting exercise-induced ischemia. *Cardiology* 1997;88:446-452.
4. Cantor A, Goldfarb B, Aszodi A, et al. Ischemia detection after myocardial infarction: Diagnostic value of exercise-induced QRS duration changes evaluated by a new computerized method. *J Electrocardiol* 1998;31:9-15.
5. Cantor A, Goldfarb B, Mai O, et al. Ischemia detection in women: The diagnostic value of exercise QRS duration changes. *J Electrocardiol* 1998;31:271-277.
6. Cantor A, Goldfarb B, Ilia R. QRS prolongation: A sensitive marker of ischemia during percutaneous transluminal coronary angioplasty. *Catheter Cardiovasc Interv* 2000;50:177-183.
7. Balady GJ, Leitschuh ML, Jacobs AK, et al. Safety and clinical use of exercise testing one to three days after percutaneous transluminal coronary angioplasty. *Am J Cardiol* 1992;69:1259-1264.
8. Dagianti A, Rosanio A, Penco M, et al. Clinical and prognostic usefulness of supine bicycle exercise echocardiography in the functional evaluation of patients undergoing elective percutaneous transluminal coronary angioplasty. *Circulation* 1997;95:1176-1184.
9. Deligonul U, Vandormael MG, Shah Y, et al. Prognostic value of early exercise stress testing after successful coronary angioplasty: Importance of the degree of revascularization. *Am Heart J* 1989;117:509-514.
10. Honan MB, Bengston JR, Pryor DB, et al. Exercise treadmill testing is a poor predictor of anatomic restenosis after angioplasty for acute myocardial infarction. *Circulation* 1989;80:1585-1594.
11. Picano E, Pirelli S, Marzilli M, et al. Usefulness of high-dose dipyridamole echocardiography test in coronary angioplasty. *Circulation* 1989;80:807-815.
12. Pirelli S, Massa D, Faletra F, et al. Exercise electrocardiography versus dipyridamole echocardiography testing in coronary angioplasty. Early functional evaluation and prediction of angina recurrence. *Circulation* 1991;83 Part 3:38-42.
13. Rosanio S, Tocchi M, Stouffer GA. Use of stress testing to evaluate patients with recurrent chest pain after percutaneous coronary revascularization. *Am J Med Sci* 1998;316:46-52.
14. Roth A, Miller HI, Keren G, et al. Detection of restenosis following percutaneous coronary angioplasty in single coronary artery disease. The value of clinical assessment and exercise tolerance testing. *Cardiology* 1994;84:106-113.
15. Biddle A. 2500 Math Formulae. Hamlyn, College Lane Publishers, 1985.
16. Simons ML, Hugenholtz PG. Gradual changes of ECG waveform during and after exercise in normal subjects. *Circulation* 1975;52:570.
17. Wolthuis RA, Froelicher VF, Hopkirk A, Fischer JR, Keiser N. Normal electrocardiogram wave form characteristics during treadmill exercise testing. *Circulation* 1979;60:1028-1035.
18. Janse MJ, Kleber AG. Electrophysiological changes and ventricular arrhythmias in the early phase of regional myocardial ischemia. *Circ Res* 1981;49:1069-1081.
19. Wilde AA, Aksnes G. Myocardial potassium loss and cell depolarization in ischaemia and hypoxia. *Cardiovasc Res* 1995;29:1-15.
20. Wagner NB, Sevilla DC, Krucoff MW, et al. Transient alterations of the QRS complex and ST segment during percutaneous transluminal balloon angioplasty of the left anterior descending coronary artery. *Am J Cardiol* 1988;62:1038-1042.
21. Spekhorst H, SippensGroenewegen A, David GK, et al. Body surface mapping during percutaneous transluminal coronary angioplasty. QRS changes indicating regional myocardial conduction delay. *Circulation* 1990;81:840-849.
22. Manyari DE, Knudtson M, Kloiber R, et al. Sequential thallium-201 myocardial perfusion studies after successful percutaneous transluminal coronary artery angioplasty: Delayed resolution of exercise-induced scintigraphic abnormalities. *Circulation* 1988;77:86-95.
23. Scholl JM, Chaitman BR, David PR, et al. Exercise electrocardiography and myocardial scintigraphy in the serial evaluation of the results of percutaneous transluminal coronary angioplasty. *Circulation* 1982;66:380-390.
24. Hecht HS, Shaw RE, Chin HL, et al. Silent ischemia after coronary angioplasty: Evaluation of restenosis and extent of ischemia in asymptomatic patients by tomographic thallium-201 exercise imaging and comparison with symptomatic patients. *J Am Coll Cardiol* 1991;17:670-677.
25. Holmes DR Jr, Vlietstra RE, Smith HC, et al. Restenosis after percutaneous transluminal coronary angioplasty (PTCA): A report from the PTCA registry of the National Heart, Lung, and Blood Institute. *Am J Cardiol* 1984;53:76C-81C.
26. King SB III, Schlumpp M. Ten-year complete follow-up of percutaneous transluminal angioplasty: The early Zurich experience. *J Am Coll Cardiol* 1993;22:353-360.
27. Mata LA, Bosch X, David PR, et al. Clinical and angiographic assessment six months after double vessel percutaneous coronary angioplasty. *J Am Coll Cardiol* 1985;6:1239-1244.
28. Nobuyoshi M, Kimura T, Nosaka H, et al. Restenosis after successful percutaneous transluminal coronary angioplasty: Serial angiographic follow-up of 229 patients. *J Am Coll Cardiol* 1988;12:616-623.
29. el Tamimi H, Davies GJ, Sritara P, et al. Inappropriate constriction of small coronary vessels as a possible cause of a positive exercise test early after successful coronary angioplasty. *Circulation* 1991;84:2307-2312.