Changes in High-Frequency QRS Components Are More Sensitive than ST-Segment Deviation for Detecting Acute Coronary Artery Occlusion

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OBJECTIVES
This study describes changes in high-frequency QRS components (HF-QRS) during percutaneous transluminal coronary angioplasty (PTCA) and compares the ability of these changes in HF-QRS and ST-segment deviation in the standard 12-lead electrocardiogram (ECG) to detect acute coronary artery occlusion.

BACKGROUND
Previous studies have shown decreased HF-QRS in the frequency range of 150–250 Hz during acute myocardial ischemia. It would be important to know whether the high-frequency analysis could add information to that available from the ST segments in the standard ECG.

METHODS
The study population consisted of 52 patients undergoing prolonged balloon occlusion during PTCA. Signal-averaged electrocardiograms (SAECG) were recorded prior to and during the balloon inflation. The HF-QRS were determined within a bandwidth of 150–250 Hz in the preinflation and inflation SAECGs. The ST-segment deviation during inflation was determined in the standard frequency range.

RESULTS
The sensitivity for detecting acute coronary artery occlusion was 88% using the high-frequency method. In 71% of the patients there was ST elevation during inflation. If both ST elevation and depression were considered, the sensitivity was 79%. The sensitivity was significantly higher using the high-frequency method, p < 0.002, compared with the assessment of ST elevation.

CONCLUSIONS
Acute coronary artery occlusion is detected with higher sensitivity using high-frequency QRS analysis compared with conventional assessment of ST segments. This result suggests that analysis of HF-QRS could provide an adjunctive tool with high sensitivity for detecting acute myocardial ischemia. (J Am Coll Cardiol 2000;36:1827–34) © 2000 by the American College of Cardiology

Clinical decisions for patients with suspected or known ischemic heart disease are commonly based on assessment of the standard 12-lead electrocardiogram (ECG). When a patient presents with acute symptoms or undergoes monitoring in coronary care units, assessment of ST-segments using the standard ECG is the only immediately available indicator of myocardial ischemia. During thrombolytic therapy for acute myocardial infarction, resolution of ST-segment elevation is one of the most useful methods for assessing reperfusion. However, it is well known that both the sensitivity and specificity of the standard ECG are limited in these situations (1,2).

Previous studies have shown changes also in the QRS complex during acute myocardial ischemia, both in standard (3–5) and high-frequency recordings (6–12). Decreased amplitudes of the QRS complex, in the frequency range of 150–250 Hz, have been demonstrated during acute ischemia produced by percutaneous transluminal coronary angioplasty (PTCA) (6,9). The correlation between the amount of change in the high-frequency QRS components (HF-QRS), using bipolar X, Y and Z leads, and the amount of ST-segment deviation in the standard 12-lead ECG was weak. There was no evident relationship between the lead with the maximal decrease in HF-QRS and the site of coronary occlusion (6).

It would be of interest to perform high-frequency analysis of all 12 standard leads to further investigate whether HF-QRS could add information to that available from the ST-segments and so serve as an adjunctive diagnostic tool in the clinical situation. The purposes of the present study in patients with prolonged balloon occlusion of one of the major coronary arteries are to: 1) quantify the changes in HF-QRS and standard ECG ST-segment deviation; 2) investigate the relationship between the changes in HF-QRS and standard ECG ST-segment during occlusion of the different coronary arteries; and 3) compare the abilities of high-frequency QRS analysis and ST-segment deviation in the standard ECG to detect acute coronary artery occlusion.

METHODS
Study population. Patients subjected to elective prolonged balloon occlusion during PTCA, using nonperfusion balloon catheters, at the Charleston Area Medical Center,
Abbreviations and Acronyms

ECG = electrocardiogram
HF-QRS = high-frequency QRS components
LAD = left anterior descending coronary artery
LCX = left circumflex coronary artery
PTCA = percutaneous transluminal coronary angioplasty
RCA = right coronary artery
RMS = root-mean-square
SAECG = signal-averaged electrocardiogram

WV, were considered for the present study, which was approved by the Investigational Review Board. Informed consent was obtained from each subject. A data form indicating the anatomic site and the exact times of inflation and deflation of the balloon was completed. If a patient received more than one balloon inflation during the same procedure, only the first inflation was considered.

The 54 patients considered from the database for the present study were those with a QRS duration <120 ms (on a control standard ECG recorded prior to the procedure) and without previous myocardial infarction, indicated by the ECG QRS scoring system of Selvester et al. (13) and its myocardial infarction screening subset (14). No myocardial infarction was defined as none of the three screening criteria.

Two patients were later excluded because of incomplete ECG analysis. Thus, a total of 52 patients were finally included, 23 women and 29 men, ages 32 to 78 years (mean 60 ± 12 years). The locations of the 52 dilatations were left main coronary artery (1 patient), left anterior descending coronary artery (LAD) (17 patients), left circumflex coronary artery (LCX) (11 patients) and right coronary artery (RCA) (23 patients).

ECG acquisition. The ECGs were recorded with equipment by Siemens-Elema AB (Solna, Sweden). Standard electrode placements were used for the precordial leads. To reduce noise from skeletal muscle, the limb leads were obtained using the Mason–Likar electrode configuration (15). The signals were digitized at a sampling rate of 1,000 Hz with an amplitude resolution of 0.6 µV and were stored on a PC hard disk for further analysis.

A preinflation ECG recording was continuously acquired at rest in the supine position for 5 min in the catheterization laboratory, prior to any catheter insertion. The inflation ECG recording was started approximately 1 min before the balloon inflation and then continued during the inflation period and for approximately 4 min after deflation. The inflation period was extracted from the recording and subjected to further signal processing.

Signal averaging. Because a low noise level is essential when analyzing the low-amplitude high-frequency signal, the recordings were signal averaged. The analysis included beat alignment in which each beat was cross-correlated to a template beat (the template beat was selected as the predominant beat morphology). The beat was shifted in relation to the template beat until the highest cross-correlation value was found. Beats with a correlation below 0.97 were excluded from averaging.

Averaging was done with different techniques depending on the type of recording. During balloon inflation, the ECG morphology is often subject to considerable changes. Accordingly, conventional blockwise averaging is not suitable and an exponentially updated beat average was used (16). This procedure tracked morphologic changes during the inflation while still providing sufficient noise reduction. The inflation recording often contained brief excessive noise periods caused by, e.g., fluoroscopic imaging and cine runs. The weight defining the exponential update was therefore made noise-dependent, i.e., a slower update was used during noise bursts. The signal averaging was discontinued when the cross-correlation with the template beat consistently dropped below 0.97. The signal-averaged ECG (SAECG) corresponding to the last accepted beat before balloon deflation was selected for further analysis.

In 49 of the 54 patients considered for the study the signal averaging could be continued until balloon deflation (an SAECG was obtained within the last 4 s of balloon inflation). In these patients, the times of the continuous inflation ranged from 1 min 9 s to 7 min 17 s (mean 4 min 32 s ± 1 min 15 s). In five patients the signal averaging was discontinued before balloon deflation. In two of these, the cross-correlation dropped below 0.97 before 30 s of inflation. These two patients were excluded from further analysis. The remaining three patients were included in the study. The time from balloon inflation to the termination of signal averaging in these three patients ranged from 2 min 0 s to 4 min 26 s (mean 3 min 7 s ± 1 min 14 s).

The 5-min preinflation recording was processed by conventional blockwise averaging technique. Trend samples of each patient’s SAECG were obtained every 15 s during the recording. A total of 20 trend samples were thus obtained from each recording (the first sample representing 15 s of averaging, the second 30 s of averaging, etc). In each of the 12 leads, the trend sample with the noise level closest to that obtained in the SAECG from the inflation period was selected for further analysis. This approach was adopted to minimize the influence of different noise levels when comparing the inflation and preinflation recordings (Fig. 1).

Standard ECG analysis. The selected SAECGs from the preinflation and inflation recordings were analyzed in the standard frequency range. The QRS onset and offset were automatically determined. This QRS duration was later used for the high-frequency analysis (Fig. 2) (17). The ST-segment level above or below the PR segment baseline at 60 ms after the J point was automatically measured in each lead. The ST deviation during inflation was determined with the preinflation SAECG as baseline.
Two sets of ST-segment criteria were used for the diagnosis of acute coronary artery occlusion:

1) “ST-elevation criteria”: ST-segment elevation from preinflation baseline of $0.1 \text{ mV}$ in at least one of the 12 leads or, in the LCX occlusions, the maximal ST depression in V2 or V3 of $0.1 \text{ mV}$. The latter part of these criteria was based on the observation that LCX occlusion in many patients produces ST depression only, mainly in V2 or V3 (2).

2) “ST-elevation/depression criteria”: ST elevation or depression from preinflation baseline of $0.1 \text{ mV}$ in at least one of the 12 leads.

High-frequency QRS analysis. The HF-QRS were extracted from the selected preinflation and inflation SAECGs using a Butterworth filter with a bandwidth of 150–250 Hz. The HF-QRS during the entire QRS duration, determined as explained above (Fig. 2) (17), were expressed as root-mean-square (RMS) values. The RMS value, reflecting the average amplitude of the signal, was calculated by squaring the amplitude of each sample, determining the mean of these squares and determining the square root of this mean.

In each lead, the change in RMS values from preinflation to inflation recording was calculated. The criteria used for a significant change in RMS value were those previously described by Aversano et al. (18): absolute change in RMS value $>0.6 \mu \text{V}$ or relative change $>20\%$. These criteria were developed by assessing repeated RMS values in 32 control subjects: 17 normal volunteers and 15 patients with a variety of chronic cardiac syndromes. The mean standard deviation was determined to $0.3 \mu \text{V}$ and the coefficient of variation to $10\%$. These results were used to develop 95% confidence limits and a significant change was defined as $>0.6 \mu \text{V}$ or $>20\%$.

Noise-level analysis. The noise level, expressed as an RMS value during 100 ms, starting 100 ms after QRS offset, was calculated in each lead. Leads were excluded from further analysis if the noise level was $0.75 \mu \text{V}$ or more or if it was impossible to attain similar noise levels (within $0.35 \mu \text{V}$) in the preinflation and inflation recordings.

Because of excessive noise in the SAECG from the inflation recording, 50 leads in 14 patients were excluded from the study. Among these 14 patients, the mean of the number of excluded leads was $3.6 \pm 2.6$, range $1–9$ leads. Exclusion due to high noise level was most frequent in the limb leads (37 leads). No leads were excluded from the ST-segment analysis in the standard frequency range. In all patients, all 12 leads were used for comparison with the HF-QRS.

Statistical methods. Data are presented as the mean $\pm$ 1 standard deviation unless otherwise specified. Comparisons of sensitivities between HF-QRS analysis and ST-segment deviation for the detection of acute coronary artery occlusion were performed with McNemar analysis. The correlation between decrease in HF-QRS and ST-segment elevation during inflation was calculated using the Spearman rank correlation coefficient ($r$). Statistical significance was defined as $p < 0.05$.
RESULTS

Comparative sensitivities for detecting acute coronary artery occlusion (Table 1, Fig. 3). During inflation the HF-QRS decreased significantly (>0.6 μV or >20%) in at least one lead in 46 of the 52 patients, corresponding to a sensitivity of 88%. The mean of the maximal absolute decrease in HF-QRS among these patients was 1.9 ± 1.2 μV, range 0.33 to 6.40 μV. Forty-four patients met both the absolute and relative criteria; two patients met the relative criterion only.

In 37 of the 52 patients there was ST-segment deviation during inflation meeting the ST-elevation criteria, corresponding to a sensitivity of 71%. In all of these 37 patients there was a decreased HF-QRS. This sensitivity was significantly lower than the 88% achieved using the high-frequency method (p < 0.002). When the individual coronary arteries were considered, the sensitivities were highest in the LAD group, both for ST elevation (94%) and for high-frequency QRS analysis (100%). The difference between the two methods was largest in the RCA group, where the ST-elevation criteria achieved a sensitivity of 61% versus 87% for the high-frequency method. Using the ST-elevation/depression criteria, the sensitivity was still higher using the high-frequency method, 88% (46/52) versus 79% (41/52). This difference was nonsignificant (p = 0.090).

In seven of the patients the HF-QRS criteria but none of the ST-segment criteria were met. All of these seven patients had chest pain during inflation. Of the two patients only meeting the ST-elevation/depression criteria, one had chest pain during the procedure.

Detailed analysis of HF-QRS. All 37 patients with high-frequency QRS data from all 12 leads in the LAD (n = 17), LCX (n = 11) and RCA (n = 23) groups were included in the more detailed analysis of the direction and magnitude of changes in HF-QRS during coronary artery occlusion.

The HF-QRS decreased significantly (>0.6 μV or >20%) in at least one lead in 32 of the 37 patients (Table 2A). The mean of the maximal decrease among these patients was 1.86 ± 1.10 μV. The mean of the number of leads showing decreased HF-QRS was 5.4 ± 3.0 leads. The largest decreases in HF-QRS were in general seen in the LAD group, both regarding the number of leads (Fig. 4) and the maximal amount of decrease.

In 24 of the 37 patients there were significantly increased HF-QRS (>0.6 μV or >20%) in one or more leads during inflation (Table 2B). Increased HF-QRS were seen in four of the five patients with no decrease in HF-QRS. The mean of the maximal increase in HF-QRS among the 24 patients was 5.4 ± 3.0 leads. The largest increases in HF-QRS were in general seen in only a few of the leads, mean 2.5 ± 1.6 leads. The largest increases in HF-QRS were seen in the LCX group, the smallest in the LAD group (Fig. 4). The increases in HF-QRS in the LCX group were most frequent in the anterior leads.

Comparison of standard and high-frequency ECG. The correlation for all 37 patients between the largest decrease in HF-QRS (in μV) in any lead and the maximal ST-segment elevation in any lead during inflation was r = −0.50, p = 0.002 (Fig. 5). In eight of the patients there were signifi-

Table 1. Sensitivity for Detection of Acute Coronary Artery Occlusion Using ST-Segment Deviation and High-Frequency QRS Components

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Sensitivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Patients</td>
<td></td>
</tr>
<tr>
<td>LAD (n = 17)</td>
<td>71</td>
</tr>
<tr>
<td>LCX (n = 11)</td>
<td>94</td>
</tr>
<tr>
<td>RCA (n = 23)</td>
<td>64</td>
</tr>
<tr>
<td>ST elevation</td>
<td>44</td>
</tr>
<tr>
<td>ST elevation/depression</td>
<td>78</td>
</tr>
<tr>
<td>High-frequency QRS components</td>
<td>88</td>
</tr>
</tbody>
</table>

LAD = left anterior descending coronary artery; LCX = left circumflex coronary artery; RCA = right coronary artery.

Figure 3. The percentage of patients (n = 52) meeting the HF-QRS criteria and ST-elevation criteria (panel A) and HF-QRS criteria and ST-elevation/depression criteria (panel B). The numbers outside the circles represent the percentage of patients not meeting any of the criteria. HF-QRS = high-frequency QRS components.
cantly decreased HF-QRS (>0.6 μV) but no significant ST elevation (<0.1 mV). There was no patient with ST elevation without a decrease in HF-QRS.

In the LAD group, most of the patients (7/9) showed both the maximal decrease in HF-QRS and the maximal ST elevation in leads V2-V4 (Fig. 6). This result was different from the LCX and RCA groups. In the RCA group, the maximal decrease in HF-QRS was distributed among eight leads, while the maximal ST-elevation was seen in lead III in 11 of the 13 patients with ST-elevation. Few patients in the LCX group had ST-segment elevation, and the maximal decrease in HF-QRS was distributed among four leads. Trends of ST-segment deviation and HF-QRS during an LCX occlusion are shown in Figure 7.

DISCUSSION

The main finding of the present study is that acute coronary artery occlusion is detected with significantly higher sensitivity using high-frequency QRS analysis compared with conventional assessment of ST-segment deviations in the standard 12-lead ECG. This result emphasizes the importance of further investigating the possibility of using high-frequency analysis as an adjunctive diagnostic tool in clinical situations.

Both for high-frequency QRS and ST-segment analysis, the sensitivity was high in the LAD group. It is well known that occlusion of the LCX is difficult to diagnose using the standard 12-lead ECG (2). Even if the sensitivity for high-frequency analysis was lower in the LCX group compared with the LAD and RCA groups, it was considerably higher than for the ST-segment analysis.

The ST-segment criteria for acute coronary occlusion used in the present study were less strict than those typically used in many clinical situations. When a patient presents with acute symptoms only ST elevation on the standard ECG is clinically considered to be indicative of coronary artery occlusion. Patients are considered not to require thrombolytic therapy if only ST depression is present (19). However, it has been shown that transmural ischemia in the posterior wall of the left ventricle often results in ST depression only (2). This was the rationale for considering ST depression in some leads as equivalent to ST elevation and therefore included in the ST-elevation criteria.

Intra- and interindividual variation in HF-QRS. Because it is documented that there is a temporal intraindividual variation in HF-QRS even at rest, the determination of a threshold for a change beyond this normal variation is essential. In a study using X, Y and Z leads, a significant change beyond the normal variation has been determined to be >0.6 μV or >20% (18). If the optimum criteria would be different using the 12 standard leads, this would affect the results in the present study. In a recently completed study, the intraindividual temporal variation in HF-QRS in the 12 standard leads was investigated at rest in patients with coronary artery disease, using the identical equipment and signal processing as in the present study (20). The temporal variation between two consecutive recordings was below 0.5 μV in all 12 standard leads and the mean absolute difference in all leads between the recordings was 0.10 ± 0.09 μV. Thus, most of the changes observed during coronary artery occlusion in the present study were well beyond those explained by normal intraindividual temporal variation.

It has been shown that there is a large interindvidual variation in HF-QRS (6). One component of the high-frequency criteria was therefore defined as a percentage decrease in HF-QRS. The use of percentage change is dubious if the amplitudes are low. In these cases, a small absolute change in HF-QRS results in a high percentage value. However, only 2 of 46 patients in the present study

Table 2. Significant Changes in High-Frequency QRS Components (>0.60 μV or >20%) During Inflation in Patients With High-Frequency Data From All 12 Leads in the LAD, LCX, and RCA Groups

<table>
<thead>
<tr>
<th></th>
<th>Maximal Significant Decrease in RMS Value in Any Lead (μV)</th>
<th>Number of Leads Showing a Significantly Decreased RMS Value</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>LAD</td>
<td>9/9</td>
<td>−2.67 ± 1.43</td>
</tr>
<tr>
<td>LCX</td>
<td>5/8</td>
<td>−1.64 ± 0.90</td>
</tr>
<tr>
<td>RCA</td>
<td>18/20</td>
<td>−1.53 ± 0.76</td>
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<table>
<thead>
<tr>
<th></th>
<th>Maximal Significant Increase in RMS Value in Any Lead (μV)</th>
<th>Number of Leads Showing a Significantly Increased RMS Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>LAD</td>
<td>4/9</td>
<td>0.58 ± 0.14</td>
</tr>
<tr>
<td>LCX</td>
<td>6/8</td>
<td>1.26 ± 0.61</td>
</tr>
<tr>
<td>RCA</td>
<td>14/20</td>
<td>0.94 ± 0.34</td>
</tr>
</tbody>
</table>

LAD = left anterior descending coronary artery; LCX = left circumflex coronary artery; RCA = right coronary artery; RMS = root-mean-square.
were considered to have a decreased HF-QRS solely based on the percentage criterion.

Changes in HF-QRS during inflation. The pathophysiologic events underlying the changes in HF-QRS are incompletely understood; more basic physiologic studies have to be performed to acquire a better understanding of the observed changes. One possible explanation given for the previously reported decrease in HF-QRS during acute ischemia is slowing of conduction velocity in the region of ischemia (21). The decreases in HF-QRS were most prominent in the LAD group, both regarding the magnitude of decrease and the number of leads with a decrease. One explanation for these results could be that because the LAD supplies a larger area of myocardium, its occlusion therefore would result in more ischemia and slow conduction within a larger area of myocardium than occlusion of the other coronary arteries.

In some patients the HF-QRS increased in some leads during inflation. The reason for these findings is unclear. An increase in HF-QRS was rare in the LAD group but common in the LCX group. The increases in HF-QRS were seen in the anterior leads in many of the LCX occlusions. The anterior wall of the left ventricle would not be expected to be ischemic during an LCX occlusion and it is anatomically opposite the posterior wall usually supplied by the LCX. One explanation for the increased HF-QRS during inflation could be enhanced electrical activity and conduction velocity in the non-ischemic myocardium in association with the already known hyperdynamic compensatory wall motion (22). Enhanced conduction velocity has also been suggested as a possible explanation for the increased HF-QRS previously observed during and immediately after exercise in healthy individuals (23).

The precordial leads showed a lead specific reduction of the HF-QRS during LAD occlusions. These leads might also show a lead-specific increase in HF-QRS during LCX occlusions if the increase is due to enhanced conduction
However, after the patients were subdivided on the basis of the artery occluded, each group contained a small number of patients. It is therefore difficult to reach definite conclusions about the changes in HF-QRS during occlusion of different coronary arteries.

Comparison with ST-segment elevation. In all of the LAD inflations, the maximal ST elevation was seen in the leads V2–V4. The maximal decrease in HF-QRS was seen in these leads in seven of the nine patients. In the LCX and RCA groups there was no evident relationship between the leads showing ST elevation and decrease in HF-QRS. One possible explanation for this finding is that the precordial leads are close to the anterior wall of the heart and therefore these leads show a lead-specific reduction of the HF-QRS.

It is well known that the leads with ST-segment elevation locate the area of ischemia (24). The results in this study suggest that the capability of high-frequency analysis to indicate the location of the ischemia is in general not as good as ST-elevation analysis.

There was a significant relationship between the decrease in HF-QRS and the amount of ST-segment elevation. It is well known that the magnitude of ST-segment elevation is proportional to the severity of ischemia (25). The ability of the high-frequency analysis to provide additional information needs to be further analyzed using nonelectrocardiographic methods, e.g., myocardial scintigraphy, as the gold standard.

Possible sources of error in the high-frequency analysis. Analysis of HF-QRS requires a low noise level and signal averaging is therefore necessary. This reduces the possibility to detect sudden changes in HF-QRS. Also, when there are major changes in ECG morphology, the correlation using the actual template beat decreases and further averaging is not possible. To reduce these sources of error in the present study, recursive signal-averaging technique was used during the inflation. Using this technique, the averaging had to be discontinued before the end of inflation in only five of the patients.

In general, the signal quality was good in the analyzed patients. The limit for exclusion due to high noise level could therefore be set to a low value. To further reduce the influence of noise, comparison between the two recordings was performed at a similar noise level.

The determination of QRS onset and offset is a critical step in the analysis and an incorrect delineation affects the RMS value. This source of error can be reduced by using the standard frequency QRS for the delineation, as was done in the present study (17).
Conclusions. Coronary artery occlusion produces changes not only in the ST-segment but also in the HF-QRS. Most of the HF-QRS changes in the present study were well beyond those reasonably explained by the normal temporal intradividual variation (18). The sensitivity for detection of coronary artery occlusion was higher for HF-QRS than for ST-segment deviation.

Assessment of different frequency bands in signal-averaged, high-resolution ECGs is possible using modern, computerized ECG recorders. The use of the information within these frequency bands is in accordance with recently suggested changes in the clinical application of electrocardiographic recordings (26). Analysis of HF-QRS could provide an adjunctive tool to detect and quantify ischemic myocardium. The large interindividual variation in HF-QRS probably makes the use of this analysis most applicable within these frequency bands is in accordance with recently suggested changes in the clinical application of electrocardiographic recordings (26). Analysis of HF-QRS could provide an adjunctive tool to detect and quantify ischemic myocardium. The large interindividual variation in HF-QRS probably makes the use of this analysis most applicable in situations in which it is possible to track changes from baseline, e.g., during thrombolytic therapy (18,27), during unstable angina and during exercise testing (28).

Acknowledgments
This study is a part of the STAFF Studies Investigations.

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