Acute myocardial ischemia monitoring before and during angioplasty by a novel vectorcardiographic parameter set

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Abstract

Background: This work evaluates the vectorcardiographic dynamic changes in ischemic patients before and during Percutaneous Transluminal Coronary Angioplasty (PTCA).
Methods: Four QRS-loop parameters were computed in 51 ischemic and 52 healthy subjects with the objective of assessing the vectorcardiographic differences between both groups: maximum vector magnitude (QRS_{mVM}), planar area (QRS_{PA}), maximum distance between centroid and loop (QRS_{mDCL}) and perimeter (QRS_{P}).The conventional ST-change vector magnitude (STC_{VM}), QRS-vector difference (QRS_{VD}) and spatial ventricular gradient (SVG) were also calculated.
Results: Statistical minute-by-minute PTCA comparison against a healthy population showed that ischemic patients monitoring is greatly enhanced when all the QRS-loop parameters, in combination with the standard STC_{VM}, QRS_{VD} and SVG indexes, are used in the classification. Sensitivity and Specificity, in turn, reached rather high values, 95.4% and 95.2%, respectively.
Conclusions: These new vectorcardiographic set of complementary QRS-loop parameters, when combined with the classics STC_{VM}, QRS_{VD} and SVG indexes, increase sensitivity and specificity for acute ischemia monitoring.

Keywords: Cardiac ischemia; QRS-loop parameters; Coronary Angioplasty

Background

Myocardial ischemia is caused by a decompensation between the oxygen supply and demand; it is frequently associated with coronary atherosclerosis. The temporary occlusion of a coronary artery derives in a reversible ischemia, while a prolonged obstruction leads to myocardial infarction with serious consequences, such as malignant arrhythmias, heart failure and/or sudden cardiac death. Percutaneous Transluminal Coronary Angioplasty (PTCA) is a therapeutic procedure used to reestablish blood flow in narrowed arteries. During PTCA, a balloon located at the tip of a catheter is inflated at the atheroma site to compress it causing simultaneously a full and controlled short-term total occlusion, which obviously also resembles an acute myocardial ischemia. Such occlusion provides an attractive opportunity to study myocardial changes due to lack of coronary patency during its initial minutes.[1]

Shortly after the beginning of balloon inflation, some changes can be detected in the electrocardiogram (ECG), such as ST-segment deviation and T-wave modifications, due to alterations in the ventricular repolarization process.[2] Several studies have demonstrated that ventricular depolarization is also modified during acute myocardial ischemia induced by PTCA. In this context, Surawicz et al. have shown, using 12-lead ECG records, that the QRS-complex terminal deflection is distorted during PTCA proportionally to the magnitude of the ST-segment shift.[3] Moreover, that high frequency QRS analysis could provide valuable information to detect acute ischemia and to quantify myocardial area at risk was suggested by Ringborn et al.[4] Recently, Romero et al. demonstrated that the upward and downward slopes of the QRS-complex change during coronary artery occlusion.[5] Those are spatially related to the ischemic area and they might physiologically be traced back to conduction

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disturbances in the ischemic segment.[2,4] Another conventional index that provides information on the cardiac conduction system operation and on the ventricular action potential duration heterogeneity is the Spatial Ventricular Gradient (SVG).[6] Haar et al. have reported that this gradient, in addition to ST analysis, has a potential role in detecting ischemia.[7]

Within the vectorcardiography framework, the momentary cardiac electrical activity is representable by a single vector in the Euclidian space, i.e., the heart vector, and the VCG precisely describes both components, magnitude and direction, as time proceeds. Several studies have proposed its use for evaluating cardiac changes during myocardial ischemia or infarction. In a recent work, Hasan et al. concluded that vectorcardiographic analysis of beat-to-beat variability in ventricular depolarization and repolarization may provide markers of electrical instability in patients with myocardial infarction.[8] Eriksson used ST_{VM}, ST-change-vector magnitude (STC_{VM}) and QRS_{VD} monitoring to give valuable prognostic information in cases of unstable angina and acute myocardial infarction, and concluded that vectorcardiography monitoring may identify myocardial reperfusion at an early stage.[9] Jensen et al. proposed $STC_{VM} = 0.05$mV as the best criterion for the detection of myocardial ischemia in VCG studies that monitor coronary angioplasty.[10]

Maximum ST-depression (in vector lead X) and STC_{VM} were the best determinants found by Lundin et al.,[11] obtained by multivariate analysis during exercise test in patients showing acute heart disease. Dellborg et al. demonstrated that monitoring myocardial ischemia with dynamic computerized continuous vectorcardiography (c-VCG) seems to be more efficient than Holter monitoring and may have a higher sensitivity.[12] Additionally, c-VCG has a full real-time capacity, so allowing monitoring over prolonged periods, while the results are immediately available without time-consuming analysis. Besides, Perez Riera et al. showed better specificity, sensitivity and accuracy of the computerized VCG when compared with conventional ECG in several cardiac pathologies.[13] Often, the advantage of the VCG is due to the constancy of the time relations between leads, while conversely, such relationships are lost in separate scalar lead analysis.

We have recently proposed a set of vectorcardiographic QRS-loop parameters computed in resting conditions records in order to distinguish ischemic patients before undergoing PTCA from healthy subjects.[14] After a classification process via discriminant analysis, it was concluded that QRS-loop parameters combined with ST_{VM} improved the sensitivity and specificity values with respect to those obtained using only the ST_{VM} index.

Herein, and as one step further, we analyze the vectorcardiographic dynamic changes of the QRS-loop parameters in acute myocardial ischemic patients before and during the PTCA procedure. For this matter, we statistically compared, minute by minute, the PTCA against a healthy population. We hypothesize that the balloon occlusion modifies the morphology of the QRS-loop and, thereafter, its parameters can be used to characterize and monitoring the acute myocardial ischemia. To prove this, we evaluated the proposed and the conventional parameters in the classification scheme.

Methods

Database

Raw clinical records were extracted from the PTB diagnostic ECG and STAFF-III databases.

The first one contains the ECG records of 52 healthy subjects (39 men, mean age 42 +/− 14 years, and 13 women, mean age 48 +/− 19 years). The ECGs in this collection were obtained by Physikalisch-Technische Bundesanstalt (PTB); the National Metrology Institute of Germany. Each record includes 15 simultaneously measured signals: the conventional 12 leads (I, II, III, aVR, aVL, aVF, V1–V6) together with the 3-Frank lead-ECGs (X, Y, Z). Each signal was digitized at 1000 Hz, with 16 bits of amplitude resolution.[15]

The second database consists of 51 ischemic patients (33 males, mean age61 +/− 13 years and 18 women, mean age 60 +/− 10 years) admitted to the Charleston Area Medical Center in West Virginia, receiving elective PTCA in one of the major coronary arteries (STAFF-III study). The study was approved by the local investigation review board, and informed consent was obtained from each patient before enrollment.[5] The mean occlusion period was 5 min 7 s. The locations of the 51 dilations were: Left Anterior Descending Artery in 11 patients, Right Coronary Artery in 14 patients and Left Circumflex Artery in 26 patients. The following inclusion criteria had to be met for the study population: no clinical or ECG evidence of an acute or recent myocardial infarction, no intraventricular conduction delay with QRS duration $\geq$120 ms [including left bundle branch block (LBBB) and right bundle branch block (RBBB)], no pacemaker rhythm, low voltage, atrial fibrillation/flutter, or any ventricular rhythm at inclusion (or during the PTCA). We also excluded patients with ECG signal loss during acquisition or with occlusion period less than 4 min 30 s.

Nine standard leads (V1-V6, I, II, III) were recorded in the study using equipment by Siemens-Elena AB (Solna, Sweden), digitized at sampling rate of 1000 Hz and 0.6 μV amplitude resolution. Synthesized orthogonal X, Y and Z leads were obtained by the Kors transform.[16] A recent study has demonstrated that Kors synthesis matrix provides a better estimation of Frank leads than the Inverse Dower transform in ischemic patients.[17]

For each patient, two ECG records were obtained. One of them (denoted as before-PTCA Record) was acquired continuously at rest in the supine position prior to angioplasty, and the other (denoted as during-PTCA Record) was obtained during the PTCA procedure. Fig. 1 illustrates a block diagram of the different stages of the analysis.

Pre-processing

First, all ECG records were pre-processed with a bandpass filter (Butterworth, 4th order, 0.2-100 Hz, bidirectional) to reduce low and high frequency noise and a notch filter (Butterworth, 2nd order, 50/60 Hz, bidirectional) to minimize the power-line interference. A cubic spline interpolation filter

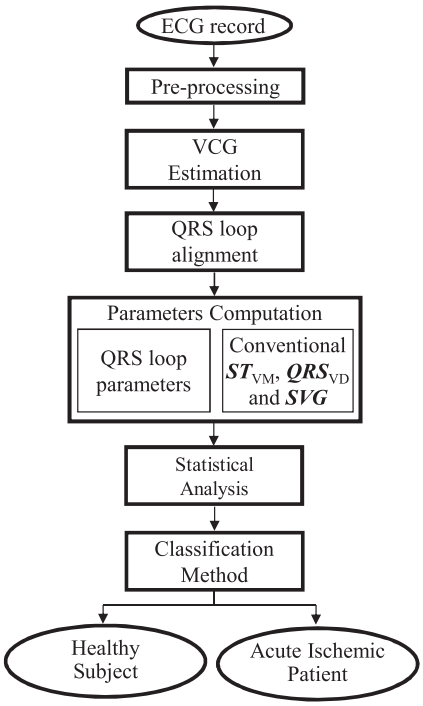


Fig. 1. General diagram of the proposed analysis technique.

was applied to attenuate ECG baseline drifts and respiratory artifacts. Thereafter, the QRS complexes and their end-points were detected in each ECG record using a wavelet-based technique.[18] Excessively noisy beats (with a RMS noise level > 40μV, measured within a 40 ms window located at 2/3 of the RR interval) were excluded. In addition, ectopic beats were also eliminated by comparing incoming signals against a previously established template with the use of a cross-correlation technique. In this study, a visually low-noise normal beat extracted from the ECG record was selected as template (or reference) beat.

VCG estimation

The VCG was obtained by simultaneously drawing on a 3-D plot the instantaneous X, Y and Z orthogonal amplitudes for every sample of the temporal interval corresponding to each detected QRS-complex, that is, from the starting point of the Q-wave (or R if there was no Q) to the final point of the S-wave (or R, if no S was present).

QRS loop alignment

The alignment of all QRS-loops in each ECG record is required in order to compensate for variations induced by extracardiac factors, such as respiratory movements.[19] This can be resolved by obtaining the Rotation (R) and Translation (T) matrices that allow the beat-to-beat alignment against a pattern or template QRS-loop, the latter dynamically obtained from the averaged QRS-complex evaluated at 30s intervals. Such matrices were computed from an adapted version[14] of the algorithm proposed by Arun et al.,[20] which provides a closed solution for their computation.

Parameter computation

The following vectorcardiographic parameters were computed from the QRS-loop for each detected beat in the ECG records.[14] For comparison, the conventional STC_{VM}, QRS_{VD} and *SVG* indexes were also calculated. Fig. 2 shows some vectorcardiographic parameters computed in a 3-D plot of an individual QRS-complex.

The analyzed parameters were:

QRS-loop maximum vector magnitude (QRS_{mVM})

The vector modulus for each QRS coordinate (X, Y, Z) was initially calculated, thereafter, the maximum value was obtained.[21] It describes the maximum magnitude of the Depolarization Vector (Fig. 2-A).

QRS-loop planar area (QRS_{PA})

It is the estimated area of the loop obtained by projecting the QRS-loop on the best adjusted plane computed by the least mean squares method (denoted as QRS-proj and Optimum Plane, respectively, see Fig. 2-A). It is thought as reflecting hemodynamic abnormalities in cardiac lesions.[22]

Maximum distance between the QRS-centroid and the QRS-loop (QRS_{mDCL})

The loop centroid (with coordinates $X_cY_cZ_c$) is initially estimated and, thereafter, the maximal Euclidean distance (E_d) from this centroid[2] to each point of the loop (X_j,Y_j, Z_j, where $j = 1, \cdots, M$, with M being the number of beat samples) is determined.[14] In this work, each E_d between the centroid and the QRS-loop was computed as $E_d = [(X_j - X_c)^2 + (Y_j - Y_c)^2 + (Z_j - Z_c)^2]^{1/2}$. The QRS_{mDCL} measures a relative distance that is independent on the position of the loop in 3-D, unlike QRS_{mVM}, which measures an absolute distance with respect to the reference system's origin (Fig. 2A).

Perimeter (QRS_P)

It is the perimeter computed over the QRS-loop projected over the Optimum Plane. It measures the loop total length and can detect loop contour changes.[14]

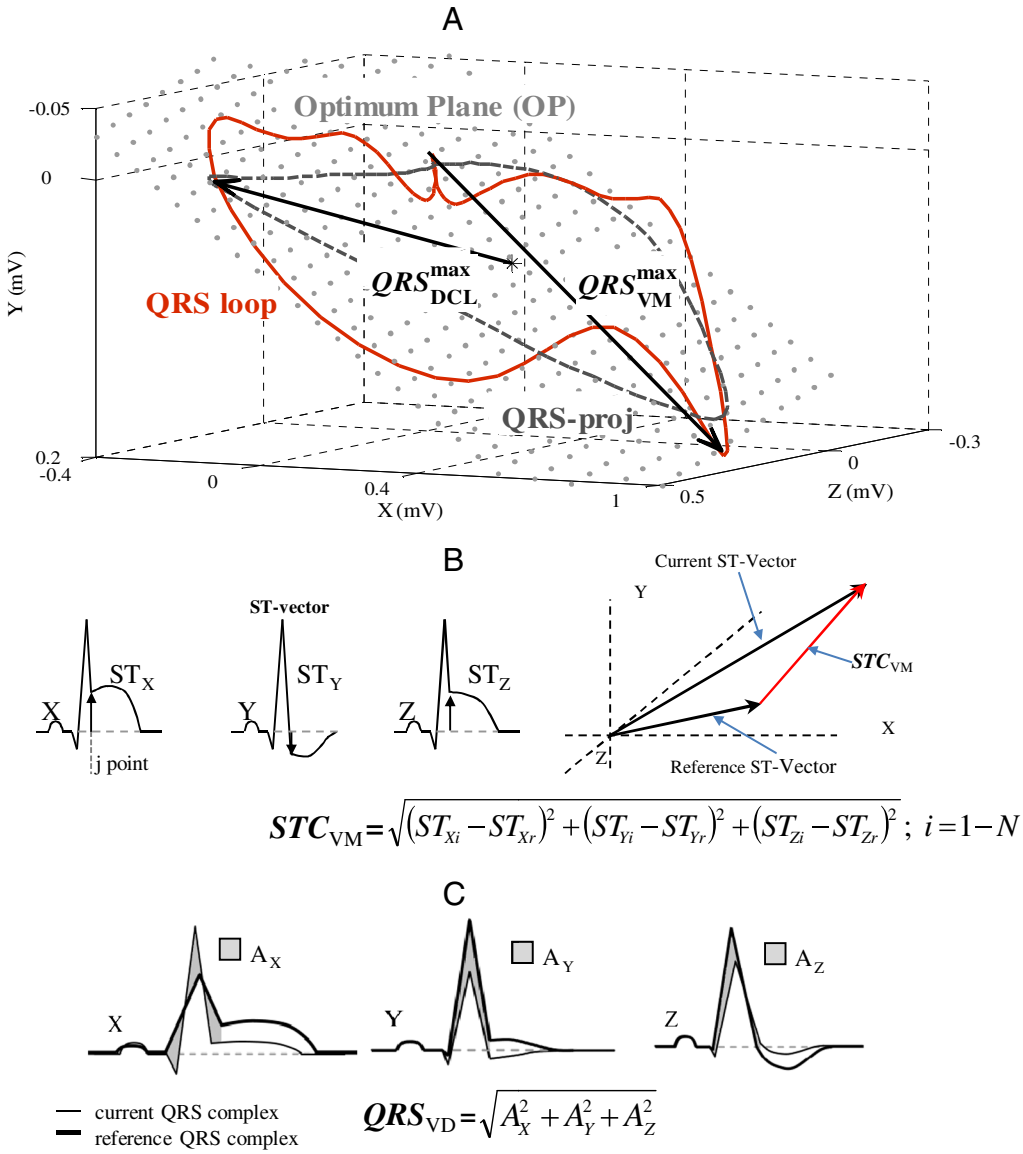
ST-change vector magnitude (STC_{VM})

The ST-vector is composed of the (X, Y and Z) ST-segment deviations from the isoelectric level, measured as the ECG signal amplitude at the J-point (Fig. 2B); it is a widely used parameter when monitoring cardiac ischemia.[8–10] This vector is the difference between the ST-vector of the current beat and the averaged beat evaluated at the first 30s of each ECG record, that is,

$$STC_{VMi} = \sqrt{(ST_{Xi} - ST_{Xr})^2 + (ST_{Yi} - ST_{Yr})^2 + (ST_{Zi} - ST_{Zr})^2}$$

where r denotes the reference beat, i is the current beat, with $i = 1, \ldots, N$, and N stands for the total number of analyzed beats (Fig. 2B).

[2] The centroid is the mean value of the coordinates X, Y and Z, computed in the QRS-proj on the optimum plane.



$$STC_{VM} = \sqrt{(ST_{Xi} - ST_{Xr})^2 + (ST_{Yi} - ST_{Yr})^2 + (ST_{Zi} - ST_{Zr})^2}\ ;\ i = 1 - N$$

$$QRS_{VD} = \sqrt{A_X^2 + A_Y^2 + A_Z^2}$$

Fig. 2. A) Some VCG characteristic parameters computed in the 3-DQRS-loop for an individual beat extracted from the record of a representative acute ischemic patient. B) Left panel: ST-vector components; the right panel explains the STC_{VM} computation. C) It explains the QRS_{VD} index calculation. Color illustration online.

QRS-vector difference (QRS_{VD})

It was defined[12] as the difference of the current QRS-complex area and the averaged QRS-complex area evaluated at the first 30s of each ECG record (Fig. 2C), i.e.

$$QRS_{VD} = \sqrt{A_X^2 + A_Y^2 + A_Z^2}$$

Spatial ventricular gradient (SVG)

It is defined as the vectorial QRS-T integral, that is:

$$SVG = \sqrt{(QRS_X + T_X)^2 + (QRS_Y + T_Y)^2 + (QRS_Z + T_Z)^2}$$

where, QRS_X, QRS_Y, QRS_Z and T_X, T_Y, T_Z are the QRS-complex and T-wave areas on the orthogonal leads, respectively, and all having units of mV · ms. Then, *SVG* has the same units. Unlike most other ECG parameters, the *SVG* is not influenced by changes in ventricular conduction pattern; it only changes if the distribution of the ventricular action potential morphology and/or duration is altered.[6]

Statistical analysis

Comparison between the healthy and the ischemic population

All parameters were computed for each detected sinus beat in every ECG record. First, we analyzed the normality of these values using the D'Agostino-Pearson's test with the aim of quantifying the discrepancy between the parameters' distribution and the Gaussian distribution. It has been observed that the underlying variables' distribution is non-Gaussian. Afterwards, comparisons between healthy (mean of each parameter values of all ECG records) and ischemic subjects (parameters computed before and during PTCA, the last one grouped at 1 min intervals) were made using the non-parametric Mann–Whitney *U* test.

Evaluation of QRS-loop changes during PTCA

In order to analyze the QRS-loop variations in each patient during an acute ischemia episode; we statistically compared the parameters' values through the PTCA procedure with respect to the first 30 s of the balloon occlusion. That was accomplished using a 30 s moving window, at 10 s intervals, from the start to the end of the PTCA recording.

Classification method

The mean values of each parameter across the entire record for healthy subjects, and at 1 min interval for ischemic patients, were calculated. These values were used as inputs to a classifier based on *Linear Discriminant Analysis* (*LDA*) to distinguish (or separating out) ischemic patients from healthy subjects.

Basically, the LDA classifier is a linear combination of variables, as follows:

$$y = \mu_0 + \mu_1 X_1 + \mu_2 X_2 + \ldots\ldots + \mu_p X_p$$

where y is the output value of the discriminant function; μ_n (with $n = 1,\ldots, p$) are the discriminant function coefficients; X_n are the discriminant variables (QRS-loop parameters and/or STC_{VM} and/or QRS_{VD} and/or SVG) and p is the number of variables in the analysis.[23] Due to, the units and the magnitudes of the discriminating variables are different (see Fig. 4), the corresponding coefficient values cannot be compared to each other to know what is the contribution of each variable to the discriminant function. Then, in order to compare and analyze the coefficients of the discriminant functions is necessary to standardize them. This was done by applying to each coefficient μ_n the following transformation:

$$c_n = \mu_n \sqrt{\frac{w_n}{m-g}}$$

where w_n is the squared sum for variable n, m is the number of studied subjects, and g is the number of groups defined for the discriminant variable.

The resulting discriminant function can be used for assigning each ECG record to a particular group or class (say, ischemic patients or healthy subjects), based on its values of discriminant variables. The model coefficients are estimated with a subset of ECG records for which the group is known. This subset of observations is sometimes referred to as the *training subset* (70% of the records of both populations were used). In order to validate the model, this discriminant function was also applied to predict the group of another different ECG records subset, referred to as *validation subset*, and using the remaining 30% of the records.

Thus, for a pair of training-validation subsets construction we: 1) randomly ordered the ECG records of both populations; 2) took 36 subjects of each population for the *training subsets*; and 3) grouped the 16 and 15 (healthy and ischemic subjects, respectively) remaining records in the *validation subset*.

Since these out comes depend on the records chosen for the training and validation stages, we randomly selected 100 different training and validation subsets to improve the statistical reliability of results. Such subsets were used to compute 100 different discriminant functions.

To evaluate the LDA classifier performance, we computed the Receiver Operating Characteristic (ROC) curve. It plots the Sensitivity (Sens) against the Specificity (Spec) values for the different possible cut-off points (we vary the cut-off values between −5and 5, in 0.01 steps) of the discriminant function.

Thereafter, the optimal cut-off point in the ROC curve was computed as the point nearest the top left-hand corner. This selection maximizes the Sens and Spec sum, when it is assumed that the 'cost' of a *false negative* result is the same as that of a *false positive* result.[24] Finally, the global performance of the classifier was evaluated with the Area Under the ROC Curve (AUC).

Results

This study tests a set of VCG parameters by means of 3-D QRS-loops to quantify and assess their morphological changes in acute ischemic patients before and during PTCA. Figs. 3 and 4, in turn, depict the results of the statistical analysis described in section 6.The former, shows the mean and Standard Error of the Mean (SEM) of each computed parameter in healthy and ischemic populations before and during the PTCA procedure. The values marked with * indicate the statistical significance ($p < 0.05$).

Fig. 4, instead, gives the percentage of PTCA records with significant differences ($p < 0.05$), when contrasting the parameters' values during the PTCA procedure with respect to the first 30 s of the balloon occlusion (this analysis was described in section 6.2).

The mean values of the classification results using these discriminant functions are shown in Fig. 5,where the Sens and Spec values can be seen using: a) only the conventional parameters (STC_{VM}, QRS_{VD} and SVG); b) all QRS-loop parameters, and c) the combination of QRS-loop and conventional parameters.

It is important to highlight that the increase of Sens often produces a Spec decrease and vice versa; e. g., an increased sensitivity (correct classification of all ischemic patients) often produces an increase of false positives (incorrect classification of same healthy subjects as ischemic) and, therefore, a decrease in specificity. In other words, we assumed in this work that the 'cost' of a false positive result (i.e., to classify a healthy subject as ischemic) is the same as that of a false negative result (that is, classifying an ischemic patient as healthy).[24] With this consideration in mind, the optimal values of Sens and Spec were found by the ROC curve shape and the optimal point was determined, as described above (Methods – Subsection 7). The standardized coefficients of each optimal discriminant function (c_0, c_1, …, c_7) are shown in Table 1 (see Section 7).

Fig. 6 shows the ROC Curves and their corresponding area under these curves (AUC), for different classification schemes using: a) only conventional parameters (STC_{VM},

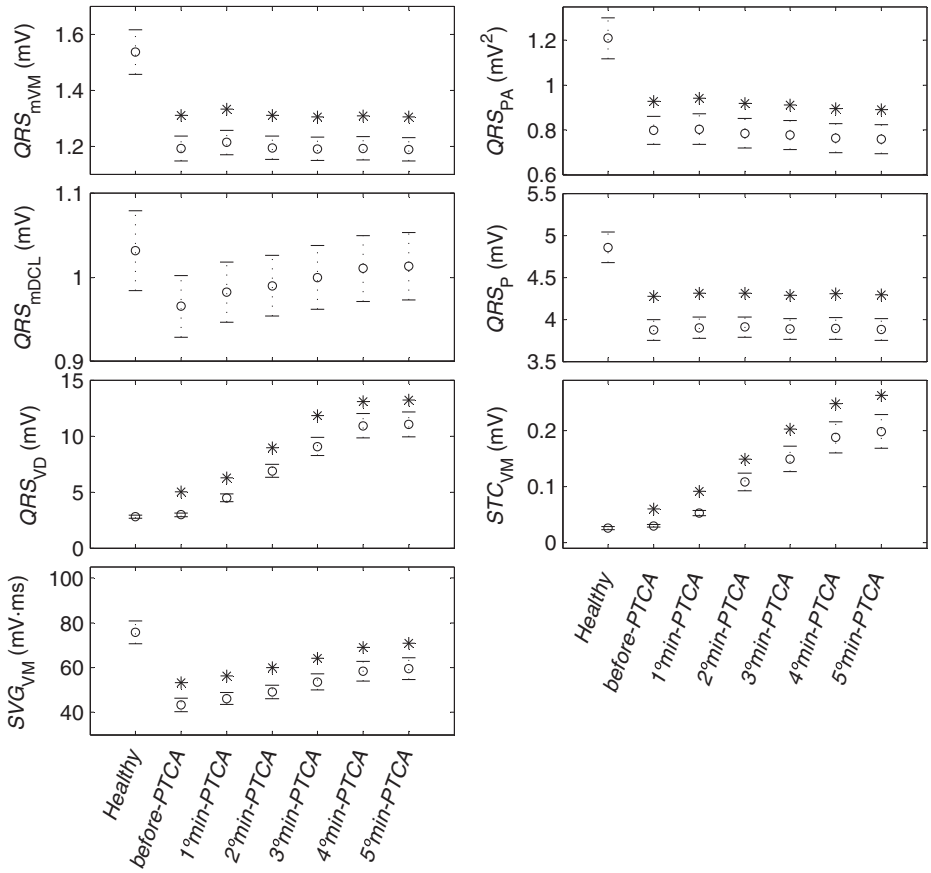


Fig. 3. Mean and standard error of the mean of each parameter computed in healthy and acute ischemic subjects (the parameters for the acute ischemic patients were grouped at intervals of 1 min, thereby obtaining 5 groups for each record). *Denoted statistical significance, $p < 0.05$ (see section 2.6).

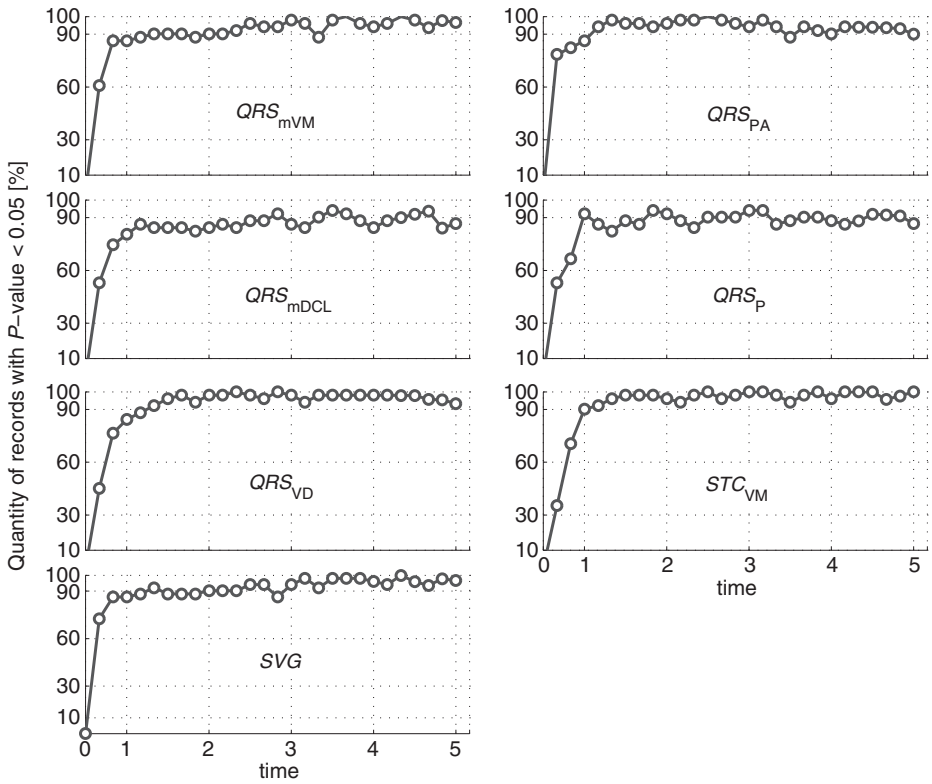


Fig. 4. Percentage of recordings that show significant changes ($p < 0.05$) during balloon inflation with respect to the beginning of PTCA. Left panel: the results for QRS_{mVM}, QRS_{mDCL} and QRS_{VD} are presented, whereas the right panel summarizes the results for QRS_{PA}, QRS_P and STC_{VM}.

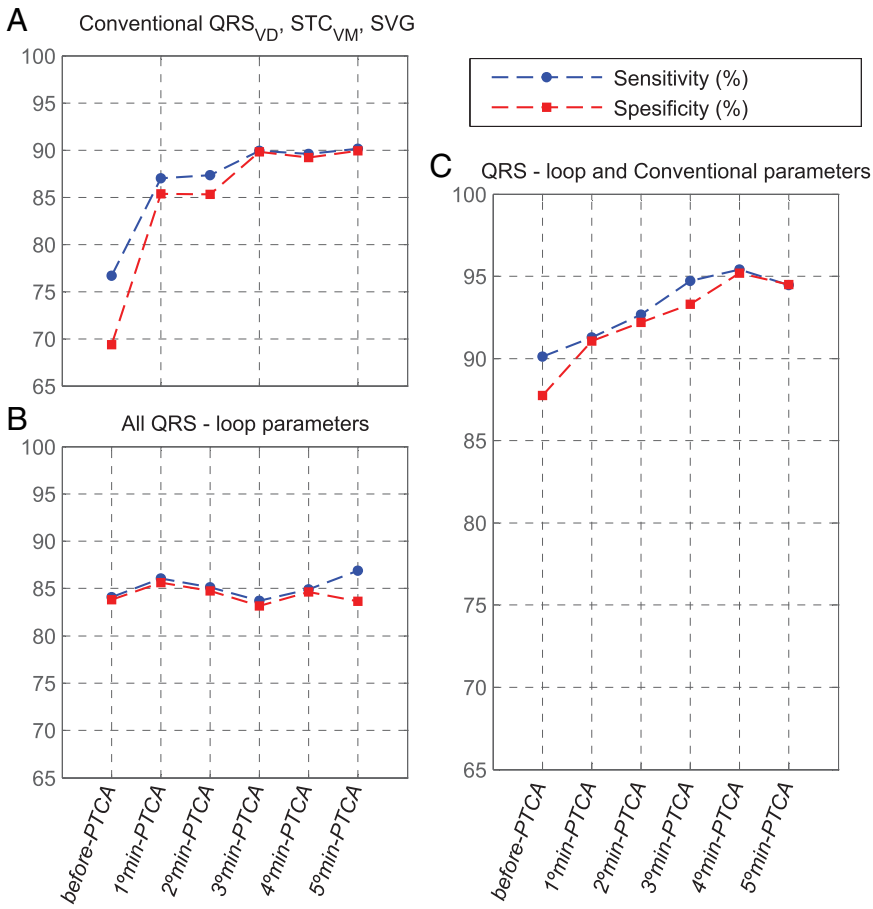


Fig. 5. Sensitivity and specificity results (obtained with a classification method described in 2.6.) using: A) only conventional parameters (STC_{VM}, QRS_{VD} and SVG); B) all QRS-loop parameters, and C) the combination of QRS-loop and conventional parameters. Color illustration online.

QRS_{VD} and SVG); b) all QRS-loop parameters, and c) the QRS-loop and conventional parameter combinations.

Discussion

Several studies have demonstrated the potential automated VCG analysis usefulness to evaluate cardiac changes during ischemia or infarction.[10–16] Furthermore, in,[25] Jensen et al. compared on-line computerized VCGs derived from 12-lead ECGs, and concluded that the first one is a more sensitive method for detecting myocardial ischemia during coronary angioplasty. However, most of the studies based on VCG use the STC_{VM}, QRS_{VD} and SVG parameters.

Besides these two conventional indexes, here in we examined 4 vectorcardiographic parameters computed in the QRS-loop to further describe cardiac dynamic changes during an episode of acute ischemia induced by PTCA. This set of QRS-loop parameters was used in a previous work to separate out healthy and ischemic patients before angioplasty.[14] We concluded that these parameters could be a complement to standard analysis in the recognition of cardiac ischemia.

On the basis of the statistical analysis, it can be observed in Fig. 3 that all the vectorcardiographic parameters (with the exception of QRS_{mDCL}) produced significant differences ($p < 0.05$) between healthy and ischemic populations, before and during PTCA. Besides, the mean values of the QRS-loop parameters have smaller changes during PTCA than the conventional indexes; however, they have greater differences with respect to the healthy subjects' mean values. It indicates that the proposed QRS-loop parameters and the conventional indexes have different behaviors, which could be used in a combined analysis to improve monitoring of acute myocardial ischemia.

To analyze whether the QRS-loop variations are significant with respect to the beginning of occlusion, we

Table 1
Standardized discriminant coefficient (c_1, c_2,.., c_7) values computed for the optimal classification before and during PTCA, using all QRS-loop in combination with the conventional parameters.

		QRS_{mvM} c_1	QRS_{PA} c_2	QRS_{mDCL} c_3	QRS_{P} c_4	QRS_{VD} c_5	STS_{VM} c_6	SVG c_7
	Before PTCA	−0.029	1.017	2.479	−3.443	0.562	0.093	−0.656
During PTCA	1 min	0.275	0.718	2.165	−2.846	0.451	0.203	−0.809
	2 min	0.278	0.491	1.722	−2.236	0.762	−0.140	−0.859
	3 min	0.363	0.418	1.342	−1.975	0.876	−0.131	−0.821
	4 min	0.252	0.435	1.337	−1.980	1.018	−0.162	−0.744
	5 min	0.264	0.238	1.004	−1.522	1.269	−0.478	−0.759

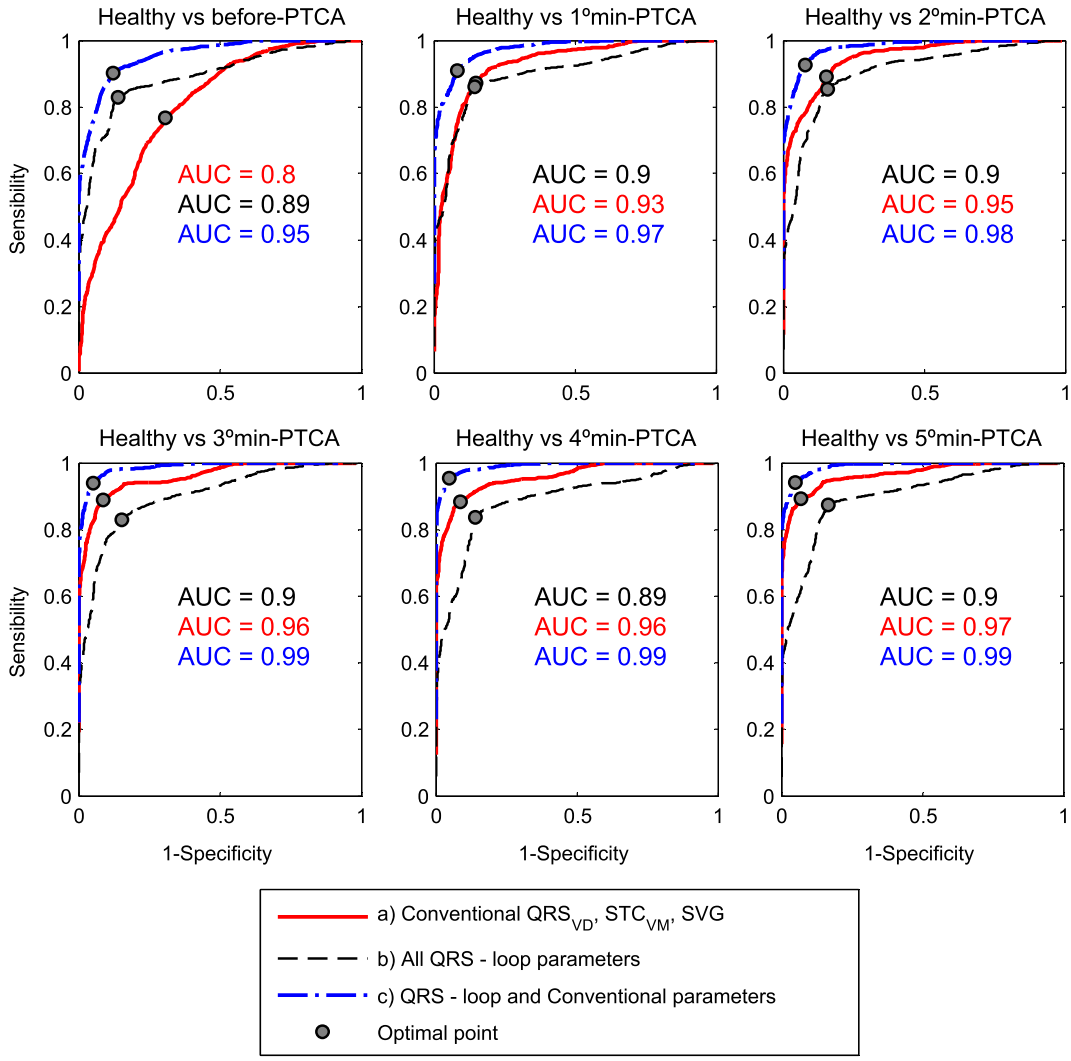


Fig. 6. ROC and AUC for different classification schemes using: A) only conventional parameters (STC_{VM}, QRS_{VD} and SVG), B) all QRS loop-parameters, and C) the QRS-loop and conventional parameter combination. Color illustration online.

computed the percentage of records that showed significant changes ($p < 0.05$) during balloon inflation (see Fig. 4). It is seen that for all parameters, around 90% of the patients have significant changes during PTCA, when statistically compared against the first 30s of the balloon occlusion, reaching sometimes even values of 100% of the records for QRS_{mVM}, QRS_{PA}, QRS_{VD}, STC_{VM} and SVG.

In Table 1 we can see the values of the standardized discriminant coefficients (c_1, c_2, …, c_7) computed for the optimal classification using all QRS-loop parameters in combination with the conventional index. It can be seen that the coefficient for the parameters QRS_{mVM} and STC_{VM} (c_1 and c_7, respectively) have lower values before and during PTCA than the others. This indicates that they have the worst discriminating power. Besides, it can be observed that all coefficients, with the exception of c_1 and c_7, have similar values before and during PTCA, so indicating that the computed discriminant functions have small modifications before and during PTCA.

The discriminant analysis (see Fig. 5) indicates that the QRS-loop parameters have a better Sens and Spec before PTCA than the conventional indexes. Also, Fig. 6 shows that they have a better performance because their AUC values are greater. In contrast, during PTCA, the conventional indexes have a better Sens, Spec and AUC value than QRS-loop parameters, which reinforces the idea that these two sets of indexes are complementary and that their combined use improves myocardial ischemia monitoring.

Moreover, minute-by-minute statistical comparison of the PTCA against a healthy population shows that acute ischemic patients monitoring is greatly enhanced when all the QRS-loop parameters, in combination with the standard STC_{VM}, QRS_{VD} and SVG indexes, are used in the classification, reaching Sens = 95.4% and Spec = 95.2%, at the 4th minute of the PTCA. Meanwhile, when using only the conventional STC_{VM}, QRS_{VD} and SVG indexes, values of Sens = 90.1 % and Spec = 89.9% at the end of the occlusion were obtained, which are lower than those reported above. Additionally, the best AUC value (see Fig. 6), using all the QRS-loop parameters in combination with the STC_{VM}, QRS_{VD} and SVG indexes, is AUC = 0.99, after the 3rd minute of the balloon inflation. Thus, it indicates high effectiveness for

the proposed classification technique. This AUC value is considered of high accuracy in diagnostic tests.[26]

Limitations

Attention must be called to the following aspects: no attempt was made to measure changes in heart diseases other than those mentioned above. In fact, we restricted the analysis to ECG signals obtained from a PTCA procedure, which in itself is an important limitation. Hence, for clinical implementation of the technique, heart conditions such as LBBB, dilated cardiomyopathy, ventricular hypertrophy, and others should be excluded. In this regard, future work should include the latter. Moreover, it is important to note that usually the patients are not monitored when in good conditions nor for this purpose in the cath lab. Due to this common situation, we used a healthy population as control accepting its implied limitations. Finally, since our study was carry out on ECG records of about 5 min long, it would be necessary to test the proposed algorithms in longer duration records (say, in ambulatory situations).

Conclusions

The proposed parameters, QRS_{mVM}, QRS_{PA}, QRS_{mDCL}, QRS_{P}, used together with the conventional STC_{VM}, QRS_{VD} and *SVG*, increase sensitivity and specificity to monitor acute myocardial ischemia. They provide additional information (assessed on the QRS-loop) to that supplied by conventional indexes. From the clinical point of view, the most important future application would be the ambulatory monitoring of ischemic patients in Holter or stress tests studies.

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