

# Analysis of vectorcardiographic dynamic changes in patients with acute myocardial ischemia

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**Abstract.** This work evaluates the vectorcardiographic dynamic changes in ischemic patients before and during Percutaneous Transluminal Coronary Angioplasty (PTCA). Four vectorcardiographic parameters were computed in 51 ischemic and 52 healthy subjects with the objective of assessing the differences between both groups: ST Vector Magnitude Area ( $ST_{VMa}$ ), T Vector Magnitude Area ( $T_{VMa}$ ), ST Vector Difference ( $ST_{VD}$ ), and T Vector Difference ( $T_{VD}$ ). The conventional ST-Change Vector Magnitude ( $STC_{VM}$ ) and Spatial Ventricular Gradient (SVG) were also calculated. Results indicate that the most of them show significant differences between healthy and ischemic subjects. Since, the statistical minute-by-minute PTCA comparison against a healthy population shows that ischemic patients monitoring reached values of Sensitivity = 99.5% and Specificity = 99.4%, when  $ST_{VD}$ ,  $T_{VD}$  and SVG were used in the classification. In conclusion the sensitivity and specificity for acute ischemia monitoring could be increase with the used of only three vectorcardiographic parameters.

## 1. Introduction

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. Such procedure 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 [3-4]. In this context, other conventional index that

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provides information on the cardiac conduction system operation and on the ventricular action potential duration heterogeneity is the Spatial Ventricular Gradient (SVG) [5]. ter Haar *et al.* have reported that this gradient, in addition to ST analysis, has a potential role in detecting ischemia [6].

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 [7]. 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 [8]. Jensen *et al.* proposed  $STC_{VM} = 0.05\text{mV}$  as the best criterion for the detection of myocardial ischemia in VCG studies that monitor coronary angioplasty [9].

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 [10]. 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 [11]. 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.

In a previous work, we analyzed a set of VCG parameters computed in the cardiac depolarization phase in ischemic patients [12]. The aim of this study was to differentiate a group of ischemic subjects from a population of healthy ones by VCG analysis of the ventricular depolarization-repolarization process. For that matter, four novel vectorcardiographic parameters (computed on repolarization segments and waves) and three conventional indexes (computed on depolarization-repolarization segments and waves) were evaluated.

As hypothesis, we state that the balloon occlusion modifies the morphology of the ST-T 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.

## 2. Materials

The 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 yrs, and 13 women, mean age 48 +/- 19 yrs). 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 [13].

The second database consists of 51 ischemic patients (33 males, mean age 61 +/- 13 yrs and 18 women, mean age 60 +/- 10 yrs) 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 [4]. The mean occlusion period was 5 min 7s. 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. We excluded patients with ECG signal loss during acquisition or with occlusion period less than 4 min 30 sec.

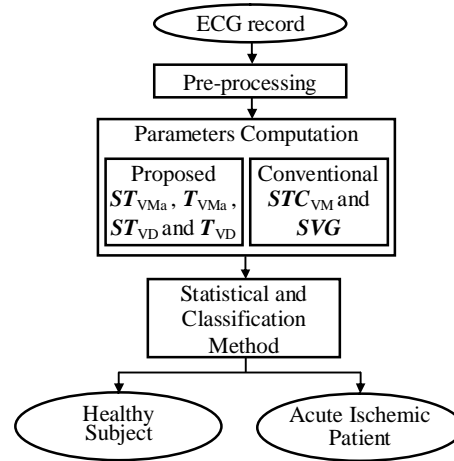
Nine standard leads (V1-V6, I, II, III) were recorded in the study using equipment by Siemens-Elena AB (Solna, Sweden), digitized at sampling rate of 1000 Hz and 0.6  $\mu\text{V}$  amplitude resolution. Synthesized orthogonal X, Y and Z leads were obtained by the Kors transform [14]. A recent study

has demonstrated that Kors synthesis matrix provides a better estimation of Frank leads than the Inverse Dower transform in ischemic patients [15].

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.

### 3. Methods

Figure 1 illustrates a block diagram of the different stages of the proposed analysis.



**Figure 1.** Proposed Analysis General Diagram.

#### 3.1. Preprocessing

First, all ECG records were preprocessed with a band-pass filter (Butterworth, 4th order, 0.2–100 Hz, bidirectional) to reduce low and high frequency noise and a notch filter (Butterworth, 2th order, 50/60 Hz, bidirectional) to minimize the power line interference. A cubic spline interpolation filter was used to attenuate ECG baseline drifts and respiratory artifacts. Thereafter, the QRS complexes, T waves and their endpoints were detected in each ECG record using a wavelet-based technique [16]. Beats with a RMS noise level  $>40 \mu V$  (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. Additionally, with this technique, we also make the time alignment of beats, required to obtain an average beat, used in the parameters computation [17]. In this study, a visually low-noise normal beat extracted from the ECG record was selected as template (or reference) beat.

#### 3.2. Parameters Computation

Four VCG parameters and two conventional indexes were computed for each detected beat.

- **ST Vector Magnitude Area ( $ST_{VMa}$ ):** It is defined as the magnitude of the vector composed by the X, Y and Z Area between the amplitude of the ECG signal interval from each J-point to J-point+80ms (ST-segment) and the isoelectric level, that is,

$$ST_{VMa} = \left( aST_X^2 + aST_Y^2 + aST_Z^2 \right)^{1/2} \quad (1)$$

This parameters is, a modification of the  $STC_{VM}$  widely used in the monitoring of cardiac ischemia [7, 8], The principal differences is  $STC_{VM}$  is evaluated at the one point on de signal (usually j-point, or j-point+60ms), by the contrast the proposed  $ST_{VMa}$  is computed during all ST segment (figure 2a).

- **T Vector Magnitude Area ( $T_{VMa}$ ):** It is defined as the magnitude of the vector composed by the X, Y and Z Area between the amplitude of the ECG signal at interval of each T wave and the isoelectric level (figure 2b), that is,

$$T_{VMa} = (aT_x^2 + aT_y^2 + aT_z^2)^{1/2} \quad (2)$$

- **ST-T-Vector Difference ( $ST-T_{VD}$ ):** It was defined as the difference area between the ECG signal at the current ST-T intervals (from each J-point to the T wave ends) and the reference of ECG signal (at ST-T intervals too) evaluated at the first 30s of each ECG record, that is,

$$ST - T_{VD} = (dA_x^2 + dA_y^2 + dA_z^2)^{1/2} \quad (3)$$

The objective of this parameter is estimated all changes produced during left Ventricular repolarization (figure 2-c).

- **T-Vector Difference ( $T_{VD}$ ):** It was defined as the difference area between the ECG signal at the current T wave intervals and the reference of ECG signal (at T intervals too) evaluated at the first 30s of each ECG record, that is,

$$T_{VD} = (dT_x^2 + dT_y^2 + dT_z^2)^{1/2} \quad (4)$$

The objective of this parameter is estimated all changes produced in the T wave (figure 2-d).

- **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. 2-e); it is a widely used parameter when monitoring cardiac ischemia [7,8]. 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,

$$STC_{VMi} = [(ST_{Xi} - ST_{Xr})^2 + (ST_{Yi} - ST_{Yr})^2 + (ST_{Zi} - ST_{Zr})^2]^{1/2} \quad (5)$$

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

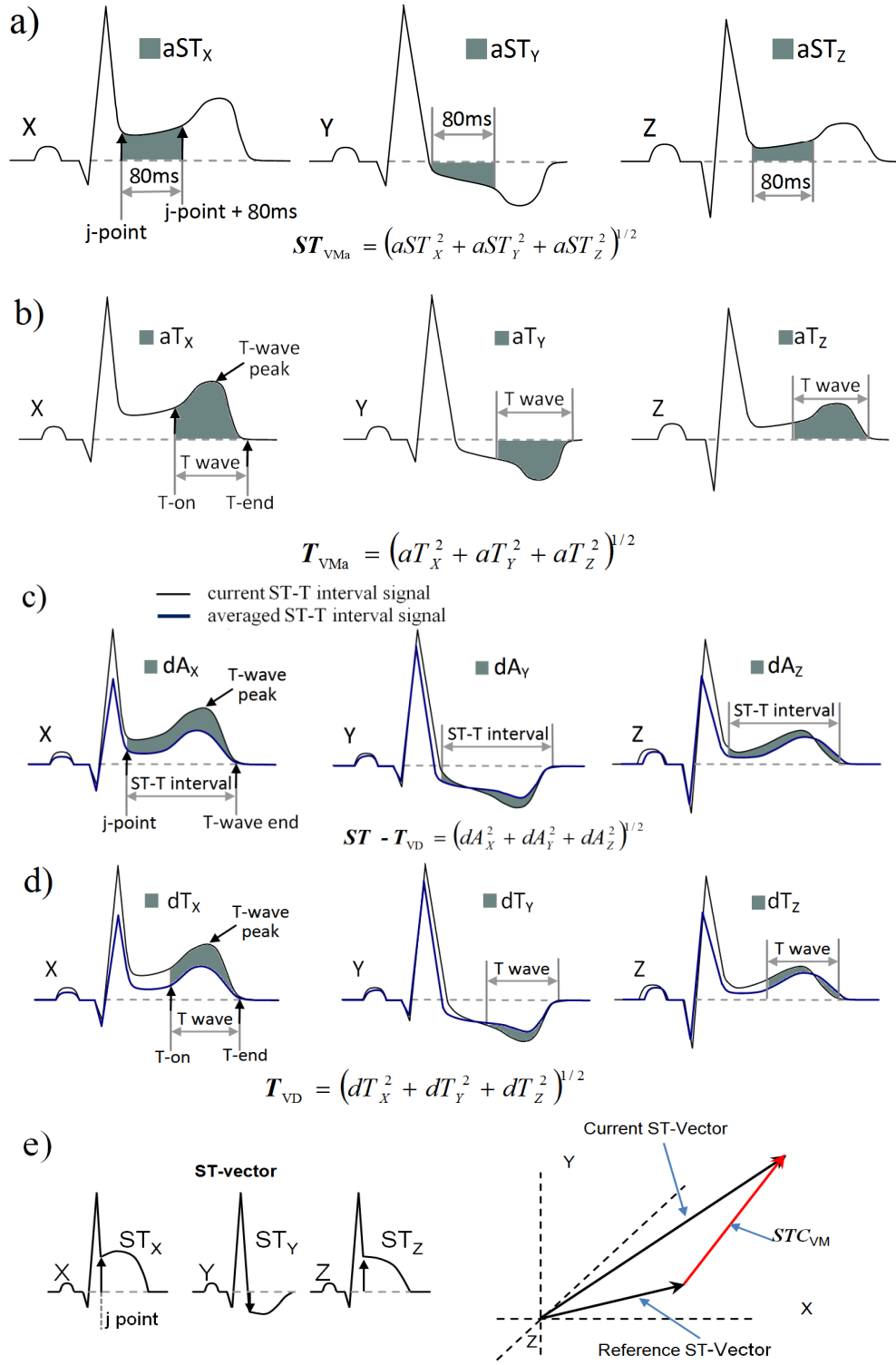
- **Spatial Ventricular Gradient (SVG):** It is defined as the vectorial QRS-T integral, that is:

$$SVG = [(aQRS_x + aT_x)^2 + (aQRS_y + aT_y)^2 + (aQRS_z + aT_z)^2]^{1/2} \quad (6)$$

where,  $aQRS_x$ ,  $aQRS_y$ ,  $aQRS_z$  and  $aT_x$ ,  $aT_y$ ,  $aT_z$  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].

### 3.3. Statistical and Classification Methods

All parameters were computed for each detected sinus beat in every ECG record. First, we analysed 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 test.



**Figure 2.** Vectorcardiographic Parameters computation.

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. The LDA classifier is a linear combination of variables, as follows,

$$y = \mu_0 + \mu_1 X_1 + \mu_2 X_2 + ..... + \mu_p X_p \quad (7)$$

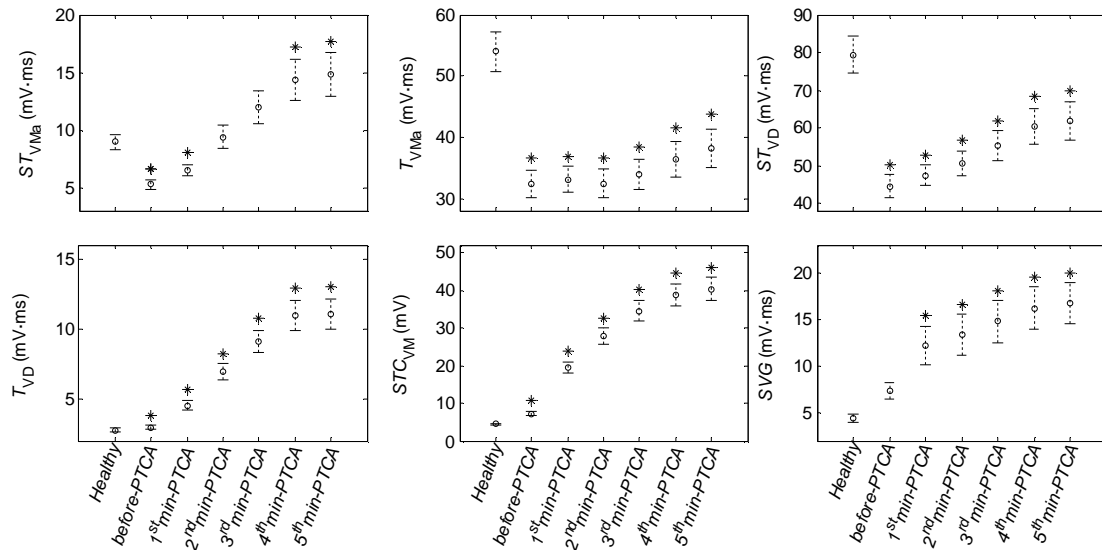
where  $y$  is the output value of the discriminant function;  $\mu_n$  (with  $n=1, \dots, p$ ) stand for the coefficients of the discriminate function;  $X_n$  are the discriminate variables (QRS-loop and/or ST-T parameters) and  $p$  is the number of variables in the analysis.

The resulting discriminant function can be used to assign each ECG record to a particular class, ischemic patient or healthy subject, based on its values of discriminate 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** (we used the 70% of ECG records of both populations). In order to validate the model, this discriminant function was used to predict the group of another different subset (referred to as **validation subset**) of the ECG records (we used the remaining 30% of the ECG records).

To evaluate the performance of the LDA classifier, we computed the **Receiver Operating Characteristic (ROC)**. It plots the Sensitivity (Se) against the 1-Specificity (Sp) values for the different possible cut-off points (cut-off values were swept between -5 and 5 in 0.01 steps) of the discriminant function. Then, the optimal cut-off point in the ROC curve was computed as the point nearest the top left-hand corner. This selection maximizes the Se and Sp sum, when it is assumed that the 'cost' of a false negative result is the same as that of a false positive one. Finally, the global performance of the classifier was evaluated with the Area Under the ROC Curve (AUC).

#### 4. Results

Figures 3 depict the results of the statistical analysis described in section 3.3. 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 ( $p$ -value  $< 0.05$ ).



**Figure 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,  $p$ -value  $< 0.05$  (see section 3.3).

Table I show the classification results (Sens and Spec mean values) for each vectorcardiographic parameters studied and for the best combination of them ( $ST-T_{VD}$ ,  $T_{VDa}$  and  $SVG$ ), before and during PTCA procedure.

Table I: Classification outcomes for each computed index and for the best combination of them

		$ST_{VMa}$		$T_{VMa}$		$ST-T_{VD}$		$T_{VDa}$		$STC_{VM}$		$SVG$		$ST-T_{VD}$ , $T_{VDa}$ and $SVG$	
		Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec
before-PTCA		63.93	69.25	82.80	69.75	67.07	69.88	58.07	79.50	71.33	54.50	69.53	81.25	90.07	84.31
during-PTCA	1 <sup>st</sup> min	75.00	50.88	82.67	67.38	88.40	94.19	80.80	83.38	75.07	76.94	68.80	73.75	92.40	93.31
	2 <sup>nd</sup> min	44.53	46.88	75.07	72.69	92.53	96.38	85.07	84.00	83.87	78.63	60.87	81.88	94.60	96.88
	3 <sup>rd</sup> min	53.40	55.06	79.93	70.69	95.07	97.56	86.27	88.88	84.47	81.88	57.27	76.56	96.87	97.56
	4 <sup>th</sup> min	51.87	63.25	78.20	68.69	95.00	97.63	89.00	88.81	88.87	82.00	66.67	61.19	97.60	98.19
	5 <sup>th</sup> min	46.20	75.81	72.60	70.56	96.53	98.25	91.13	90.50	87.07	83.50	62.20	63.00	99.53	99.38

Table II shows the Area Under the ROC Curve (AUC), for classification schemes using only one index at a time and using the parameters  $ST-T_{VD}$ ,  $T_{VDa}$  and  $SVG$  combined.

Table II Area Under the ROC Curve (AUC) for different classification schemes

	$ST_{VMa}$		$T_{VMa}$		$ST-T_{VD}$		$T_{VDa}$		$STC_{VM}$		$SVG$		$ST-T_{VD}$ , $T_{VDa}$ and $SVG$	
	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec	Sens	Spec
before-PTCA	0.73	0.78	0.76	0.68	0.63	0.83	0.91							
during-PTCA	1 <sup>st</sup> min	0.64	0.77	0.95	0.85	0.82	0.81	0.98						
	2 <sup>nd</sup> min	0.43	0.78	0.98	0.89	0.89	0.77	0.99						
	3 <sup>rd</sup> min	0.55	0.75	0.98	0.91	0.92	0.72	1.00						
	4 <sup>th</sup> min	0.62	0.73	0.99	0.92	0.94	0.67	1.00						
	5 <sup>th</sup> min	0.61	0.70	0.99	0.93	0.94	0.66	1.00						

## 5. Discussion and Conclusions

Several studies have demonstrated the potential automated vectorcardiographic analysis usefulness to evaluate cardiac changes during ischemia or infarction [5-11]. Furthermore, in [9], Jensen *et al.* compared on-line computerized VCG's derived from 12-lead ECG's, 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  $STC_{VM}$  and  $SVG$  parameters.

Also these two conventional indexes, here in we examined 4 vectorcardiographic parameters computed in the ST-T interval to further describe cardiac dynamic changes during an episode of acute ischemia induced by PTCA.

On the basis of the statistical analysis, it can be observed in figure 3 that all the vectorcardiographic parameters (with same exception: the  $ST_{VMa}$  for 2<sup>nd</sup> and 3<sup>rd</sup> min during PTCA and  $SVG$  before-PTCA) produced significant differences ( $p$ -value < 0.05) between healthy and ischemic populations, before and during PTCA. Besides, the four proposed parameters, similar to conventional indexes, tend to gradually increase its mean value during angioplasty. This similar behaviour could be used in a combined analysis to improve monitoring of acute myocardial ischemia.

The discriminant analysis (see Table I) indicates that the vectorcardiographic parameter with the best global performance was  $ST-T_{VD}$ , which reached Sen=96.5%, Spec=98.2%, and AUC=0.99.

Moreover, minute-by-minute statistical comparison of the PTCA against a healthy population shows that acute ischemic patients monitoring is greatly enhanced when the parameters  $ST-T_{VD}$ ,  $T_{VDa}$  and  $SVG$  are used in the classification, reaching **Sens = 99.5% and Spec = 99.4%**, at the 5<sup>th</sup> minute of the PTCA. Meanwhile, the best classification using only the conventional  $STC_{VM}$  or  $SVG$  indexes, reaching values of Sens = 88.9 % and Spec = 82.0% at the 4<sup>th</sup> minute the occlusion, which are lower

than those reported above. Additionally, the best AUC value (see Table II), using the parameters  $ST-T_{VD}$ ,  $T_{VDa}$  and  $SVG$  is  $AUC = 1.00$ , after the 3<sup>th</sup> 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 [18].

In conclusion: The proposed technique based on vectorcardiographic study could be used in addition to the conventional ST-T analysis for a better monitoring of ischemic patients. 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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