Bivariable analysis of ventricular late potentials in high resolution ECG records

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Abstract. In this study the bivariable analysis for ventricular late potentials detection in high-resolution electrocardiographic records is proposed. The standard time-domain analysis and the application of the time-frequency technique to high-resolution ECG records are briefly described as well as their corresponding results. In the proposed technique the time-domain parameter, QRSD and the most significant time-frequency index, ENQRS are used like variables. A bivariable index is defined, that combines the previous parameters. The propose technique allows evaluating the risk of ventricular tachycardia in post-myocardial infarct patients. The results show that the used bivariable index allows discriminating between the patient’s population with ventricular tachycardia and the subjects of the control group. Also, it was found that the bivariable technique obtains a good valuation as diagnostic test. It is concluded that comparatively, the valuation of the bivariable technique as diagnostic test is superior to that of the time-domain method and the time-frequency technique evaluated individually.

1. Introduction
Within the group of cardiovascular pathologies, which are the first cause of mortality in the developed countries [1], the acute myocardial infarction (AMI) is responsible of the 75% of cardiac death. The patients who survive the infarct can develop during the first year a malign ventricular tachycardia (VT) with a probable death, caused by a reentry mechanism generated in the infarction zone, which alter the pattern of normal conduction of the cardiac electrical impulse [2].

A special type of cardiac electrical signals denominated ventricular late potentials (VLP) can be detected in post-infarct patients with this reentry arrhythmogenic substrate. The generation of these potentials indicates a greater risk to develop spontaneous VT that can possibly end with patient’s sudden death. Therefore, an early detection of VLP can identify post-infarct patients with high risk of VT.

The VLP are signals of very low amplitude (in the range of µV) and high frequential content (between 40 and 250 Hz), that are located at the end of QRS complex and in the initial part of ST segment [3]. Due to these characteristics, the VLP are not detectable in the conventional surface electrocardiogram (ECG). For this reason, other electrocardiographic techniques must be used in order to detect these cardiac micropotentials. The high-resolution ECG (HRECG) is the specific electrocardiographic technique oriented to the detection of VLP. This technique has a greater amplitude resolution (converters A/D of 12 or more bits are generally used) and a sample rate greater than 1 KHz. The main disadvantage of HRECG in the detection of VLP is related to the low signal to
noise ratio (SNR) of these micropotentials, which are usually masks by noise. The technique most widely used to improve the SNR of VLP is the signal averaging with temporal coherence. This technique consists of the averaging a set of beats previously detected and aligned. The application of this method results in the so called signal-averaged HRECG [4].

In a previous study, the results of time-domain analysis of VLP in signal-average HRECG records [5] were exposed. In another paper, a VLP analysis technique by means of time-frequency representations (TFR) applied to signal-averaged HRECG records was put forward [6]. Both methods were applied in signal-average HRECG records acquired in: a) a group of patients with a previous history of AMI who later showed ventricular tachycardia and b) a population of patients without evidences of cardiac disease considered like control.

In this paper, a diagnostic index is trying to be defining as the result of some kind of combination between the best of temporal parameters and the most significant time-frequency (T-F) index, of VLP analysis. The purpose of this study is establish if the mentioned index allows a better evaluation of VT in post-infarct patients than that obtained with the temporal and T-F parameters individually.

2. Materials

In this study, it has been used the results of time-domain analysis and T-F analysis of 132 HRECG records of patients clinically classified in 2 groups: a) VT group: made up of 59 patients who have undergone a AMI and later suffered ventricular tachycardia (spontaneous or induced during electrophysiological study) and b) LAR group: made up of 73 patients without evidences of cardiac disease and therefore considered with low risk of arrhythmias. All the records were obtained with the HRECG commercial system Predictor® (Corazonix Corp.), in the Veterans Hospital of Oklahoma, U.S.A. The orthogonal XYZ leads were acquired during 10 minutes, with a sample frequency of 2000 Hz.

3. Methodology

3.1. Time-Domain Analysis of HRECG

The time-domain analysis is the standard technique of VLP detection in signal-averaged HRECG records [7]. This technique is based in the evaluation 3 time-domain indexes calculated on the temporal vector magnitude (TVM) of the averaged and filter XYZ leads.

This TVM is obtained consecutively applying to the XYZ leads of a continue HRECG record, the algorithms of detection of QRS complexes, alignment and averaging of cardiac cycles, so a signal-averaged HRECG record is obtained. After that, the averaged signal of each lead is filtered then the filtered leads Xf, Yf and the Zf are combined in the so call vector magnitude, defined in (1). Next the initial (QRS_{ON}) and final (QRS_{OFF}) QRS complex points are determined over the TVM. Finally, the three time-domain standard parameters [7], [8] QRSD, LAS40 and RMS40 on VLP detection are estimated.

\[
VMT = \sqrt{Xf^2 + Yf^2 + Zf^2}
\]  

(1)

In this study only the QRSD index, defined in (2), was used. Since the mentioned index is the one that had the best diagnostic valuation in a previous study of our group [5].

\[
QRSD = QRS_{OFF} - QRS_{ON}
\]  

(2)

Furthermore, it must be indicated that the standard documents [7], [8] has defined abnormal values the 3 time-domain parameters, for QRSD case this value is established to be superior than 114 ms.
3.2. Time-Frequency Analysis of HRECG
For the T-F analysis of the HRECG, different time-frequency representations (TFR) were applied to the vector magnitude (VM) of the HRECG records. Two TFR of Cohen’s class were used [9]: a) Wigner-Ville Distribution (WVD) and b) Choi-Williams Distribution (CWD). After the previous TFR were applied to the VM, three different energy indexes were calculated: a) Energy of VLP \((E_{VLP})\), b) Energy of the VLP normalized with respect to the one of the QRS complex \((E_{QRS})\) and c) Energy of the VLP normalized with respect to the total energy of the beat \((E_{TOTAL})\). These 3 indexes are defined in (3), (4) and (5), respectively.

\[
E = \sqrt{\frac{\sum_{f=f_{\text{min}}}^{f_{\text{max}}} \sum_{t=t_{\text{min}}}^{t_{\text{max}}} (\text{TFR}_{gf})^2}{k}} \quad (3)
\]

where \(t_{\text{min}}\) and \(t_{\text{max}}\) represent the temporal limits of T-F plane region where it is considered according to the energy that is being calculating. Analogously, \(f_{\text{min}}\) and \(f_{\text{max}}\) represent the frequential limits of the TFR. The constant \(k\) constitutes a normalization parameter and it is computed from the product of the number of rows and columns of the resulting T-F region after the election of \(t_{\text{min}}, t_{\text{max}}, f_{\text{min}}\) and \(f_{\text{max}}\).

\[
E_{\text{QRS}} = \frac{E_{\text{VLP}}}{E_{\text{QRS}}} \quad (4)
\]

\[
E_{\text{TOTAL}} = \frac{E_{\text{VLP}}}{E_{\text{TOTAL}}} \quad (5)
\]

\(E_{\text{VLP}}, E_{\text{QRS}}\) y \(E_{\text{TOTAL}}\) are calculated varying the T-F limits of (3).

In a previous study of our group [6], it has been determined that \(E_{\text{QRS}}\) calculated in the T-F region of \([-55 \text{ ms} , \text{QRS}_{\text{off}} + 25 \text{ ms} ; 55 \text{ Hz} 250 \text{ Hz}\] for WVD is the most significant diagnostic index for VT and LAR groups.

3.3. Bivariable Analysis of HRECG
In this study, a bivariable analysis between the time-domain index, QRSD, and the time-frequency parameter for the WVD, \(E_{\text{QRS}}\), was made. Illustrating \(E_{\text{QRS}}\) values on the abscissas axis and QRSD values on the Y-axis, for the two groups, LAR and VT; it is possible to set down a straight line which separates both groups. The equation of this straight line can be written down like:

\[
QRSD = a \times EN_{\text{QRS}} + b \quad (6)
\]

where \(a\) represents the slope of the line and \(b\) is the y-intercept. The value for the slope which best separate both groups was empirically determined; and it is \(a = 64\).

In the other hand, this straight line defines a threshold which separates the control group (LAR) from the VT patients. The belonging conditions are defined in (7) and (8). So, the patients that satisfy (7) condition belong to VT group, while those who fulfill (8) condition are included in LAR group.

\[
QRSD - 64 \times EN_{\text{QRS}} > b \quad (7)
\]

\[
QRSD - 64 \times EN_{\text{QRS}} \leq b \quad (8)
\]
3.4. Diagnostic Value of Bivariable Analysis
In order to evaluate the effectiveness of bivariable analysis of HRECG as diagnostic test, it had been constructed, for different values of b, the ROC (Receiver Operating Characteristic) curves [10]. In these curves sensitivity vs. (1-specificity) for different cut points are illustrated. Sensitivity (SEN) is defined as the probability of correctly classify an individual whose real state is the one defined as positive with respect to the condition that the clinical test studies. The specificity (SPE) is the probability of correctly classify an individual whose real state is the one defined as negative [11]. ROC curves provide a global representation of the diagnostic accuracy. They are always increasing, reflecting the relation between SEN and SPE. If the diagnostic test considered did not allow discriminating between groups, curve ROC would be a diagonal line that links the left inferior and right superior vertices. As the exactitude of the test increases the curve moves from the diagonal towards the left superior vertex (100% of SEN and 100% of SPE) corresponding to a test of perfect discrimination between groups.
In addition to SEN and SPE it is common to use the diagnostic indexes of positive predictive value (PPV), and negative predictive value (NPV). Where, PPV is the proportion of patients with positive test results who are correctly diagnosed and NPV is the proportion of patients with negative test results who are correctly diagnosed [12].

4. Results

4.1. Time-Domain Analysis of HRECG
The mean and standard deviation for QRSD index, obtained for both groups, LAR and VT, are shown in table 1. See, that QRSD mean value for post-infarct patients of VT group is grater than those of LAR group [5].

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Table 1. Mean value and standard deviation of QRSD index for patients of LAR and VT groups.

| Index   | LAR Group     | VT Group     |
|---------|---------------|--------------|
| QRSD (ms) | 103.58 ± 18.53 | 141.99 ± 28.33 |
```

4.2. Time-Frequency Analysis of HRECG
The mean and standard deviation for ENQRS (WVD) index, obtained for both groups, LAR and VT, are shown in table 2. It can be seen, that the mean value of this index is superior for LAR group compared with that for VT group [6].

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Table 2. Mean value and standard deviation of ENQRS (WVD) index for patients of LAR and VT groups.

| Energy   | LAR Group     | VT Group     |
|----------|---------------|--------------|
| ENQRS (WVD) | 0.634 ± 0.266 | 0.214 ± 0.188 |
```

4.3. Bivariable Analysis of HRECG
Conditions (7) and (8) were applied to the 132 HRECG records using different values of b. As a result, a threshold straight line which better separates LAR and VT groups was obtained, and it is shown in figure 1 for b=104. Also, the dispersion for LAR and VT groups using ENQRS y QRSD indexes is shown in the same figure.
4.4. Diagnostic Value of Bivariable Analysis

In order to evaluate the effectiveness of bivariable analysis of HRECG as a diagnostic tool, a ROC curve of the threshold straight line for different values of $b$, was constructed and it is shown in figure 2. The used cut values are exposed in table 3. With a comparative aim in the same figure the ROC curves of ENQRS and QRSD indexes, obtained in previous studies [5], [6], are shown.

**Table 3. $b$ values used for the different cut points of figure 2.**

| Point | A | B | C | D | E | F | G | H | I | J |
|-------|---|---|---|---|---|---|---|---|---|---|
| $b$ value | 194 | 184 | 174 | 164 | 154 | 144 | 134 | 124 | 114 | 104 |

| Point | K | L | M | N | O | P | Q | R | S |
|-------|---|---|---|---|---|---|---|---|---|
| $b$ value | 94 | 84 | 74 | 64 | 54 | 44 | 34 | 24 | 14 |

See that the 3 ROC curves are near to the superior left vertex of the graph, point that corresponds to an ideal test of perfect discrimination. As well, the curve of bivariable analysis is located above the other two. Also on this curve the J point, corresponding to a cut value of $b=104$, is the one that shows the best diagnostic indexes for SEN, SPE, PPV and NPV. Replaced $b$ in (6), the straight line defined in (9) is obtained.

$$QRSD = 64 \times EN_{QRSD} + 104$$ (9)
In table 4 the best statistics valuation for the time-domain parameter (QRSD), the T-F index (EN_QRS) and the threshold straight line of bivariable analysis are shown.

### Table 4. Diagnostic indexes for the time-domain parameter QRSD, the T-F index EN_QRS (WVD) and for the bivariable combination defined in (9).

| Index               | SEN(%) | SPE(%) | PPV (%) | NPV (%) |
|---------------------|--------|--------|---------|---------|
| QRSD (ms)           | 86.4   | 80.8   | 78.5    | 88.1    |
| EN_QRS (WVD)        | 83.05  | 86.3   | 83.05   | 86.3    |
| QRSD=64xEN_QRS+104  | 86.44  | 93.15  | 91.07   | 89.47   |

5. Discussion

The results of the time-domain analysis for the QRSD parameter, exposed in table 1, show the mean of this index in VT group was superior to that of LAR group. These outcomes are in concordance with the abnormality values established in the standard document and with the medical history of the post-infarct patients with high VT risk. In reference to the QRSD valuation as a diagnostic test, the ROC curve of figure 2 and also the diagnostic indexes of table 4, gives it a good valuation.

From table 2 of T-F analysis comes up that EN_QRS (WVD) index shows a mean value grater in LAR group than in VT group. In the other hand, from figure 2 and table 4 result that this T-F index obtains a good valuation as diagnostic test.

Finally, the results of bivariable analysis illustrated in figure 1 show that the straight line QRSD=64xEN_QRS+104 discriminates the LAR patients from those of VT group, establishing thus itself like a threshold between both groups.

Also, the exposed results in figure 2 and table 4 show that bivariable analysis of signal average HRECG is the one which obtains the best valuation as diagnostic test and the highest diagnostic indexes, in comparison with the other two parameters consider in an individual way.
6. Conclusion

From time-domain analysis can be concluded that the QRSD, like a diagnostic test, is valuated satisfactorily in the evaluation of the VT risk in post-infarct patients. Also, it was observed that SEN, SPE, PPV and NPV values for this index are high.

In the same way, it is concluded that the $E_{\text{QRS}}$ (WVD) index from the T-F analysis is efficient like diagnostic test in the VLP analysis. In addition, the results for SEN, SPE, PPV and NPV indexes are also elevated, locating in the same range of those of QRSD.

In this study, it has been done a bivariable analysis of VLP in signal average HRECG records of a group made up of 59 patients with a previous history of acute myocardial infarction and later suffered ventricular tachycardia and in a group of 73 patients without evidences of cardiac disease used like control group (LAR).

The objective of this study was to define a diagnostic index resultant of the combination of time-domain parameter, QRSD, and T-F index, $E_{\text{QRS}}$, for VLP analysis that allows the evaluation of VT risk in post-infarct patients. And also, determine if this analysis is superior, like diagnostic test, to the time-domain analysis and to the T-F technique, both consider individually.

The results found indicate that the combination $QRSD = 64 \times E_{\text{QRS}} + 104$ constitutes a threshold which separates the LAR patients from those of VT group. Also the bivariable analysis technique of signal average HRECG records obtains the best valuation as diagnostic test for evaluate VT risk in post-infarct patients. Showing, for $b = 104$, values of SEN, SPE, PPV and NPV superior to those of time-domain analysis and T-F analysis used individually.

7. Future Work

As future work of this investigation studies in more numerous populations of post-infarct patients are proposed to be done, in order to obtain results more representatives statistically.

In the other hand, other analysis indexes should be examined and new VLP analysis techniques like wavelet transform should be proposed, in order to improve the correct classification percentages of VT and LAR group patients.

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