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Analysis of QRS loop changes in the Beat-to-Beat Vectocardiogram of Ischemic Patients undergoing PTCA

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Abstract— **In the present work, we have studied dynamic changes of QRS loop in the Vectocardiogram (VCG) of 80 patients that underwent Percutaneous Transluminal Coronary Angioplasty (PTCA). The VCG was obtained for each patient using the XYZ orthogonal leads of their electrocardiographic (ECG) records acquired before, during and after PTCA procedure. In order to analyze the variations of VCG, it has been proposed in this study the following parameters a) Maximum module of the cardiac depolarization vector, b) Volume, c) and Area of vectocardiographic loop corresponding to the QRS complex of each beat, d) Maximum distance between Centroid and the Loop, e) Angle between the XY plane and the Optimum Plane, f) Relation between the Area and Perimeter. The results obtained indicate that the parameters proposed show significant statistics differences (p-value<0.05) before, during (with some exceptions at the first minute of balloon inflation) and after PTCA. We conclude that the variations observed in the proposed parameters correctly represent not only the morphological changes in the depolarization VCG but also they reflect the modifications in the levels of cardiac ischemia induced by PTCA.**

I. Introduction

The myocardial ischemia is a cardiac pathology characterized by the decompensation of myocardial oxygen supply and demand. It is frequently associated to coronary atherosclerosis, which blocks the normal flow of blood towards the cardiac muscle. Shortly after the beginning of insufficient myocardial perfusion, some changes appeared in the electrocardiogram (ECG) such as ST segment deviations [1], T wave alternans (TWA) [2] and modifications in the duration of this wave [3], due to alterations in the process of ventricular repolarization. Similarly, other studies have shown that QT interval, the upward and downward QRS slopes and the duration of the QRS complex suffer variations during one episode of ischemia in PTCA [1], [4]. This indicates that not only the waves and segments related to ventricular repolarization (T wave, ST segment) are modified in the ECG records but also the characteristic waves of ventricular depolarization (Q, R and S waves) are altered during ischemia.

PTCA provides an excellent model to investigate the electrophysiological changes of transmural ischemia. The sudden complete coronary occlusion produced by balloon angioplasty allows the study of the initial minutes of the ischemic process [5]. Several studies have shown different ECG changes evoked by PTCA when the occlusion was prolonged [5], [6].

During the last decade, the Vectocardiogram (VCG) has been proposed as a tool to analyze the prognostic significance [7] and to study the changes of QRS complex [8] during PTCA. VCG is defined as the graphic record of the direction and magnitude of the characteristic electric forces of heart activity during a cardiac cycle. Several studies have shown different ECG changes evoked by PTCA during the time course of the ischemic process.

In a previous study of this group we analyzed the dynamic changes of QRS loop in ischemic patients undergoing PTCA [9]. The changes were analysed in the frontal plane of VCG determined from the standard leads I and III. A limitation of this work is that only examines the VCG changes in this plane disregarding other possible variations in other planes.

In order to overcome this limitation, in this study we propose the 3-D analysis of the VCG constructed from XYZ orthogonal leads. The dynamic changes of QRS loop are statically evaluated in each detected beat by these parameters: Maximum Module of the Depolarization Vector (MMDV), Volume (V), Planar Area (PA), Maximum Distance between Centroid and the Loop (MDCL), Angle between the XY plane and the Optimum Plane (AXYOP) and Relation between the Area and Perimeter (RAP). In this way, the aim of this study is to analyze the ability of these parameters to describe the dynamic VCG changes during PTCA procedure.

II. Materials

The study group consists of 80 ischemic patients (53 males, 27 females) at the Charleston Area Medical Center in West Virginia receiving elective PTCA in one of the major coronary arteries (STAFF III study). The occlusion period was of 4 minute 26 seconds in average considerably longer than that of usual PTCA procedures because the treatment protocol included a single prolonged occlusion rather than a series of brief occlusions. The locations of the 80 dilations were: left anterior descending artery (LAD) in 28 patients

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right coronary artery (RCA) in 35 patients and left circumflex artery (LCx) in 17 patients.

Eight leads (V1-V6, I, II) were recorded using equipment by Siemens-Elena AB (Solna, Sweden) and digitized at sampling rate of 1000 Hz and amplitude resolution of 0.6 μV. Leads III, aVR, aVL and aVF were derived from leads I and II. Synthesized orthogonal XYZ leads were also obtained from the Inverse Dower transform [10].

For each patient considered in the study two ECG records were analyzed, one obtained before angioplasty (denoted as Control Recording) and other obtained during and after PTCA procedure (denoted as PTCA Recording).

III. Methods

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

A. Preprocessing

All ECG records were preprocessed with a notch filter (Butterworth, 4th order, 60 Hz, bidirectional filter) in order to minimize the powerline interference and with a low-pass filter (Butterworth, 8th order, 100 Hz, bidirectional filter) to reduce high frequency noise. An additional filter, based on cubic spline interpolation, was used in order to attenuate ECG baseline drifts and respiratory artifacts. After filtering, the QRS complexes and their corresponding endpoints were detected in each ECG record using a modified algorithm of the QRS detector proposed by Pan and Tompkins [11].

B. VCG Estimation

The VCG is obtaining by drawing simultaneously in a 3-D plot the instantaneous amplitudes of XYZ orthogonal leads for each time sample in the temporal interval corresponding to QRS complex, that is, from the starting point of Q wave (or R if there is not Q) to the final point of S wave (or R if there is not S).

Figure 2 illustrates the evolution of VCG loop corresponding to averaged QRS complex obtained for the first minute of Control ECG and for each 30 seconds segment of the 3 initial minutes of PTCA recording. It can be seen that the QRS loop exhibits important morphologic changes during PTCA.

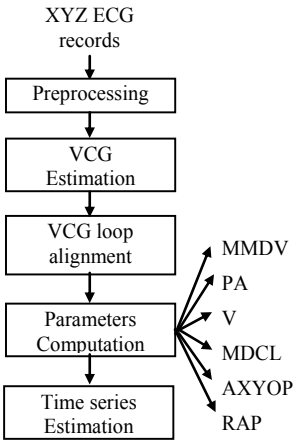

Fig.1. General diagram of the proposed technique for the analysis of VCG changes of QRS loop in ischemic patients undergoing PTCA.

C. VCG loop alignment

In order to analyze the beat-to-beat variations of QRS loops, it is previously necessary to align them. The spatial alignment of VCG loops compensates the changes in the orientation of the cardiac electrical axis caused by various extracardiac factors, like as the respiratory induced movements of the heart [12].

The VCG spatial alignment problem can be resolved by obtaining the Rotation (R) and Translation (T) Matrices that allow to align the VCG of each beat in ECG record with a VCG template obtained from the averaged beat of the first minute of Control Recording.

In this work, R and T matrices were obtained by using the algorithm proposed by *Arun et al.* [13]. It is based on Singular Values Decomposition (SVD) and gives a closed solution in the computation of both matrices. In Fig.3.a it can be seen 7 non-aligned VCG loops with their corresponding centroids (in red) and the VCG template (in blue), whereas in Fig. 3.b shows the same 7 VCG loops after alignment process. The VCGs correspond to the same patient of Fig. 2.

D. Parameters Computation

The following parameters were computed from the VCG corresponding to QRS loop for each detected beat in Control and PTCA recordings.

1) Maximum Module of the Depolarization Vector (MMDV): In order to find it, the module vector for each coordinate (X, Y, Z) of VCG is initially calculated, and then the maximum value is obtained (Fig. 4).

2) Volume (V): In order to achieve a more accurate estimation of the volume of the 3D VCG representation, it

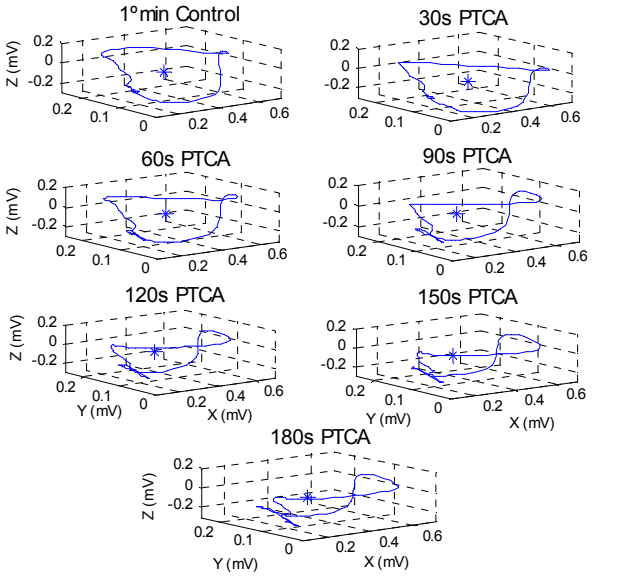

Fig.2. Evolution of VCG loop corresponding to averaged QRS complex in Control Recording and for each 30 second segment in PTCA Recording of patient # 51.

has been found the set of points that produce the minimum convex volume (using the "Convex Hull" technique[1]), and that contain all points of VCG loop. Then, the volume of this convex figure is evaluated.

3) Planar Area (PA): It is the estimated area of the loop obtained by projecting the VCG on the best adjusted plane (*VCG_proy*) computed by least mean squares (Fig. 4).

4) Maximum Distance between Centroid and the Loop (MDCL): In order to find it, the centroid of VCG loop is initially estimated and then the euclidean distance from this centroid to each point of the loop is determined in order to find its maximum value (Fig.4).

5) Angle between the XY plane and the Optimum Plane (AXYOP): Due to the VCGs are spatially aligned, the variations of the angle between the optimum plane estimated for the computation of PA parameter and XY plane are only due to morphological changes of VCG loop.

6) Ratio between the Area and Perimeter (RAP): This ratio is evaluated over the VCG projected in the optimum plane. Its variations also reflect morphological changes of VCG loop.

E. Time Series Estimation

For each proposed parameter, three time series were determined: *a) Before-PTCA*, containing its beat-to-beat values obtained from the Control Recording in the time interval from 60s to 180s; *b) During-PTCA*, containing its values taken from the PTCA recording corresponding to the three first minutes of balloon inflation; and *c) After-PTCA*; with its values corresponding to the first minute after balloon was deflated.

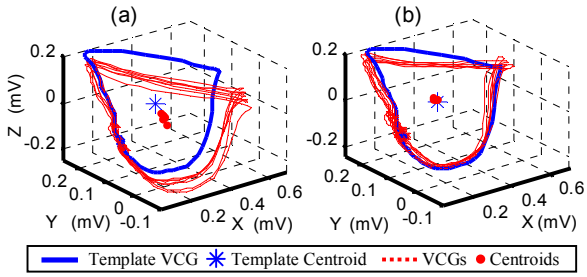

Fig.3. Example of VCG spatial alignment for the Control Recording of patient # 51. (a) VCGs before alignment. (b) The same VCGs after alignment.

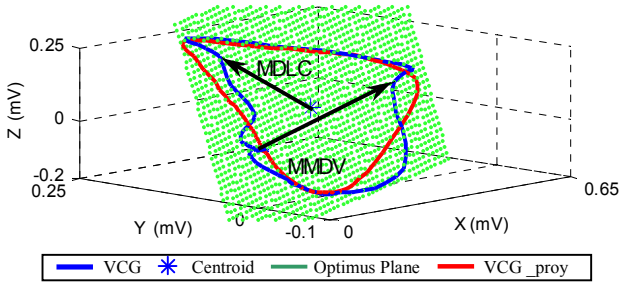

Fig. 4. Some characteristic VCG parameters computed in VCG loop for the same recording and patient of Fig. 3

[1] The Convex Hull or convex envelope for a set of points X in a real vector space V is the minimal convex set containing X

IV. RESULTS

In order to assess the changes occurred in the QRS loop during all PTCA procedure, the variations of each proposed parameter were computed for each time series (before; during and after PTCA), by calculating:

a) Mean value of the parameter at 10 s interval ($MV_{ti\text{-}tf}$) where *ti* and *tf* are the initial and final time of the considered time interval.

b) Mean value of the parameter in the first minute of the Control Recording ($MVCR_{0\text{-}60}$).

c) Normalized Absolute Differences (NAD) calculated as:

$$NAD_{ti-tf} = \frac{\left| MV_{ti-tf} - MVCR_{0-60} \right|}{MVCR_{0-60}} \qquad (1)$$

d) The average of de NAD value Before-PTCA (NAD-Ref)

Figure 5 shows the mean NAD values for each time series considering all the studied patients. In this figure it can be seen that the NAD values for all time series determined during and after PTCA are higher than their corresponding ones computed before PTCA. Also it can be observed that NAD values for V, AP and AXYPO parameters show an increased tendency during PTCA.

Table I shows the results represented by the mean value ± Standard Error of the Mean (SEM) of NAD values for each parameter considering the 80 analyzed records.

The statistical analysis was realized by comparing the average of NAD value before PTCA (NAD-Ref) versus the NAD value during and after PTCA (denoted NAD-$D_{ti\text{-}tf}$ and NAD-$A_{ti\text{-}tf}$ respectively), where *ti-tf* is the time interval used, e.g. NAD_$D_{80\text{-}90}$ indicate the NAD value between 80 and 90 s during PTCA procedure and NAD-$A_{20\text{-}30}$ is the NAD value between 20 and 30 s after PTCA procedure. To do this statistical comparison: the Gaussian distribution of the NAD values for each time series was performed using the Kolmogorov-Smirnov test. As the series did not follow a Gaussian distribution we transformed their values using function logarithm to create a Gaussian distribution.

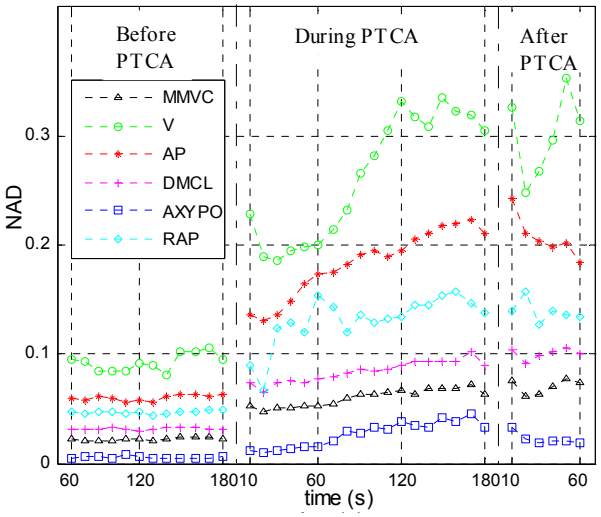

Fig. 5. Time evolution of NAD value for the proposed parameters for each time series considering all analyzed records.

TABLE I
MEAN VALUES ± SEM OF NAD FOR EACH PARAMETER (N = 80).

	MMDV	V	PA	MDCL	AXYOP	RAP
NAD-Ref	0,022 ± 0,003	0,091 ± 0,008	0,060 ± 0,006	0,032 ± 0,005	0,006 ± 0,001	0,046 ± 0,011
NAD-D_{0-10}	0,052 ± 0,008 *	0,226 ± 0,025 *	0,135 ± 0,018 *	0,074 ± 0,012 *	0,011 ± 0,002	0,088 ± 0,016
NAD-D_{20-30}	0,050 ± 0,008 *	0,183 ± 0,018 *	0,135 ± 0,018	0,073 ± 0,012 *	0,012 ± 0,002	0,122 ± 0,043
NAD-D_{50-60}	0,053 ± 0,008 *	0,196 ± 0,024	0,171 ± 0,021 *	0,078 ± 0,013 *	0,016 ± 0,005	0,152 ± 0,053 *
NAD-D_{80-90}	0,062 ± 0,011 *	0,263 ± 0,034 *	0,187 ± 0,023 *	0,087 ± 0,015 *	0,028 ± 0,007 *	0,132 ± 0,028 *
NAD-$D_{110-120}$	0,065 ± 0,010 *	0,327 ± 0,044 *	0,188 ± 0,026 *	0,089 ± 0,014 *	0,039 ± 0,011 *	0,119 ± 0,014 *
NAD-$D_{140-150}$	0,067 ± 0,010 *	0,329 ± 0,050 *	0,210 ± 0,028 *	0,093 ± 0,015 *	0,037 ± 0,009 *	0,119 ± 0,013 *
NAD-$D_{170-180}$	0,062 ± 0,010 *	0,297 ± 0,054 *	0,203 ± 0,028 *	0,088 ± 0,014 *	0,027 ± 0,007 *	0,110 ± 0,012 *
NAD-A_{0-10}	0,076 ± 0,012 *	0,324 ± 0,041 *	0,241 ± 0,031 *	0,116 ± 0,021 *	0,033 ± 0,009 *	0,134 ± 0,015 *
NAD-A_{20-30}	0,064 ± 0,009 *	0,265 ± 0,032 *	0,202 ± 0,027 *	0,104 ± 0,019 *	0,019 ± 0,006 *	0,124 ± 0,020 *
NAD-A_{50-60}	0,074 ± 0,011 *	0,308 ± 0,050 *	0,181 ± 0,023 *	0,100 ± 0,015 *	0,018 ± 0,005 *	0,130 ± 0,028 *

The symbol * denotes $p < 0.05$ versus NAD-Ref situation

Therefore, the series were analyzed by one-way analysis of variance, and the comparisons were made using Dunnet's post-hoc test. The results (Table I) show that NAD values during and after PTCA (NAD-$D_{ti\text{-}tf}$ and NAD-$A_{ti\text{-}tf}$) compared against NAD-Ref value are statistically significant (p-value < 0.05), with some exceptions at the first minute during PTCA.

V. DISCUSSION AND CONCLUSIONS

The present study examines the QRS loop changes in the Beat-to-Beat Vectocardiogram of ischemic patients undergoing PTCA procedure.

It can be seen in Fig. 2 that there are dynamic morphological changes in the QRS loop during PTCA, compared with the QRS loop before angioplasty. In order to evaluate the beat-to-beat variations of QRS loop, six parameters (MMDV, V, PA, MDCL, AXYOP, and RAP) were estimated before, during and after PTCA.

The *Normalized Absolute Differences* (NAD), has been proposed in order to assess the relative difference between the mean values of the parameter at 10 s intervals during and after PTCA respect its mean value at the first minute of Control Recording. The evolution of NAD for each parameters shown in Fig. 5, indicates that the NAD values during and after PTCA are higher than their corresponding ones computed before PTCA. Also it can be observed that NAD values for all parameters show an increased tendency during PTCA. Also, it can be seen that the evolution of the parameters RAP and V have high dispersion during PTCA, which is caused by the great difference in the values of this parameter among the studied patients. This indicates that it is not a good parameter to take inferences on the whole population. The dispersion of RAP parameter during PTCA can be due to this parameter is the ratio between the Area and Perimeter of the QRS loop whose variations are different during PTCA.

The statistical analysis shown in Table I demonstrate that the NAD values of six parameters have significant differences (with some exceptions at the first minute of the PTCA) considering all 80 records.

In conclusion, the variations observed in the VCG before during and after PTCA at the cardiac depolarization can be described correctly through the parameters suggested. Since these variations are mainly due to the variations in the cardiac perfusion. It is concluded that VCG parameters can be used in the monitoring of myocardial ischemia.

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