Study of Morphological Parameters of QRS Loop Using Singular Value Decomposition during Ischemia Induced by Coronary Angioplasty

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Abstract

In this work we studied dynamic changes of ventricular depolarization loop evolution based on the Singular Value Decomposition (SVD) technique of 80 patients that underwent Percutaneous Transluminal Coronary Angioplasty (PTCA). The 8 independent ECG leads are subjected to SVD technique and are used to construct a new representation of QRS-SVD loops. In order to analyze the variations of QRS-SVD loops before, during and after PTCA, we proposed the following parameters: Maximum Module of the Depolarization Vector, Planar Area, Maximum Distance between Centroid and the Loop, Angle between the S1S2 plane and the Optimum Plane and Ratio between the Area and Perimeter. The results indicated that the parameters proposed show significant statistics differences during and after PTCA procedure vs. control. We concluded that the variations in the QRS-SVD loop before, during and after PTCA at ventricular depolarization can be described correctly through the proposed parameters.

1. Introduction

The myocardial ischemia occurs from decompensation of myocardial oxygen supply and demand. It is frequently associated to coronary atherosclerosis. The temporary occlusion of a coronary artery derive in reversible ischemia, while a prolonged obstruction gets as result myocardial infarction with serious consequences such as malignant arrhythmias, heart failure and/or sudden death. Shortly after the beginning of insufficient myocardial perfusion, some changes appeared in the electrocardiogram (ECG) mostly at the repolarization but also at the depolarization [1]. 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. Several studies have shown different ECG changes evoked by PTCA when the occlusion was prolonged [2]. During the last decade, the Vectocardiogram (VCG) has been proposed as a tool to analyze the prognostic significance and to study the changes of QRS complex during PTCA [3]. Previously, we analyzed the dynamic changes of QRS loop in ischemic patients undergoing PTCA using the VCG constructed from XYZ orthogonal leads [4]. In the present study we propose the 3D analysis of the QRS loop evolution based on the Singular Value Decomposition (SVD) technique. When SVD technique was applied onto the 8 independent electrocardiographic leads (I, II, V1-V6), 8 components of the ECG are obtained ordered according to their importance [5]. The first three important components are considered as a vectorcardiographic signal which can be shown in a 3D space. We evaluated the dynamic changes of beat-to-beat QRS-SVD loop parameters. The aim of this study is to analyze the ability of these parameters to describe the dynamic ventricular depolarization changes during acute ischemia.

2. Data set

The study group consisted of 80 ECG records from patients at the Charleston Area Medical Center in West Virginia undergoing elective prolonged balloon occlusion during PTCA in one of the major coronary arteries (STAFF-III study) [5]. This group was selected from a total of 108 patients, with the condition that QRS complexes could be delineated during PTCA. The mean inflation duration was 4' 28" with a standard deviation of 74". Nine leads (V1-

V6, I, II, III) were recorded using equipment by Siemens-Elena AB (Solna, Sweden) and digitized at sampling rate of 1 KHz and amplitude resolution of 0.6 uV. Two ECG were acquired for each patient in supine position. First, a control 5-minute ECG was recorded some time before the PTCA procedure and the second ECG was recorded during and after PTCA procedure. The locations of the 80 dilations were: left anterior descending coronary artery (n=28), right coronary artery (n=35) and left circumflex coronary artery (n=17).

3. Methods

3.1. 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 Cut off, bidirectional filter) to reduce high frequency noise. Cubic spline interpolation was used for baseline wander. After filtering, the QRS complexes and their corresponding endpoints were detected in each ECG record using a modified algorithm of the QRS detector proposed in [6].

3.2. Processing

The eight independent leads of preprocessed ECG records were subjected to SVD technique obtaining the new leads $\mathbf{s_i}$ (i = 1,...,8). Therefore the depolarization inscription vectors in $\mathbf{s(n)} = [\mathbf{s_1(n)}, \mathbf{s_2(n)}, \mathbf{s_3(n)}]$ pseudo-leads were called QRS-SVD loop. Fig. 1 shows the evolution of QRS-SVD 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-SVD loop exhibits morphologic changes during PTCA.

In order to analyze the beat-to-beat variations of QRS-SVD loops, it is previously necessary to align them. The spatial alignment of QRS-SVD 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 [7]. The VCG-SVD of each beat was aligned with a VCG-SVD template obtained from the averaged beat of the first minute of Control Recording [8]. In Fig. 2a it can be seen four non-aligned QRS-SVD loops with their corresponding centroids (dotted line) and the VCG-SVD template (filled line), whereas in Fig. 2b shows the same four VCG-SVD loops after alignment process.

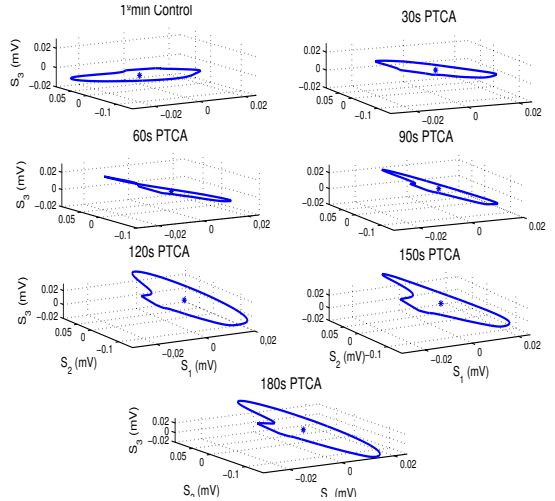

Figure 1. Evolution of VCG-SVD loop corresponding to averaged QRS complex in Control Recording and for each 30 second segment in PTCA Recording of patient #51.

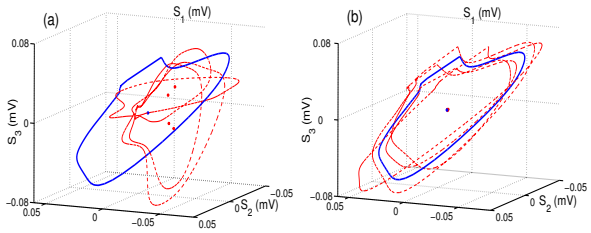

Figure 2. Example of VCG-SVD spatial alignment for the Control Recording of patient #51. (a) VCG-SVDs before alignment. (b) The same VCG-SVDs after alignment.

3.3. Parameters computation

The following parameters were computed from the VCG-SVD corresponding to QRS-SVD 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 $\mathbf{s(n)}$ of VCG-SVD is initially calculated, and then the maximum value is obtained (Fig.3). 2) Planar Area (PA): It is the estimated area of the loop obtained by projecting the VCG-SVD on the best adjusted plane (VCG-proy) computed by least mean squares (Fig.3). 3) Maximum Distance between Centroid and the Loop (MDCL): In order to find it, the centroid of VCG-SVD 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. 3). 4) Angle between the $[\mathbf{s_1(n)}, \mathbf{s_2(n)}]$ plane and the Optimum Plane (AS_1S_2OP): Due to the VCG-SVD are spatially aligned, the variations of the angle between the optimum plane estimated for the computation of PA parameter and $[\mathbf{s_1(n)}, \mathbf{s_2(n)}]$ plane are only due to morpho-

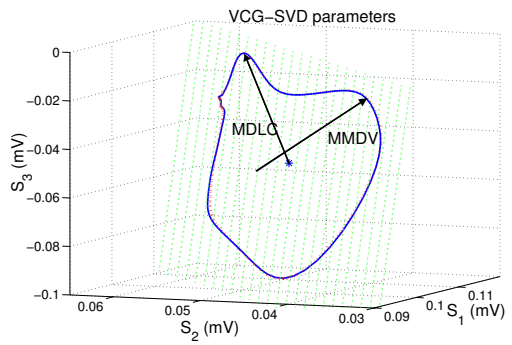

Figure 3. Some characteristic parameters computed in VCG-SVD loop (patient #51). VCG-SVD (filled line), VCG-proy (dotted line), optimum plane (plane dotted line)

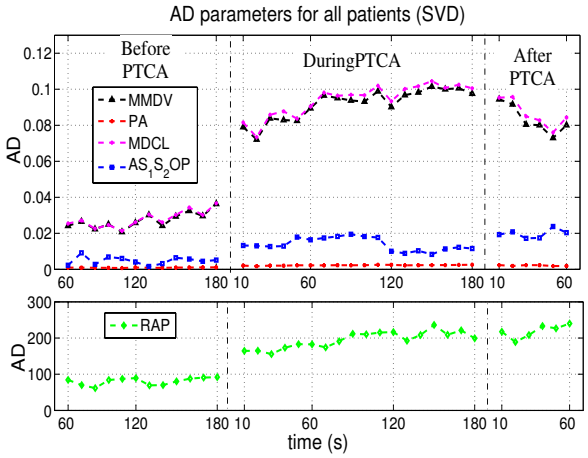

Figure 4. Time evolution of AD value for the proposed parameters for each time series considering all analyzed records.

logical changes of VCG-SVD loop. 5) Ratio between the Area and Perimeter (RAP): This ratio is evaluated over the VCG-SVD projected in the optimum plane. Its variations also reflect morphological changes of VCG-SVD loop.

3.4. Time series estimation

For each proposed parameter, 3 time series were determined: a) Before-PTCA, containing its beat-to-beat values obtained from the Control in the time interval from 60s to 180s; b) During-PTCA, containing its values taken from the PTCA recording corresponding to the 3 first minutes of balloon inflation; and c) After-PTCA; with its values corresponding to the first minute after balloon was deflated.

4. Results

In order to assess the changes occurred in the QRS-SVD 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 ($MV_{\text{ti-tf}}$) 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 ($MVCR_{\text{0-60}}$). c) Absolute Differences (AD) calculated as:

$$AD_{\text{ti-tf}} = |MV_{\text{ti-tf}} - MVCR_{\text{0-60}}| \quad (1)$$

d) The average of the AD value Before-PTCA (AD_{Ref}). Figure 4 shows that the AD values for all time series determined during and after PTCA are higher than before PTCA. Table I shows the results represented by the mean value $\pm$ SEM of AD values for each parameter considering the 80 analyzed records. The statistical analysis was realized by comparing the average of AD value before PTCA (AD_{Ref}) versus the AD value 'during' and after PTCA (denoted $AD_{\text{Dti-tf}}$ and $AD_{\text{Ati-tf}}$ respectively), where ti-tf is the time interval used, e.g. $AD_{\text{D80-90}}$ indicate the AD value between 80 and 90 s during PTCA procedure and $AD_{\text{A20-30}}$ is the AD value between 20 and 30 s 'after' PTCA procedure. A non-parametric test was used because the underlying distribution of the AD values for each time series were unknown. Therefore, the series were analyzed by Kruskal-Wallis test and the comparisons were made using Dunn's post-hoc test. The results shows that MMDV, PA, MDCL values during and after PTCA compared against their corresponding values before PTCA are statistically significant. However, few and nothing significant differences were found for RAP and AS_1S_2OP parameters.

5. Discussion and conclusions

5.1. QRS-SVD loop alignment

The present study examines the QRS-SVD 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-SVD loop during PTCA, compared with the QRS-SVD loop before angioplasty. In order to evaluate the beat-to-beat variations of QRS loop, five parameters (MMDV, PA, MDCL, AS_1S_2OP, and RAP) were estimated before, during and after PTCA. The AD has been proposed in order to assess the absolute 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 AD for each parameters (Fig. 4), indicates that the AD values during and after PTCA are higher than their control. Also it can be observed that AD

Table 1. Mean values ± SEM of AD for each parameter (n=80). ^{A}p<0.05, ^{B}p<0.01, ^{C}p<0.001,*vs.* AD_{Ref}.

	MMDV (μV)	PA (μV^2)	MDCL (μV)	AS_1S_2OP (rad)	RAP (mV)
AD_{Ref}	25.8±2.7	(2.4±1.2) e03	26.2±2.7	(9.2±1.9) e-03	106.76±12.33
$AD_{\text{D0-10}}$	81.1±9.2^{C}	(3.6±1.1) e03	81.9±9.2^{C}	(17.2±4.5) e-03	200.1±26.5
$AD_{\text{D20-30}}$	83.4±9.7^{C}	(4.2±1.2) e03^{A}	84.5±9.7^{C}	(18.4±4.9) e-03	197.9±26.6
$AD_{\text{D50-60}}$	89.1±9.2^{C}	(3.9±1.2) e03^{A}	88.9±8.9^{C}	(23.9±7.8) e-03	221.08±30.37
$AD_{\text{D80-90}}$	94.9±9.6^{C}	(4.2±1.3) e03^{B}	97.1±9.6^{C}	(25.4±8.3) e-03	252.1±33.5^{A}
$AD_{\text{D110-120}}$	89.7±9.6^{C}	(4.8±1.4)e03^{B}	91.1±9.3^{C}	(19.2±3.7) e-03	251.4±37.6
$AD_{\text{D140-150}}$	99.0±10.1^{C}	(4.3±1.4) e03^{B}	100.9±9.8^{C}	(13.7±2.2) e-03	262.6±35.9^{C}
$AD_{\text{D170-180}}$	94.4±11.3^{C}	(4.3±1.5) e03^{A}	96.7±11.1^{C}	(19.0±4.5) e-03	234.1±35.9^{A}
$AD_{\text{A0-10}}$	84.2±8.6^{C}	(4.1±1.3) e03^{A}	86.1±9.0^{C}	(25.1±7.4) e-03	231.5±32.7
$AD_{\text{A20-30}}$	72.7±8.1^{C}	(4.3±1.3) e03^{B}	76.8±8.8^{C}	(24.8±9.5) e-03	241.6±36.8^{A}
$AD_{\text{A50-60}}$	68.6±8.4^{C}	(4.0±1.3) e03^{A}	72.3±8.6^{C}	(29.0±9.6) e-03^{A}	278.2±47.3^{A}

values for all parameters show an increased tendency during PTCA. Table I shows that the MMDV, PA and MDCL (with some exceptions) parameters have significant differences when were compared with control situation. Also, it can be seen that the evolution of the parameters AS_1S_2OP and RAP 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 variations observed in the VCG-SVD before during and after PTCA at the ventricular depolarization can be described correctly through the parameters proposed. It was shown that these variations are mainly due to the modifications in the cardiac perfusion. Therefore, it is concluded that the temporal evolution of VCG-SVD parameters can provide complementary information to the traditional ST-segment analysis in the clinical study of myocardial ischemia. In this study we have observed that the best parameters to discriminate acute ischemia were MMDV, PA and MDCL (Table 1). The myocardial acute ischemia modifies the electrophysiologcal properties of ventricular cells, reducing the upstroke slope and the amplitude of the action potential. Likewise, these phenomena could be reflected as a reduction in the upward and downward slopes of the QRS complex [1]. The results presented encourage the undertaking of deeper studies to better understand the relationship between QRS-SVD parameters and changes in cellular action potential level during acute ischemia.

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References

[1] Pueyo E, Sörnmo L, Laguna P. QRS slopes for detection and characterization of myocardial ischemia. IEEE Trans on Biomed Eng 2008;55(2).

[2] Wagner NB, Sevilla DC, Krucoff MW, Lee KL, Pieper KK, Bottner RK, Selvester RH, Wagner GS. Transient alterations of the QRS complex and ST segment during percutaneous transluminal balloon angioplasty on the left anterior descending coronary artery. Am J Cardiol 1988;62:1038–1042.

[3] Bacharovaa L, Mateasika A, Katinaa S, Horacekb M, Engblomc H, Wagner GS. Changes in QRS complex during PTCA: Comparison of vectorcardiographic and topographic presentation of orthogonal ecg. Inter J of Bioelectromag 2003;5:96–97.

[4] Correa R, Laciar E, Arini P, Jané R. Analysis of QRS loop changes in the beat-to-beat vectocardiogram of ischemic patients undergoing PTCA. 31st IEEE EMBS Conference 2009;Accepted.

[5] Acar B, Yi G, Hnatkova K, Malik M. Spatial, temporal and wavefront direction characteristics of 12-lead T-wave morphology. Med Biol Eng Comput 1999;37:574–584.

[6] Pan J, Tompkins W. A real-time qrs detection algorithm. IEEE Trans Biomed Eng 1985;32:230–236.

[7] Sörnmo L. Vectocardiographic loop alignment and morphologic beat-to-beat variability. IEEE Trans Biomed Eng 1998; 45(12):1401–1413.

[8] Arun KS, Huang TS, Blostein SD. Least-squares fitting of two 3-d point sets. IEEE Trans Patt Anal Mach Intell 1987; 9(5):698–700.

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