Analysis of T Wave Morphology Parameters with Signal Averaging During Ischemia Induced by Percutaneous Transluminal Coronary Angioplasty

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Abstract

Electrocardiographic repolarization abnormalities can be detected by Principal Components Analysis of the T-wave. In this work we studied the effect of signal averaging on the mean value and reproducibility of the ratio of the 2nd to the 1st eigenvalue (P_{CA}^{21}) and the absolute and relative T-Wave residuum ($T_{\mathrm{WR}}^{\mathrm{rel}}$ and $T_{\mathrm{WR}}^{\mathrm{abs}}$) in the ECG during ischemia induced by Percutaneous Transluminal Coronary Angioplasty. Results showed that $T_{\mathrm{WR}}^{\mathrm{rel}}$ and $T_{\mathrm{WR}}^{\mathrm{abs}}$ evaluated from the average of 10 complexes had lower values and higher reproducibility than those obtained from 1 complex. On the other hand P_{CA}^{21} calculated from 10 complexes did not show statistical differences versus the P_{CA}^{21} calculated on single beats. The results of this study corroborate that, with a signal averaging technique, the 2nd and the 1st eigenvalue are not affected by noise while the 4th to 8th eigenvalues are so much affected by this, suggesting the signal averaged before calculation of absolute and relative T-wave residuum.

1. Introduction

The electrocardiographic (ECG) ventricular repolarization dispersion (VRD) can be evaluated by parameters based on the Principal Component Analysis (PCA) such as the ratio of the 2*nd* to the 1*st* eigenvalue (P_{CA}^{21}) and either relative or absolute T-wave residuum ($T_{\mathrm{WR}}^{\mathrm{rel}}$ and $T_{\mathrm{WR}}^{\mathrm{abs}}$). These parameters, applied to 12-lead standar ECG quantify the spatial complexity of ventricular repolarization and may become a noninvasive diagnostic tool in different cardiac pathologies [1]. The aim of this work is to evaluate the PCA-based parameters derived from signal averages in ischemic patients. We hypothesize, according to the results of Batdorf et al. in healthy subjects [2], that the PCA-based morphology parameters obtained during ischemia in averaged ECG will present lower values and better reproducibility than when computed from a single beat. For that purpose, we evaluated VRD in the course of transmural ischemia induced by Percutaneous Transluminal Coronary Artery (PTCA) procedure [3]. The balloon-inflation PTCA provides an advantageous model of the first minutes of acute ischemia in humans, due to a total interruption of blood flow throw the ventricles.

2. Methods

2.1. Data set

The study group consisted of 93 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) [3]. This group was selected from a total of 108 patients, with the condition that T-wave could be delineated during the complete time course of ischemia. The mean inflation duration was 4' 28" with a standard deviation of 74". Eight independent ECG leads (V_1-V_6, 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. 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 PTCA intervention. The occlusion sites: left anterior descending (LAD) coronary artery in 29 patients, right coronary artery (RCA) in 45 patients and left circumflex (LCx) coronary artery in 19 patients, were also considered jointly for this study.

Table 1. Mean values ± SEM of T-wave morphology parameters. ^{A}p<0.001 and ^{B}p<0.0001 against control. ^{C}p<0.0001 represent significant differences between 10-Cx and 1-Cx.

	beats	C	O_1	O_2	O_3
$T^{\text{abs}}_{\text{WR}}$ ($m\text{V}^2$)	1Cx	0.087±0.007	0.18±0.026 ^{A}	0.211±0.029 ^{A}	0.200±0.023 ^{A}
	10Cx	0.012±0.001 ^{C}	0.037±0.004 ^{C,B}	0.046±0.004 ^{C,B}	0.041±0.004 ^{C,B}
$T^{\text{rel}}_{\text{WR}}$ (%)	1Cx	0.29±0.04	0.65±0.10 ^{A}	0.59±0.10 ^{A}	0.61±0.10 ^{A}
	10Cx	0.05±0.01 ^{C}	0.10±0.01 ^{C,B}	0.17±0.02 ^{C,B}	0.15±0.02 ^{C,B}
P^{21}_{CA} (%)	1Cx	5.92±1.07	10.27±1.23 ^{A}	9.99±1.10 ^{A}	11.45±1.34 ^{A}
	10Cx	3.80±0.45	9.26±1.25 ^{B}	9.94±1.25 ^{B}	9.62±0.02 ^{B}

2.2. ECG processing

For a total of 93 patients, the 8 ECG leads were processed in control situation and PTCA procedure respectively. The QRS fiducial points were detected on a multilead basis by an automatic QRS detector [4]. Cubic spline interpolation was used for baseline wander rejection and the ECG delineation system based on the Wavelet Transform has been used for T-wave location and delineation [5]. We analyzed the morphological T-wave parameters for both single complex (1-Cx) and average of 10 complexes (10-Cxs). Before Singular Value Decomposition (SVD) was applied on 10-Cx, we computed the running signal average of 10 beats where first the beats are aligned by a cross-correlation technique. The "template beat" was obtained through direct averaging of 10 beats. Second new jitter-corrected beats (arising from analysis windows) were used into the "final average beat" if the cross-correlation coefficient between the new beats and the "template beat" in each channel was greater than 98%, otherwise the beat is rejected. Two rejected beats were the accepted limit on the computation of each ith" final average beat". The cross-correlation coefficient was calculated from the QRS, which was segmented by taking a 200 msec. interval centered at the QRS-fiducial point previously detected [6] [4].

The computation of T-wave morphological parameters, calculated from 1-Cx and 10-Cxs, were obtained from onto N-samples windows (W_{i}), which defines ventricular repolarization phase for the i^{th} beat of ECG. These windows were calculated as the earliest and latest reliable T-wave onset and end between the 8 independent ECG leads. Afterward SVD was applied obtaining one set of 8 singular values σ_j ($j = 1, \ldots, 8$), which are ordered such that $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq ..... \geq \sigma_8 \geq 0$. SVD technique finds a system of eight orthogonal directions (S1...S8), in which S1 contains most of the ECG energy that is, it corresponds to the direction in which the ECG signal varies most. S2 contains most of the remaining ECG energy, and so forth. It has been shown that the first three directions S_1 S_2 S_3, contain 98 % of the whole ECG energy [7] representing the dipolar component, while the last 5 represent the so-called non-dipolar components of the T-wave respectively. Then we computed just as in [2]:

- The ratio of second to the first eigenvalue multiplied by 100 expressed as

$$P^{21}_{\text{CA}_i} = 100 * (\sigma^2_{i,2}/\sigma^2_{i,1}) \tag{1}$$

- The absolute T-wave residuum to quantify the non-dipolar components as the sum of the fourth to the eight eigenvalues, calculated as

$$T^{\text{abs}}_{\text{WR}_i} = \sum_{l=4}^{8} \sigma^2_{i,l} \tag{2}$$

- The relative T-wave residuum to quantify the relative contribution of $T^{\text{abs}}_{\text{WR}_i}$ with respect the total energy, calculated as

$$T^{rel}_{\text{WR}_i} = 100 * (\sum_{l=4}^{8} \sigma^2_{i,l} / \sum_{l=1}^{8} \sigma^2_{i,l}) \tag{3}$$

The 3 T-wave morphology parameters were obtained from a single complex and from the 10 complexes in the signal averaging.

3. Results

The series $T^{\text{abs}}_{\text{WR}}$, $T^{\text{rel}}_{\text{WR}}$ and P^{21}_{CA} were calculated during control and balloon inflation in PTCA procedure and, for the sake of robustness, it was applied a median filter with a windows size of 7.5 sec on the three series of parameters.

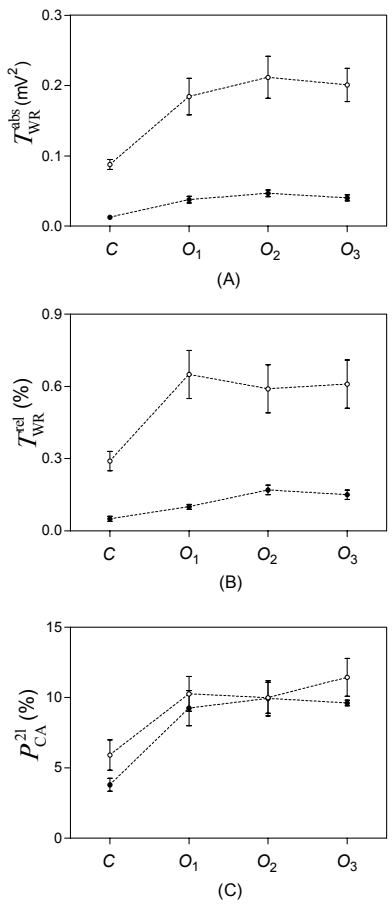

Figure 1. The effect of using a single complex versus 10 complex signal average on the mean±SEM in control and during PTCA procedure. (A) Absolute T-wave residuum, (B) Relative T-wave residuum and (C) the ratio of second to the first eigenvalue. 1-Cx (blank circle) and 10-Cx (filled circles).

We characterized 4 different time instants: T-wave morphology parameters during Control Situation (C) associated to the median value of 5 minutes just before the start of occlusion, T-wave morphology parameters during the first minute (O_1) associated to the median of 7,5 sec centered around the first minute, the second (O_2) and the third (O_3), for their respective minutes of the occlusion procedure.

We analyzed the statistical distribution of T-wave morphological parameters using the Kolmogorov-Smirnov test. Therefore a two-tailed nonparametric Mann-Whitney test was used because the parameter series did not follow a Gaussian distribution.

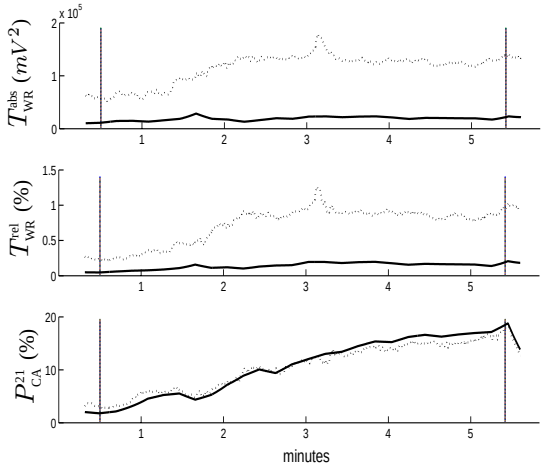

Figure 2. Example of time evolution of T-wave morphological parameters for both 1-Cx (dotted line) and 10-Cxs (black line) during PTCA procedure. The vertical lines represents the start and end of occlusion (patients #10).

Table 2. Reproducibility estimated as SDs of within-subject variance of all T-wave morphology parameters. A *p<0.0001 represents significant differences between 10-Cx and 1-Cx.

Cx	T^{abs}_{WR} (mV^2)	T^{rel}_{WR} (%)	P^{21}_{CA} (%)
1	0.027	0.09	1.27
10	0.004*	0.01*	0.99

Table 1 shows the results represented by the mean value ± of the Standard Error of the Mean (SEM) of C, O_1, O_2 and O_3 values for each T-wave morphological parameter considering the 93 analyzed records. The results demonstrated that T^{abs}_{WR}, T^{rel}_{WR} and P^{21}_{CA} values during PTCA compared against control situation were statistically significant for 1-Cx as well as 10-Cx analysis. Also we have studied the effect of ECG signal averaging *vs.* a single complex. The results shows that T^{abs}_{WR} and T^{rel}_{WR} values for 1-Cx compared against 10-Cx value are statistically significant, for both control and during PTCA procedure. However, nothing significant differences were found for P^{21}_{CA} parameter.

The mean value ± SEM of T^{abs}_{WR}, T^{rel}_{WR} and P^{21}_{CA} parameters are plotted in Figure 1, also it can be observed that T-wave morphological parameters show an increased tendency during PTCA.

Table 2 shows standard deviations (SDs) of within-subject variance of T^{abs}_{WR}, T^{rel}_{WR} and P^{21}_{CA}. For minute-to-minute observation intervals of control situation we have observed significantly less variance for both T^{abs}_{WR} and T^{rel}_{WR} as the quantities of complexes were increased from 1 to 10. We have not observed P^{21}_{CA} statistically significant dif-

ferences between 1-Cx to 10-Cxs respectively. In Figure 2 we can show time-course evolution of T_{WR}^{abs}, T_{WR}^{rel} and P_{CA}^{21} during PTCA procedure (patients #10).

4. Discussion and conclusions

We have hypothesized that PCAR parameters obtained from ECG signal averaging with 10 complexes would have lower mean values and more reproducibility than those derived from a single complex analysis during control and PTCA procedure. The obtained results indicate that:

1) T_{WR}^{abs} and T_{WR}^{rel} computed from 10-Cx show lower values, and higher reproducibility than those obtained from 1-Cx. This results suggests that a big amount of absolute and relative T-wave residuum on one beat is due to noise.

However P_{CA}^{21} with averaging did not show statistical significant with respect to P_{CA}^{21} on single beats; possibly because the numerator of P_{CA}^{21} (2*nd* eigenvalue) is not so much affected by noise as it is the numerator of relative T-wave residuum; obtained from the smaller 4-to-8 eigenvalues.

2) The results were obtained as from control situation (corresponding to patients with cardiac disease) and PTCA (corresponding acute ischemic process). The results observed were concordant with the study from healthy subject done by Batdorf et al. [2].

3) The results showed that signal averaging technique can provide more significant differences than a single complex analysis. The ECG ventricular repolarization dispersion parameters (i.e, both relative or absolute T-wave residuum) can be improved through the use of signal-averaged technique.

On the other hand, we have found the following limitations for this study. Batdorf et al. [2] shows that 200 complexes of signal averaging have lower noise and higher reproducibility than 10 complexes of signal averaging. In this work we did not increase the beats quantity into the signal average technique because dynamic ST-changes during PTCA could be affected the measure of T-wave morphology. Furthermore, we have observed increases in noise of the ECG during PTCA procedure, a phenomenon that should be quantified for different stages of the angioplasty procedure. Then, future studies are needed to investigate the optimal and maximum beats number that it is feasible to include into the average technique for PTCA studies. Also, we have analyzed the normal reproducibility or dispersion in T_{WR}^{abs}, T_{WR}^{rel} and P_{CA}^{21} during five minute. This analysis does not include any electrodes position changes as often happens in clinical applications.

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