Spatial Characterization of Ischemia in 12-lead ECG Recordings during PCI using both Depolarization and Repolarization Indices

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Abstract

Spatial characterization of ischemia is addressed by evaluating ECG-derived indices: the ST level at J point plus 60 ms, ST_{J+60}; S wave amplitude, S_a; the upward and downward QRS slopes ($\mathcal{I}_{\text{US}}$ and $\mathcal{I}_{\text{DS}}$); and high-frequency QRS in the band 150-250 Hz, HF-QRS$_{(150-250)}$ over 12-lead ECG signals recorded during prolonged elective PCI. Absolute changes of each index $\mathcal{I}$ during coronary occlusion, $\Delta_{\mathcal{I}}$, and their relative changes, $\mathcal{R}_{\mathcal{I}}$, were quantified. Mean $\bar{\mathcal{R}}_{ST_{J+60}}$ = 14.5, $\bar{\mathcal{R}}_{S_a}$ = 15.2 and $\bar{\mathcal{R}}_{\mathcal{I}_{\text{DS}}}$ = 6.2 times their normal variations in pre-PCI recordings, respectively, showed the most pronounced changes as well as a very similar and distinctive lead-profiles depending on the occlusion site. We conclude that the ECG-derived indices from the final part of the QRS complex show high sensitivity for detection of ischemia. Moreover, their spatial distributions show the largest changes in leads closest to the region adjacent to the occluded artery, which can be considered for occlusion site identification.

1. Introduction

Early diagnosis of acute ischemic heart disease is essential to optimize treatment and hence clinical outcome of this large patient population. Today changes in the repolarization phase (ST-T) of the standard ECG is the most widely used tool to detect acute myocardial ischemia. In addition to detection of the ischemia, localizing the area and estimating its severity add valuable information for risk stratifying each patient and making it possible to tailor the treatment. Important ischemia induced changes also in the depolarization phase (QRS) might add valuable information beyond the ST-T analysis. Several studies in the literature have quantified ischemia induced changes in the ECG during percutaneous coronary intervention (PCI), and have investigated the relationship between those ECG changes and the occlusion site. In [1], global ECG indices derived from the Karhunen Loéve transform were compared with local ECG indices, and combinations of both types of indices were used for identification of the occluded artery. In [2] analysis of T wave alternans (TWA) was used to provide spatial distributions of ischemia induced ECG changes as a function of the occlusion site.

In the present study we analyze recordings acquired before and during prolonged PCI-induced ischemia with the purpose of assessing the lead-by-lead spatial profiles of the ischemic changes in the ECG, with emphasis on depolarization. This analysis is made for several ECG-derived indices: classical (ST elevation, QRS duration, R and S wave amplitude) and others recently proposed (high frequency components and the slopes of the QRS complex), evaluated in groups of patients clustered according to the occluded artery: left anterior descending artery (LAD), left circumflex artery (LCX), and right coronary artery (RCA).

2. Methods

2.1. Population

The total study population comprises 83 patients wich were admitted to the Charleston Area Medical Center in West Virginia, USA, for elective PCI in one of the major coronary arteries (STAFF III dataset) [3, 4]. All ECGs were recorded using the equipment by Siemens-Elema AB (Solna, Sweden). Nine standard leads (V1-V6, I, II, and III) were recorded and digitized at a sampling rate of 1 kHz with amplitude resolution of 0.6 μV. The remaining leads were calculated to generate the standard 12-lead ECG.

For each patient, two ECG recordings were processed. The first one is a control recording continuously acquired at rest for 5 minutes in a supine position prior to the PCI procedure. The second recording was acquired during the PCI procedure with a mean occlusion duration of 4 min and 26 s (range 1 min and 30 s - 7 min and 17 s). The electrodes were located at the same position in the two recordings, either by keeping the electrodes or by marking their positions. The occlusion sites of the PCI procedures were: LAD in 25 patients, LCX in 18, and RCA in 40.

2.2. Preprocessing

All the ECG signals involved in the study are preproce-

ssed as follows: (1) QRS detection, (2) normal beats selection according to [5], (3) baseline drift attenuation via cubic spline interpolation, and (4) delineation using a wavelet-based technique [2].

2.3. Normalization procedure

Respiration and other low frequency modulations on the ECG affect the QRS complex amplitude and, consequently, the estimates of the ECG indices measured in this study. This generates variability in the quantification of the ischemia-induced ECG changes, particulary when those changes are computed as refered to the normal variations of the evaluated ECG indices. To compensate for this, an ECG signal normalization procedure is performed [6]. In brief, the normalization considers a 15-s running window centered around each processed beat $b_i(n)$, with i denoting beat index and n beat sample. The median R_{m_i} of the R wave amplitudes corresponding to the N beats within the window is computed: $R_{m_i} = median\ \{R_{i-N/2}, ..., R_{i+N/2}\}$, and the normalized beat $\hat{b}_i(n)$ is defined as $\hat{b}_i(n) = \frac{R_{m_i}}{R_i} b_i(n)$. The normalization is applied to both control and PCI recordings.

2.4. Ischemic indices

The indices $\mathcal{I}$ computed in this study are: ST level measured at J point plus 60 ms (ST_{J+60}); R and S wave amplitudes (R_a and S_a, respectively); QRS duration (QRS_d); upward ($\mathcal{I}_{US}$) and downward ($\mathcal{I}_{DS}$) slope of the QRS complex and the high frequency content of the QRS complex measured in the band 150-250 Hz ($HF\text{-}QRS_{(150-250)}$) [7].

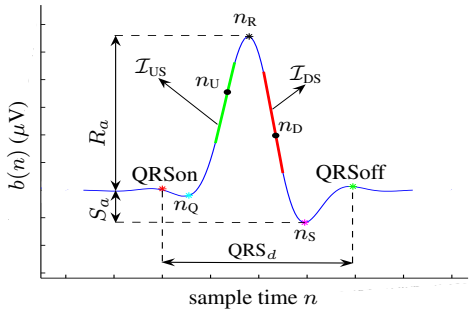

Figure 1. ECG indices measured in the present study.

The indices ST_{J+60}, R_a, S_a and QRS_d are computed from the ECG delineation marks. The QRS slopes, $\mathcal{I}_{US}$ and $\mathcal{I}_{DS}$, are the slope values that result from fitting two lines to the 8-ms segments of the QRS complex centered at the points with maximum and minimum slope, respectively, within the QRS [6, 7]. The upward slope is measured between the Q and R waves, and the downward slope between the R and S waves. The index $HF\text{-}QRS_{(150-250)}$ is computed as the root mean square of the averaged band-pass filtered signal using a Butterworth bidirectional filter between 150 and 250 Hz [7]. Figure 1 shows most of the above described ECG indices.

Once the ECG indices have been computed, their values are averaged in subensembles of 8 beats in both control and PCI recordings. Absolute changes of each index $\mathcal{I}$ along the occlusion time, $\Delta_{\mathcal{I}}$, are computed every 10 s from the start until the end of the occlusion [1, 7].

To quantify the ischemia induced changes in relative terms with respect to the normal variation measured from the control recording, the parameter $\mathcal{R}_{\mathcal{I}}$ is computed as the ratio between the absolute changes, $\Delta_{\mathcal{I}}$, and the normal fluctuactions in the control recording prior to the PCI quantified as its standard deviation, $\sigma_{\mathcal{I}}$: $\mathcal{R}_{\mathcal{I}}(t)=\frac{\Delta_{\mathcal{I}}(t)}{\sigma_{\mathcal{I}}}$ [6, 7].

2.5. Spatial analysis

In order to spatially characterize myocardial ischemia the mean $\bar{\Delta}_{\mathcal{I}_{END}}(l)$ and the standard deviation $\sigma^{\Delta_{\mathcal{I}}}_{END}(l)$ over patients of the absolute changes $\Delta_{\mathcal{I}}$ ocurred at the end of the occlusion are computed. For this analysis, patients are clustered in three groups according to the occluded artery (LAD, RCA and LCX).

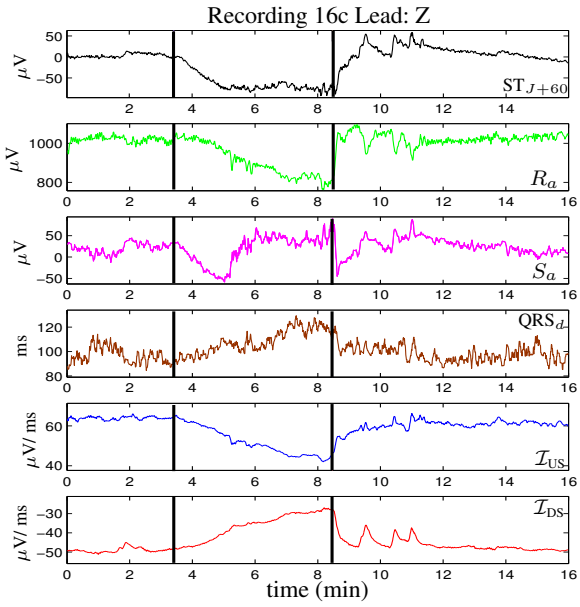

Figure 2. ECG indices evaluated for a particular patient in lead Z. Vertical lines mark the begining and end of the artery occlusion, respectively.

Aditionally, to study the 3D profile of the changes from the analyzed indices across different projections (sagittal, frontal and transversal), the Dower Inverse Matrix (DIM) [8] is applied in two differents ways: 1) DIM is applied to generate the three orthogonal leads X, Y and Z from the standard 12-lead ECG signals and the absolute ischemia induced changes $\Delta_{\mathcal{I}}$ are computed over those X, Y, and Z leads; 2) Ischemia-induced absolute changes $\Delta_{\mathcal{I}}$ are com-

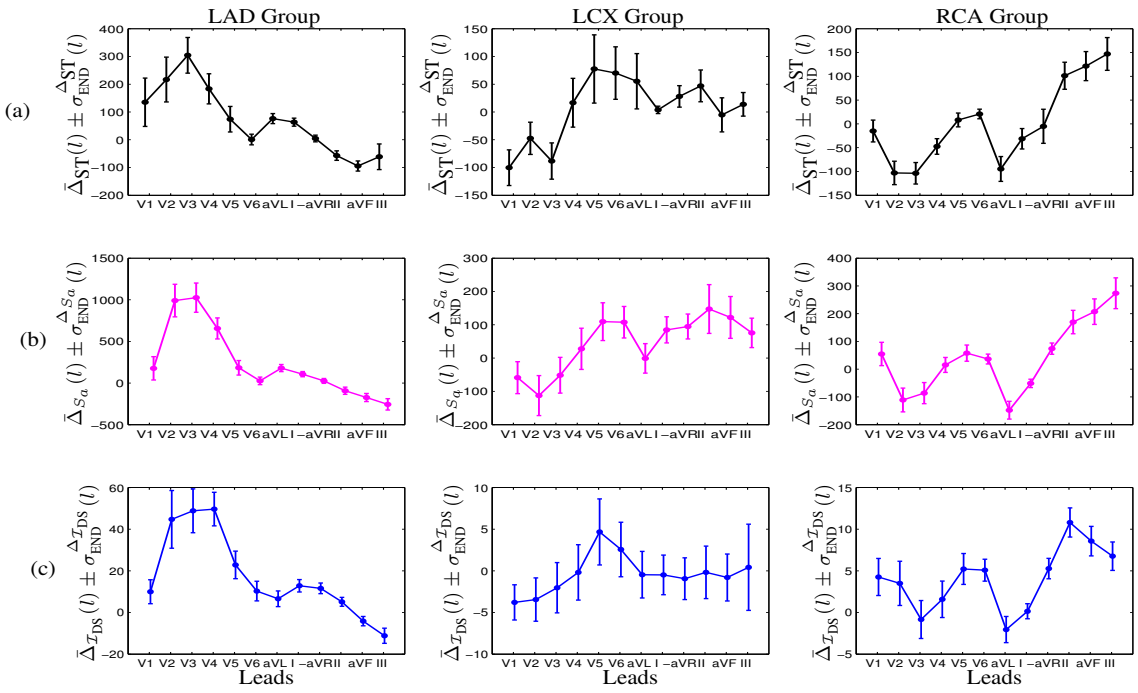

Figure 3. (a) Spatial distribution of the ST_{J+60} absolute changes $\Delta_{\mathrm{ST}_{J+60}}$ for LAD, LCX and RCA groups. (b) Spatial distribution of the S_a absolute changes Δ_{S_a} for the in LAD, LCX and RCA groups. (c) Spatial distribution of the $\mathcal{I}_{\mathrm{DS}}$ absolute changes $\Delta_{\mathcal{I}_{\mathrm{DS}}}$ in LAD, LCX and RCA groups.

puted over each of the 12 standard leads, and DIM is applied on the resulting 12 time series to generate three transformed orthogonal vectors representative of those changes.

3. Results

Figure 2 shows ECG indices along time computed for a patient in transformed lead Z. It can be observed how the ECG indices change their values after ballon inflation and how they go back to their initial values after ballon deflation. Notice that ST_{J+60} and S_a experience an abrupt change in their values within the first 1.5 min after the start of occlusion, while all the others indices keep a gradual evolution until the end of it.

Spatial characterization of ischemia induced changes is presented in Figure 3. Each of the rows in that figure shows $\bar{\Delta}_{\mathcal{I}_{\mathrm{END}}}(l) \pm \sigma^{\Delta_{\mathcal{I}}}_{\mathrm{END}}(l)$ for each lead l, when computed for any of the indices ST_{J+60}, S_a and $\mathcal{I}_{\mathrm{DS}}$. Each of the columns correspond to an occlusion group (LAD, LCX, and RCA). It can be observed that the three indices present similar spatial profiles and that are highly dependent of the occlusion site. In the LAD group the most prominent changes were seen in leads V2-V4. In the LCX and RCA groups the most pronounced changes were noticed in leads V4-V6 and II, aVF and III, respectively. If relative changes $\mathcal{R}_{\mathcal{I}}$ are used for the spatial characterization, comparable lead-by-lead profiles are obtained. Table 1 shows averaged values of $\Delta_{\mathcal{I}}$ and $\mathcal{R}_{\mathcal{I}}$ computed for each of the occlusion groups in those leads identified as more sensitive to ischemia induced changes whereas the averaged relative change over patients and leads were $\bar{\mathcal{R}}_{ST_{J+60}}$= 14.5, $\bar{\mathcal{R}}_{S_a}$= 15.2 and $\bar{\mathcal{R}}_{\mathcal{I}_{\mathrm{DS}}}$= 6.2 times their normal variations at control.

Two of the other analyzed indices, R_a and $\mathcal{I}_{\mathrm{US}}$, show similar profiles between them, but those are weakly distinctive in terms of the occlusion site. The indices QRS_d and $\mathrm{HF\text{-}QRS}_{(150-250)}$ present even less distinctive spatial profiles.

Table 1. Averaged $\Delta_{\mathcal{I}}$ and $\mathcal{R}_{\mathcal{I}}$ values of ST_{J+60}, S_a, and $\mathcal{I}_{\mathrm{DS}}$ in each of the occlusion groups and leads identified as more sensitive to ischemia induced changes.

	LAD (V2-V4)	LCX (V4-V6)	RCA (II-aVF-III)
$\bar{\Delta}_{ST_{J+60}}$	234.8 ± 66.4	54.7 ± 50.9	123.2 ± 31.1
$\bar{\Delta}_{S_a}$	890.8 ± 165.8	81.6 ± 55.3	216.9 ± 47.9
$\bar{\Delta}_{\mathcal{I}_{\mathrm{DS}}}$	48.9 ± 11.5	7.5 ± 4.1	8.6 ± 1.7
$\bar{\mathcal{R}}_{ST_{J+60}}$	29.8 ± 7.74	10.7 ± 4.55	24.4 ± 5.49
$\bar{\mathcal{R}}_{S_a}$	39.2 ± 8.12	13.7 ± 4.05	21.4 ± 5.01
$\bar{\mathcal{R}}_{\mathcal{I}_{\mathrm{DS}}}$	16.1 ± 3.25	5.08 ± 1.28	6.13 ± 0.98

Figure 4 shows the frontal, transversal, and sagittal projections of the 3D spatial $\Delta_{\mathcal{I}_{\mathrm{DS}}}$ vector computed at the end of the occlusion for each artery group (LAD, RCA and LCX). Figure 4-(a), where DIM is applied to the ECG signals, the RCA group shows smaller averaged vectors than those of the other groups, while the LAD group presents the largest averaged vectors. In Figure 4-(b) where DIM

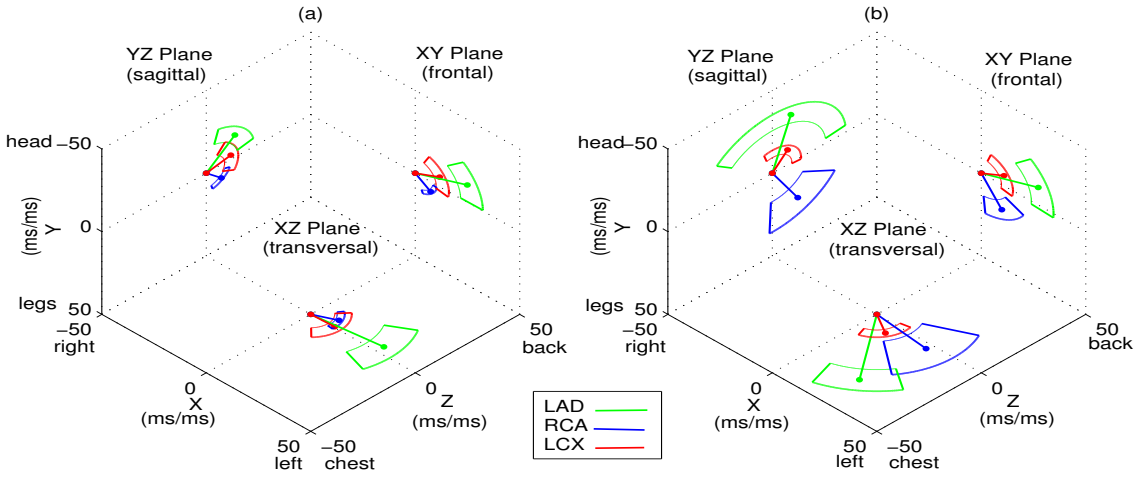

Figure 4. Averaged 3D vector $\Delta_{\mathcal{I}_{\text{DS}}}$ for each of the three occlusion groups in the frontal, transversal, and sagittal projections: (a) DIM applied over standard 12-lead ECG; (b) DIM applied over $\Delta_{\mathcal{I}_{\text{DS}}}$ series. The lines represent the group average vectors, with circular sectors covering once the standard deviation in magnitude and angle of the axis.

is applied over the $\Delta_{\mathcal{I}_{\text{DS}}}$ series, LCX and RCA groups are less overlapping than in Figure 4-(a), and the three occlusion groups can be separated in a better way.

4. Discussion and conclusions

In addition to conventional ST segment changes, ECG-derived indices from the final part of the QRS complex ($\mathcal{I}_{\text{DS}}$ and S_a) show high sensitivity for detection of PCI-induced ischemia. Spatial profiles of the ischemia induced changes for the indices ST_{J+60}, S_a and $\mathcal{I}_{\text{DS}}$, either when computed using absolute values $\Delta_{\mathcal{I}}$ or relative values $\mathcal{R}_{\mathcal{I}}$, are clearly different for the three occlusion site groups. In each group, the spatial profiles show the largest changes in the leads closest to the ischemia region, in agreement with results reported by Martínez *et al.* [2] and García *et al.* [1] when investigating other indices in the same study population. The occlusion site clustering is more pronounced when indices are analyzed in a 3D space generated by Dower transformation of the 12-lead ischemia-induced changes rather than when the indices are computed on the X, Y, and Z leads and ischemia induced changes are subsequently evaluated.

The analysis of depolarization changes presented in this study hence allows the spatial characterization of regional ischemia, where the marked and distinctive spatial profile could be considered for occlusion site identification.

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