International Journal of Bioelectromagnetism
Vol. 15, No. 1, pp. 77 - 82, 2013

www.ijbem.org

Detecting Acute Myocardial Ischemia by Evaluation of QRS Angles

Daniel Romero[a,b], Pablo Laguna[a,b], Esther Pueyo[b,a]

[a]*Communications Technology Group, I3A, University of Zaragoza, Zaragoza, Spain*

[b]*CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Zaragoza, Spain*

Correspondence: Daniel Romero, I+D+i Building, c/ Mariano Esquillor, s/n, 50018, Zaragoza, Spain.
E-mail: daromero@unizar.es, phone +34 976 76 10 00, Ext: 5468

Abstract. In the present study we evaluated three angles, obtained from the main slopes of the QRS complex, and used them to assess ischemic-induced changes in patients undergoing percutaneous coronary intervention (PCI). These QRS angles, denoted by φ_R, φ_U and φ_D, were evaluated in 12-lead electrocardiogram (ECG) recordings of 79 patients obtained before and during coronary occlusion. At baseline (before occlusion) the QRS angles showed very little variations, while after start of occlusion both φ_U and φ_D developed a fast and abrupt change. Relative ischemic changes of φ_U and φ_D during PCI reached up to 98 and 126 times their normal variations observed at baseline, respectively, being V2 and V3 the most sensitive leads. We conclude that evaluation of QRS angles from the standard 12-lead ECG represents a sensitive marker for detection of acute myocardial ischemia.

Keywords: Ischemia, QRS angles; ECG

1. Introduction

The standard 12-lead electrocardiogram (ECG) is the most widely used non-invasive tool in the evaluation of acute myocardial ischemia, both in the pre-hospital setting and in the emergency room. By convention, changes occurring during the repolarization phase (ST-T segment) are conventionally used for detection. In addition to that, changes also develop in the depolarization phase (QRS complex) of the ECG during acute ischemia, which could add information beyond the ST-T analysis. Nevertheless, all these changes have historically been more difficult to characterize and have not come into clinical practice.

A more reliable method for characterizing changes in the QRS complex due to both amplitude and duration changes has been proposed by measuring the two main slopes of the QRS complex, i.e. the upward and downward slopes of the R wave [Pueyo et al., 2008]. Subsequently, that method has been improved by incorporating a normalization process to attenuate the normal variations of the slopes at baseline, thereby increasing their sensitivity to ischemia-induced changes [Romero et al., 2011].

In this study we propose the evaluation of three QRS angles, which are obtained as the angles of the triangle formed by the lines of the QRS complex shown in Fig. 1. The main objective of the present study is to assess the dynamic evolution of these indices during coronary occlusion and characterize the spatial distribution of their changes in relation to the occlusion site.

2. Material and Methods

2.1. Data

The study population comprised 79 patients taken from the STAFF III dataset [García et al., 2000]. All these patients were admitted to the Charleston Area Medical Center in West Virginia, USA, for prolonged, elective percutaneous coronary intervention (PCI) due to stable angina pectoris. Patients undergoing an emergency procedure or who presented signal loss during acquisition were not considered.

All ECG signals were recorded using equipment provided 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 an amplitude resolution of 0.6 μV. Subsequently, the three augmented leads aVL, -aVR and aVF were generated from the limb leads to yield the complete standard 12-lead ECG.

Prior to the PCI procedure, a control recording was acquired continuously during 5 min at resting state and in supine position for each patient. Another continuous ECG was acquired during the PCI, starting before balloon inflation and ending after balloon deflation. The duration of the occlusion procedure ranged from 1'30" to 7'17" (mean: 4'26"). The occluded arteries during the PCI procedures were: left anterior descending coronary artery (LAD) in 25 patients, right coronary artery (RCA) in 38 patients, and left circumflex artery (LCX) in 16 patients.

2.2. ECG preprocessing

All signals involved in the study were preprocessed as follows: (1) QRS detection, (2) normal beats selection according to [Moody and Mark, 1982], (3) baseline drift attenuation via cubic spline interpolation, (4) delineation using a wavelet-based technique [Martínez et al., 2004], and (5) ECG normalization [Romero et al., 2011].

2.3. QRS angles

The QRS angles measured in this study are illustrated in Fig. 1:

- the R wave angle φ_R: the angle opposite to the R line l_R.
- the up (U) angle φ_U: the angle opposite to the down line l_D.
- the down (D) angle φ_D: the angle opposite to the up line l_U.

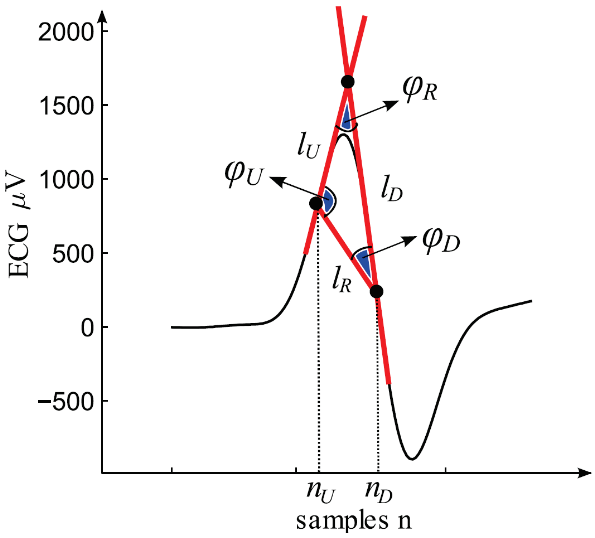

Figure 1. *Example of the QRS angles for a particular beat of a recording analyzed in this study.*

These three angles are calculated from the URD triangle, which is built by the intersection of the three lines l_R, l_U and l_D shown in Fig. 1. The angles φ_R, φ_U and φ_D inside the URD triangle are calculated using the methodology described in the following:

1. l_U and l_D are the lines obtained by least square fitting the ECG signal $x(n)$ in 8-ms windows centered at points of maximal inflection n_U and n_D, respectively:

$$l_U = \alpha_1 n + \alpha_0, \; n = n_U - 4, \dots, n_U + 4 \tag{1}$$

$$l_D = \beta_1 n + \beta_0, \; n = n_D - 4, \dots, n_D + 4 \tag{2}$$

   where n represents the time in samples and α_0, α_1, β_0 and β_1 are the coefficients obtained from the fitting.

2. l_R is the line obtained by joining the points $[n_U, x(n_U)]$ and $[n_D, x(n_D)]$. The slope θ of l_R is given by:

$$\theta = \frac{x(n_D) - x(n_U)}{n_D - n_U} \tag{3}$$

3. The angles φ_R,φ_U and φ_D are subsequently calculated. Assuming φ_R is an acute angle (0º < φ_R < 90º), it can be calculated as:

$$\varphi_R = \arctan\left(\left|\frac{\alpha_1 - \beta_1}{1 + \alpha_1\beta_1}\right|\right), \quad (4)$$

Depending on the sign of the slope θ, we first calculate φ_U or φ_D. If θ > 0,

$$\varphi_U = \arctan\left(\left|\frac{\alpha_1 - \theta}{1 + \alpha_1\theta}\right|\right),$$

$$\varphi_D = 180º - (\varphi_U + \varphi_R). \quad (5)$$

If θ < 0,

$$\varphi_D = \arctan\left(\left|\frac{\beta_1 - \theta}{1 + \beta_1\theta}\right|\right),$$

$$\varphi_U = 180º - (\varphi_D + \varphi_R). \quad (6)$$

The two possible orders are set to guarantee that the angles are well-evaluated, as equations Eq. 4, Eq. 5 and Eq. 6, are only valid for the smaller of the two angles generated by the interception of two lines.

2.4. Change quantification during PCI

Absolute $\Delta_\emptyset$ and relative $R_\emptyset$ changes during the PCI procedure were tracked for each angle $\emptyset = \{\varphi_R, \varphi_U, \varphi_D\}$. $\Delta_\emptyset(t)$ was calculated every 10 s from the start of occlusion (t = 0) until the end, by subtracting from the current value $\emptyset(t)$ the initial reference $\emptyset_{ref}$, which is given by the averaged value of the index $\emptyset$ during the first 5 s of the occlusion. $R_\emptyset(t)$ was calculated as the ratio between the absolute change observed during PCI, $\Delta_\emptyset(t)$, and the normal fluctuations of $\emptyset$ observed during the control recording prior to the PCI, defined by the standard deviation (SD) $\sigma_\emptyset$ of $\emptyset$ [García et al., 2000]:

$$R_\emptyset(t) = \Delta_\emptyset(t) / \sigma_\emptyset. \quad (7)$$

2.5. Other QRS indices

To assess the sensitivity of the QRS angles to the ischemia-induced changes in comparison to other depolarization indices, the following indices were computed: R-wave amplitude (Ra), upward slope of the QRS complex (I_{US}) and downward slope of the QRS complex (I_{DS}) [Romero et al., 2011].

3. Results and Discussion

3.1. QRS indices

Figure 2 (a) shows an example of the QRS angles φ_R, φ_U and φ_D evaluated for a particular patient in lead V4. Figure 2 (b) and (c) display the QRS slopes and R-wave amplitude, used here for comparison. As can be observed from Fig. 2, the QRS angles are very stable at baseline and then show a fast and abrupt change after the start of the occlusion, specially φ_U and φ_D, which are almost complementary. φ_R presents smoother variations. From Fig. 2 it is possible to appreciate that the absolute variation of φ_R is approximately around 1º, whereas it is around 170º for φ_U and φ_D. The QRS slopes and R wave amplitude, evaluated for the same recording and lead, show a notable change during occlusion as well, but their evolution is slower as compared to the angles φ_U and φ_D.

In control (before the start of coronary occlusion), the mean values of φ_R computed in each lead and averaged over patients, $\bar{\varphi}_R(l)$, were 1.2 ± 0.8º for lead V4 and 6.6 ± 5.9º for lead I, which represent the lowest and highest values of all the leads. Normal fluctuations given by the SD of the index in control, and averaged over patients, $\bar{\sigma}_R(l)$, ranged between 0.02º and 0.71º, depending on the lead. In the case of φ_U and φ_D, mean values and normal variations in control were higher. Mean values of φ_U angle varied between 54º (lead V6) and 174º (lead V3), with normal variations in control of 0.75º and 5.83º, respectively. For φ_D angle, mean values in control ranged between 4º and 122º, for leads V3 and V6, and their variations in control were of 0.73º and 5.80º, respectively. Both angles φ_U

and φ_D were found to be almost complementary, so that when one increases the other one decreases, as reflected in Fig 2 (a). Quantification of QRS changes following PCI-induced ischemia are presented in the following section.

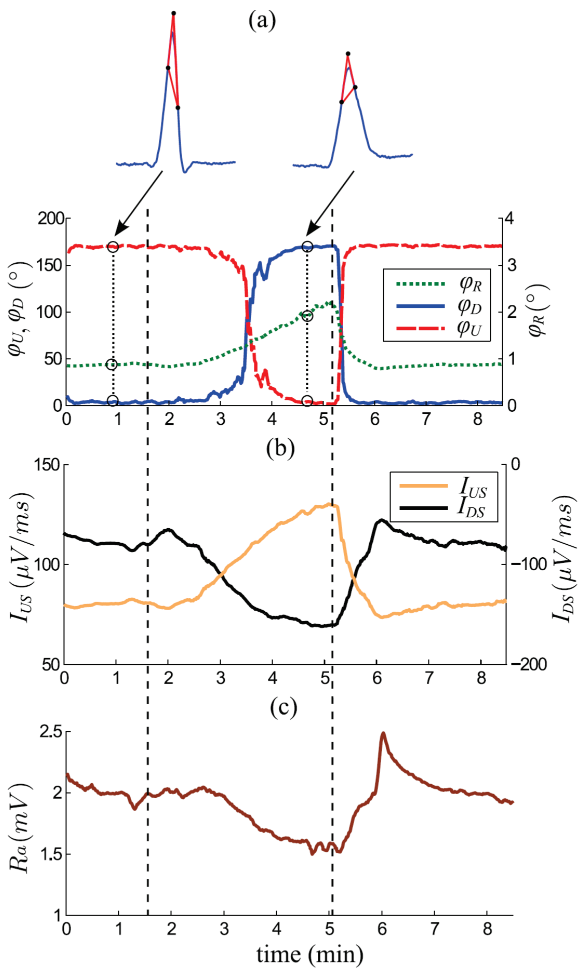

Figure 2. *(a) Time course of QRS angles and illustrative beats taken at specific time instants representative of pre-occlusion and occlusion periods. (b) QRS slopes and (c) R-wave amplitude evolution. All represented indices were evaluated for a particular patient in lead V4. Dashed lines mark the occlusion period during recording.*

3.2. Temporal evolution of ischemia-induced changes

The evolution of changes observed for the QRS angles φ_U and φ_D are shown in Fig. 3. In this figure, absolute $\Delta_\emptyset(t)$ and relative $R_\emptyset(t)$ changes, averaged over patients of the whole study population and of the LAD subgroup, are displayed along 4 min of occlusion in the most sensitive leads V2 and V3. The other two subgroups, RCA and LCX, presented lower changes, well below those observed for the whole study population in the same leads. Maximum relative changes of φ_U, determined from the whole study group, achieved up to 98 and 84 times their normal variations observed in control in leads V2 and V3, respectively. In the case of φ_D, the maximum relative changes were of 126 and 97 for the same leads. In the LAD subgroup, the maximum relative changes of φ_U were of 571 (lead V2) and 736 (lead V3) and for φ_D they were of 817 (lead V2) and 736 (lead V3), being significantly higher than for the total population. Regarding absolute changes $\Delta_\emptyset(t)$ for these two indices, it can be observed from Fig. 3 that the angles vary, in mean, around 80-100º in the LAD subgroup, whereas for the whole study population, the variation caused by the induced ischemia was around 15-20º.

The results observed for the φ_R angle were considerably less notable than for φ_U and φ_D, which can be explained by the lower changes observed in the amplitude and width of the R wave. The relative change of this index achieved up to 15 times their normal variations in lead V3 and 19 in lead -aVR, when averaged over the whole population. Maximum relative changes were of 66 and 62 for the same leads in the LAD subgroup. Nevertheless, the increase in the averaged absolute changes of φ_R in most of the leads suggests a widening of the QRS complex due to the induced ischemia. This index φ_R could be a robust and potential tool to estimate a surrogate measure related to the QRS complex duration.

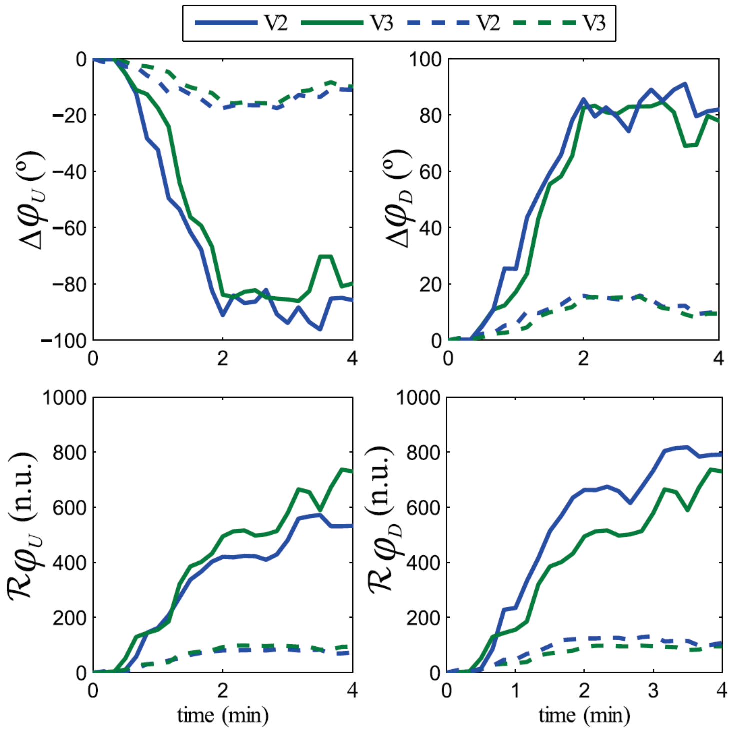

Figure 3. *Averaged absolute $\Delta_\emptyset(t)$ (top panels) and relative $R_\emptyset(t)$ (bottom panels) changes ($\emptyset$ = φ_U and φ_D) averaged over patients during occlusion for LAD subgroup (solid lines) and the whole study population (dashed lines) in leads V2 and V3.*

In comparison to other depolarization indices, the results obtained for the QRS angles, especially for φ_U and φ_D, far exceed those obtained for other QRS-derived indices like QRS slopes, I_{US} and I_{DS}, and R-wave amplitude Ra. Maximum relative changes reached up to 9.3 in lead V3 for I_{DS} and 6.01 for I_{US} in lead V2 as was previously reported in [Romero et al., 2011]. In the case of Ra index, the maximum relative change was achieved in lead II, being of 7.7 times their normal variations in control.

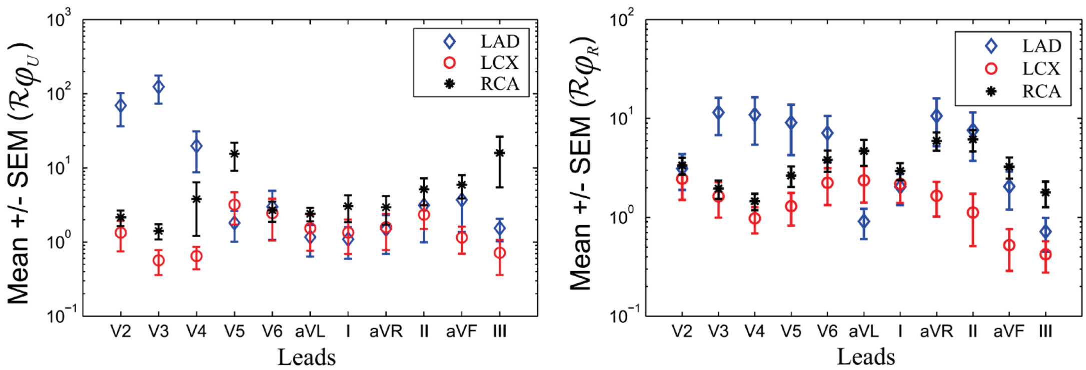

Figure 4. *Changes distribution across leads for R_{φ_U} and R_{φ_R} measured at the end of the occlusion. LAD: left anterior descending coronary artery; LCX: left circumflex artery; RCA: right coronary artery.*

3.3. Spatial distribution of ischemia-induced changes

To further explore the clinical value of the QRS angles proposed here, ischemia-induced changes were analyzed across leads by clustering patients according to their occluded artery. Relative changes for both φ_U and φ_R angles were computed at the end of the occlusion and averaged over patients.

Results for φ_D are not presented, as associated spatial distribution nearly coincide with those of φ_U. Fig. 4 shows mean ± standard error of the mean (SEM) for φ_U and φ_R in each lead for each of the three subgroups. Lead V1 is not represented, as in several patients the QRS angles could not be measured in that lead due to the QRS morphology (usually QS complex). According to the results shown in Fig. 4 the LAD subgroup could be separated from the LCX and RCA subgroups by evaluating φ_U and φ_R changes in leads V2-V5. The three subgroups could be separated by evaluating φ_U in leads V3-V4 and φ_R in lead V5. These results suggest that identification of the occluded artery could be performed based on evaluation of QRS angles.

4. Conclusions

In this study QRS angles have been proposed for evaluation of ischemia-induced changes. Relative changes of the three QRS angles (φ_R, φ_U and φ_D) are suggested as an adjunct tool to conventional ST-T analysis for improving acute ischemia diagnosis. QRS angles could additionally help in the identification of the occluded artery. The nonlinear nature of the QRS angles with respect to other QRS indices (slopes and amplitude) results in a higher sensitivity to ischemia-induced alterations, and abrupt relative changes of QRS angles could be used as a trigger for ischemia alarm.

Acknowledgements

This work was supported by projects TEC2010-21703- C03-02 and TEC2010-19410 from MINCIN, Spain, and by Grupo Consolidado GTC from DGA, Spain. E. P. acknowledges the financial support of Ramón y Cajal program from the Spanish Ministry of Economy and Competitiveness.

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