A Vectorial Approach for Evaluation of Depolarization Changes during Acute Myocardial Ischemia

D. Romero[1,2], M. Ringborn[3], P. Laguna[1,2], O. Pahlm[4], E. Pueyo[1,2],

[1]Communications Technology Group, I3A, University of Zaragoza, Spain
[2]CIBER de Bioingenieria, Biomateriales y Nanomedicina (CIBER-BBN), Zaragoza, Spain
[3]Department of Cardiology, University of Lund, Sweden
[4]Department of Clinical Physiology, University of Lund, Sweden

Abstract

In the present study we evaluated the upslope ($\mathcal{I}_{\text{US}}$), downslope ($\mathcal{I}_{\text{DS}}$) and terminal slope ($\mathcal{I}_{\text{TS}}$) of the QRS complex in both standard and derived ECG leads obtained from spatial QRS loops, either by the vectorcardiogram (VCG) or by principal component analysis (PCA), in 79 patients undergoing prolonged, elective percutaneous coronary intervention (PCI). For each patient, the slope indices $\mathcal{I}_{\text{US}}$, $\mathcal{I}_{\text{DS}}$ and $\mathcal{I}_{\text{TS}}$ were evaluated in the PCI recording as well as in a control recording acquired before the PCI procedure, and relative factors of change during PCI were calculated. We showed that $\mathcal{I}_{\text{US}}$ and $\mathcal{I}_{\text{DS}}$ computed over VCG and PCA leads present higher sensitivity to the ischemia-induced changes than the same indices evaluated over the standard 12-lead ECG. Mean relative factors of change were 10.5 and 12.4 for $\mathcal{I}_{\text{US}}$ and $\mathcal{I}_{\text{DS}}$ in PCA, and 7.87 and 13.7, respectively, in VCG, representing an increase in sensitivity of up to 103% for $\mathcal{I}_{\text{US}}$ and 46% for $\mathcal{I}_{\text{DS}}$ compared to measurements obtained in lead V3. We conclude that evaluation of slope indices in leads derived from QRS loops significantly increases their potential value for detection of acute myocardial ischemia.

1. Introduction

Early diagnosis of patients with acute myocardial ischemia is essential to optimize treatment and hence clinical outcome. In addition to patient history and clinical examination, the standard 12-lead electrocardiogram (ECG) is the most important tool in the acute evaluation, both in the pre-hospital setting and in the emergency room. By convention, changes in the repolarization phase (ST-T) are most widely used to detect acute myocardial ischemia. Changes also occur in the depolarization phase (the QRS complex) of the ECG during acute ischemia that could add information beyond the ST-T analysis. However, these changes have historically been more difficult to characterize and have not come into clinical practice. In a recent study a more reliable method for characterizing changes in the QRS complex due to both amplitude and duration changes have been proposed by measuring the upslope and down-slope of the R wave during myocardial ischemia induced by elective PCI [1]. That method was subsequently improved in [2] by incorporating a normalization procedure that attenuates the variations of the slopes indices at control, thereby increasing their sensitivity to ischemia-induced changes. In this study we propose the evaluation of the slope indices over new derived leads obtained by projection of 3D vector-based ECG loops computed from the vectorcardiogram (VCG) or principal component analysis (PCA) as in [3] and [4].

Our aim was to evaluate and compare the performance of the QRS slope indices in monitoring the QRS changes along the dynamic ECG recordings during PCI-induced ischemia on the standard 12-lead ECG and on leads derived from the spatial QRS loop.

2. Methods

2.1. Population

The study population comprised 79 patients taken from the STAFF III dataset, which contains patients admitted to the Charleston Area Medical Center in West Virginia, USA, for prolonged, elective PCI due to stable angina pectoris [5]. All patients met the following inclusion criteria: no clinical or ECG evidence of an acute or recent myocardial infarction, no intraventricular conduction delay with QRS duration $\geq$ 120 ms (including LBBB, RBBB), no pacemaker rhythm, low voltage, atrial fibrillation/flutter or any ventricular rhythm at inclusion or during the PCI. Also patients undergoing an emergency procedure, or who presented signal loss during acquisition were not considered.

All ECGs 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 sam-

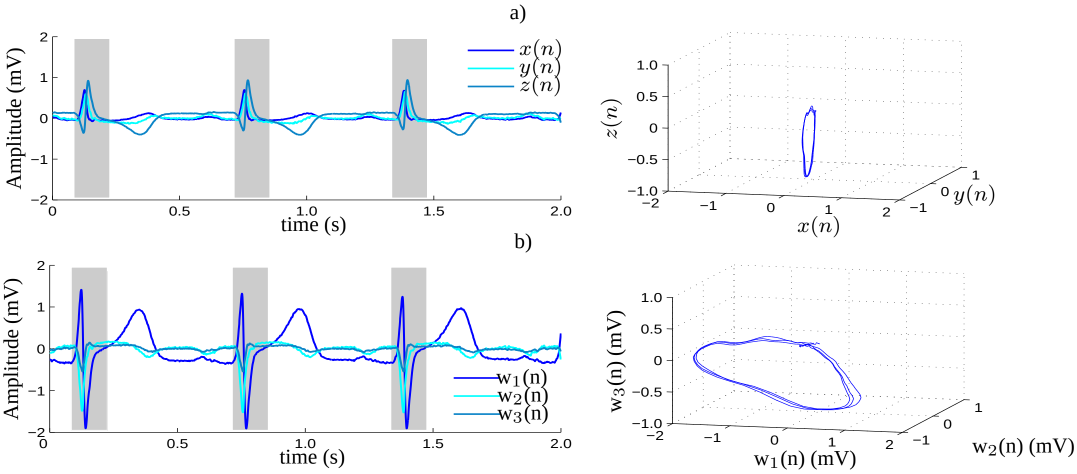

Figure 1. a) Orthogonal X, Y and Z leads derived from Dower Inverse Matrix in a time segment, and their corresponding loops; b) Transformed orthogonal ECG leads obtained from the PCA technique, and their corresponding loops.

pling rate of 1 kHz with an amplitude resolution of 0.6 μV. The three augmented leads aVL, -aVR and aVF were then generated from the limb leads to yield the complete standard 12-lead ECG. For each patient a control recording was acquired continuously for 5 min, at rest in supine position prior to the PCI procedure. Another continuous ECG was acquired during the PCI, starting before balloon inflation and ending after deflation. The duration of the occlusion ranged from 1 min 30 s to 7 min 17 s (mean 4 min 26 s). The occlusion sites of 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. Leads derived from the QRS loops

a) *QRS loop from the VCG:* From the standard 12-lead ECG $l_1(n), \ldots, l_{12}(n)$ it is possible to generate the three orthogonal leads $x(n)$, $y(n)$, and $z(n)$ by applying the Dower Inverse Matrix over leads V1-V6, I and II [6]. These orthogonal leads can be represented in a 3D space so that one can observe the variations of the electrical heart vector (VCG), given by $\mathbf{v}_{\text{VCG}}(n) = [x(n), y(n), z(n)]^T$. During depolarization, the dominant direction $\mathbf{u}$ of the QRS loop (QRS$_{\text{VCG}}$) points to the QRS loop tip, called the *mean electrical axis*. Thus, determining the main direction of the QRS$_{\text{VCG}}$ loop, a new lead was obtained by projecting the loop onto that vector. For this analysis we first searched for the main direction $\mathbf{u}$ by maximizing the following equation:

$$\mathbf{u} = [u_x, u_y, u_z]^T = [x(n_0), y(n_0), z(n_0)]^T,$$

with

$$n_0 = \arg\max_n [x^2(n) + y^2(n) + z^2(n)] \qquad (1)$$

where n spans over the samples of the running beat from 10 ms before QRS onset location (n_{ON}) to 130 ms after n_{ON}. Then the new projected lead $g(n)$ was calculated by projecting the points of the QRS$_{\text{VCG}}$ loop onto the $\mathbf{u}$ axis:

$$g_{\text{VCG}}(n) = \frac{\mathbf{v}_{\text{VCG}}^T(n)\,\mathbf{u}}{\|\mathbf{u}\|}. \qquad (2)$$

b) *QRS loop using PCA:* One way to implement PCA is by applying singular value decomposition (SVD) on the standard 12-lead ECG to generate a new lead system that concentrates the most energy of the signal in a small set of leads [7]. Specifically, the SVD was applied over leads V1-V6, I and II to obtain 8 transformed leads $\mathrm{w}_k(n)$, $k = 1, 2, \ldots, 8$, by using the following transformation:

$$\mathbf{w}(n) = \mathbf{U}^T\,\mathbf{l}(n) \qquad (3)$$

where the vector $\mathbf{l}(n) = [l_1(n), l_2(n), \ldots, l_8(n)]^T$ contains the original leads (only V1-V6, I and II) and $\mathbf{U}$ is the matrix containing the right singular vectors of a training set obtained from $\mathbf{L}=[\mathbf{l}_1, \ldots, \mathbf{l}_8]$, with $\mathbf{l}_k = [l_k(1), l_k(2), \ldots, l_k(N)]^T$, and N the number of samples in the recording. The new lead system given by the orthogonal transformed leads $\mathrm{w}_1(n)$, $\mathrm{w}_2(n)$ and $\mathrm{w}_3(n)$ (the first 3 of the 8 transformed leads $\mathrm{w}_k(n)$ which mostly concentrate the energy of the original leads) was subsequently used to represent the QRS loop in a different way, called the QRS$_{\text{PCA}}$ loop. Analogously to the process described in section 2.2, the same methodology was applied here to compute a new lead $g_{\text{PCA}}(n)$ by projecting the QRS$_{\text{PCA}}$ loop onto its dominant direction using equations (1) and (2). The only difference with respect to 2.2 is that $\mathbf{v}_{\text{VCG}}(n)$ was replaced with $\mathbf{v}_{\text{PCA}}(n)$, defined as:

$$\mathbf{v}_{\text{PCA}}(n) = [\mathrm{w}_1(n), \mathrm{w}_2(n), \mathrm{w}_3(n)]^T. \qquad (4)$$

Examples of the two approaches described above (VCG and PCA) are presented in Fig. 1.

2.3. Preprocessing

All signals involved in the study were preprocessed as follows: (1) QRS detection, (2) normal beats selection according to [8], (3) baseline drift attenuation via cubic spline interpolation, (4) delineation using a wavelet-based technique [9], and (5) ECG normalization [2].

2.4. Depolarization indices

Once the two leads derived from the spatial QRS loops, $g_{\text{VCG}}(n)$ and $g_{\text{PCA}}(n)$ were obtained, the next step was to compute the QRS slope indices (defined below) over all the standard leads as well as on those two derived leads. The methodology employed to compute the slope indices is described in detail in [10]:

- $\mathcal{I}_{\text{US}}$: the upward slope of the R wave.
- $\mathcal{I}_{\text{DS}}$: the downward slope of the R wave.
- $\mathcal{I}_{\text{TS}}$: the upward slope of the S wave (in leads V1-V3).

The $\mathcal{I}_{\text{TS}}$ index corresponding to the upslope of the S wave was only computed for leads V1-V3, where the S wave is usually more pronounced.

The relative change during the PCI procedure was tracked by the parameter $\mathcal{R}_{\mathcal{I}}$, for each index $\mathcal{I}$, and was referred to the normal variation of $\mathcal{I}$ measured at resting state [5]. $\mathcal{R}_{\mathcal{I}}$ evaluated at time t_j, with t_j taken in increments of 10 s from the occlusion start ($t = 0$), was defined as the ratio between the change observed during PCI evaluated up to time t_j, denoted by $\Delta_{\mathcal{I}}(t_j)$, and the normal fluctuations of $\mathcal{I}$ observed during the control recording prior to the PCI, defined by the standard deviation (SD) of $\mathcal{I}$, denoted by $\sigma^{\mathcal{I}}$: $\mathcal{R}_{\mathcal{I}}(t_j) = \Delta_{\mathcal{I}}(t_j)/\sigma^{\mathcal{I}}$.

3. Results

3.1. Depolarization changes during ischemia evaluated in standard ECG leads

The relative changes $\mathcal{R}_{\mathcal{I}}$ of the QRS slopes measured during PCI were computed and averaged over patients for the standard 12-lead ECG. The performances of the three QRS slopes ($\mathcal{I}_{\text{US}}$, $\mathcal{I}_{\text{DS}}$ and $\mathcal{I}_{\text{TS}}$) were analyzed for the precordial leads V1-V3, where we found that the two last slopes within the QRS complex (i.e. $\mathcal{I}_{\text{DS}}$ and $\mathcal{I}_{\text{TS}}$) present similar behaviors along time, but not so for $\mathcal{I}_{\text{US}}$. Figure 2 shows the averaged relative factor of change ($\bar{\mathcal{R}}_{\mathcal{I}}$) for the three slopes during 5 min of coronary occlusion in leads V2 and V3. It is clear that there is a strong relationship between the slopes. In all the other leads, where the $\mathcal{I}_{\text{TS}}$ index was not evaluated, the $\mathcal{I}_{\text{DS}}$ slope presented higher sensitivity to the ischemia-induced changes than $\mathcal{I}_{\text{US}}$, with maximum values reached in leads V3 and V5. In lead V3, the maximum averaged factors of change ($\bar{\mathcal{R}}_{\mathcal{I}}$) of $\mathcal{I}_{\text{DS}}$ and $\mathcal{I}_{\text{US}}$ were found to be 9.31 and 5.11, respectively. In lead V5, the maximum $\bar{\mathcal{R}}_{\mathcal{I}}$ were 8.06 and 6.01.

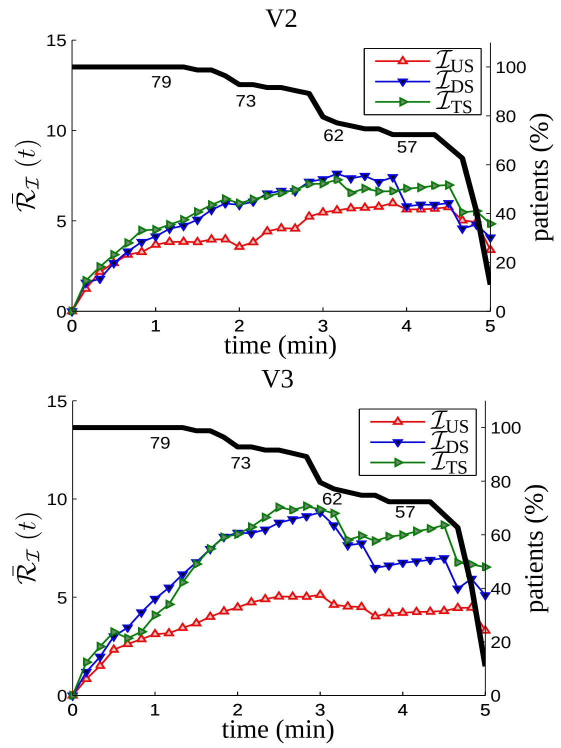

Figure 2. Averaged relative changes $\mathcal{R}_{\mathcal{I}}$ of the three QRS slopes ($\mathcal{I}_{\text{US}}$, $\mathcal{I}_{\text{DS}}$ and $\mathcal{I}_{\text{TS}}$) in leads V2 and V3. The black lines represent the percent of patients that remain under occlusion at each time instant.

3.2. Depolarization changes during ischemia evaluated in QRS loop-derived leads

To corroborate whether the new approaches based on the QRS loop provide QRS-slope measurements that perform better than those directly measured on the standard 12-lead ECG, we compared the relative slope changes averaged over the whole population in lead V3 and the two leads obtained by projection of the QRS loops (g_{VCG} and g_{PCA}). As can be observed in Fig. 3, the methods based on the QRS loop were superior.

Regarding $\mathcal{I}_{\text{US}}$ (see Fig. 3-a), the PCA-derived lead was more sensitive to the ischemia-induced relative changes ($\mathcal{R}_{\mathcal{I}}$) than the VCG-derived lead, with their maximum $\bar{\mathcal{R}}_{\mathcal{I}}$ values being 10.5 (103% higher than in V3) and 7.87 (54% higher than in V3), respectively. In the case of $\mathcal{I}_{\text{DS}}$ (Fig. 3-b) the two loop methods showed very similar behavior, with maximum relative factors of 12.4 and 13.7 for PCA- and VCG-derived leads, which were 36% and 47% higher, respectively, compared to lead V3. Despite the fact that the maximum absolute change for $\mathcal{I}_{\text{DS}}$ in the VCG-derived lead was slightly inferior to that of the PCA-derived lead, its variation in the control was substantially smaller, thus explaining the slightly superior relative factor of change found for $\mathcal{I}_{\text{DS}}$ in the VCG-derived lead.

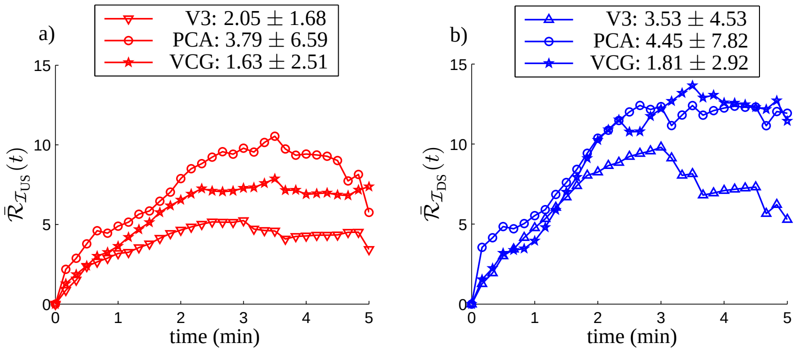

Figure 3. Evolution of the averaged relative factor of change $\bar{\mathcal{R}}_{\mathcal{I}}$ for $\mathcal{I}_{\text{US}}$ (a) and $\mathcal{I}_{\text{DS}}$ (b) during PCI. Mean $\pm$ SD of $\sigma^{\mathcal{I}}$ over patients in the control recordings are displayed on top of each graph.

4. Discussions and conclusion

In this study we measured the slopes of the QRS complex ($\mathcal{I}_{\text{US}}$, $\mathcal{I}_{\text{DS}}$ and $\mathcal{I}_{\text{TS}}$) and assessed their performances for evaluation of myocardial ischemia induced by coronary occlusion during prolonged PCI. We proposed an improvement for the quantification of QRS slope changes with the purpose of providing more sensitive estimates of the occurrence of significant changes in the depolarization phase during ischemia. In a previous work we introduced a dynamical ECG normalization to avoid very low-frequency oscillations that directly influence the variability of the estimated slopes, specially at baseline recordings, and that normalization led to an increase in the ratio $\mathcal{R}_{\mathcal{I}}$, representative of the relative changes in the slope indices during PCI [2]. In the present study the QRS slopes were also evaluated in leads derived from the QRS loops obtained by two different ways: from VCG and from PCA. The results obtained using these methods far exceeded those obtained in the standard 12-lead ECG system, reaching up to 103% improvement for $\mathcal{I}_{\text{US}}$ and 46% for $\mathcal{I}_{\text{DS}}$ measured in $\mathcal{R}_{\mathcal{I}}$ with respect to lead V3. That superiority is justified by the fact that the slopes measured from the QRS loop show higher absolute changes during the induced ischemia due to the fact that the loop-derived leads result from the projection onto a dominant vector with maximized amplitude, either generated from the VCG loop or the PCA loop.

Results based on the QRS loop approaches seem to be more sensitive to the induced ischemia than evaluation of the QRS slopes from the standard leads. QRS slope analysis could act as a robust method of depolarization evaluation in addition to repolarization changes in risk stratification during monitoring of patients with acute ischemia.

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Address for correspondence:

Daniel Romero Pérez
I3A, Mariano Esquillor s/n / 50018 / Zaragoza / Spain
e-mail: daromero@unizar.es