Detection of Acute Ischemia Episodes from QRS Angles Changes Using a Laplacian Noise Model

Daniel Romero[1,3], Juan Pablo Martínez[2,3], Pablo Laguna[2,3], Esther Pueyo[3,2]

[1] Laboratoire Traitement du Signal et de l'Image. Université de Rennes I, France
[2]Biomedical Signal Interpretation and Computational Simulation, I3A, University of Zaragoza, Spain
[3]CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Zaragoza, Spain

Abstract

Ischemia detectors represent a useful diagnosis tool to identify acute ischemic episodes in coronary artery disease patients. In this paper, a detector of acute ischemic events based on the analysis of the QRS angles is presented. This acute ischemia detector has been developed by modelling the ischemia-induced changes in the QRS angles as an abrupt change with a certain transition time, assuming a Laplacian noise-model. The standard 12-lead electrocardiogram was used to test the proposed detector. For such proposal, we analyzed 79 patients undergoing a PCI procedure during about 5-min occlusion duration in one of the major coronary artery (LAD=25, RCA=38 and LCX=16). The three detector at the groups of patients presented good outcomes in terms of sensitivity and specificity achieving up to Se=72.7%, Sp=95.5% *in the LAD group,* Se=75.2%, Sp=97.2% *in the RCA group and* Se=72.2%, Sp=100%. *in the LCX group. We conclude that the QRS angles can be used as a trigger for detecting acute myocardial ischemia although this must be further validated with other contexts in which ischemic events occur more gradually.*

1. Introduction

Ischemia detectors are commonly applied in Holter monitoring, typically during 24 hours, to assess patients with suspected or known coronary artery disease. Most ischemia detectors are based on evaluation of changes in the ST segment deviation of the electrocardiogram (ECG), which has been traditionally considered as the most sensitive marker to diagnose ischemia in clinical practice [1,2]. Because ST segment changes result from many other causes apart from ischemia, such as variations in the heart electrical axis due to body position changes (BPC), heart rate-related events, electrical conduction changes or ECG artifacts, the specificity of ST-based detectors is low. ST-based ischemia detectors need to be robust enough to distinguish between ischemic and non-ischemic episodes of ST segment changes, which still remains a challenge.

Other developed ischemia detectors have also included changes in the T-wave morphology and in the entire ST-T complex rather than in the ST segment deviation only [3,4]. When ischemia progresses, ECG changes start to be reflected also in the depolarization phase and thus those changes could be used to trigger an alert indicating the presence of a more severe ischemia. A recent method was proposed in [5] to evaluate ECG depolarization by calculating the angles of a triangle approximating the QRS complex. Changes in those angles were temporally and spatially characterized during coronary occlusion and were found to correlate with the amount of ischemia.

In this work we present and evaluate a myocardial acute ischemia detector based on the evaluation of changes in the QRS angles, for which a model of abrupt change with different transient times contaminated by Laplacian noise is assumed.

2. Methods

2.1. Population

The study population comprised 79 patients from the STAFF III dataset admitted to the Charleston Area Medical Center in West Virginia, USA, for prolonged, elective percutaneous coronary intervention (PCI) due to stable angina pectoris [6]. Patients undergoing an emergency procedure or presenting signal loss during acquisition were not included in the analysis.

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 sampling 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 system. For each patient, two ECG recordings were acquired. The first one served as a control recording and was continuously acquired at rest supine position for 5 min prior to the PCI procedure. The second one was used for ischemia analysis and was continuously acquired during the PCI procedure (from balloon inflation to 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 coronary artery (LCX) in 16 patients.

2.2. Preprocessing

All ECG signals involved in the study were preprocessed before evaluation of the analyzed indices as follows: (1) QRS complex detection, (2) selection of normal beats , (3) baseline drift attenuation via cubic spline interpolation and (4) wave delineation using a wavelet-based technique [7].

2.3. QRS angle-based indices

The QRS angles evaluated in this study, illustrated in Fig. 1, were denoted as:

- ϕ_{U}: the Up angle of the R wave
- ϕ_{D}: Down angle of the R wave

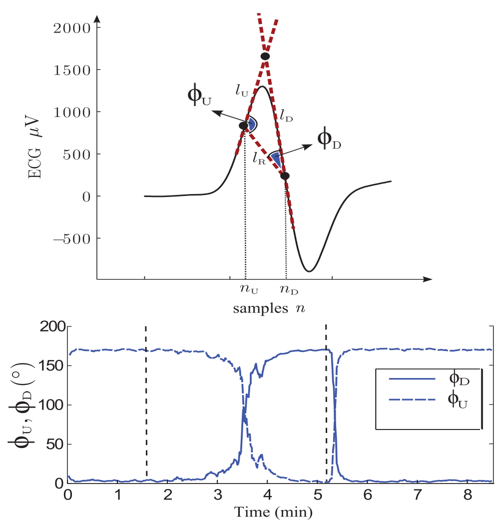

Figure 1. QRS angles evaluated in the study.

The full methodology used to compute the QRS angles is described in [5]. QRS angle series evaluated in each individual lead were filtered to remove outliers, using a median absolute deviation method and were subsequently resampled at 1 Hz.

2.4. GLRT-based ischemia detector method

Based on previously reported non-linear patterns of change in the QRS angles during PCI and following balloon release [5], an ischemia detector was designed in which a sudden change with a linear transition was searched for in the QRS angles series throughout the entire recording time. Specifically, the angle change following an acute ischemic episode was modeled as a step-like change with a gradual transition of T s of duration (with T an even-valued integer):

$$h[n] = \begin{cases} 1 & n = 0, ..., \frac{D-T}{2} - 1, \\ 1 - \frac{2}{T}(n - \frac{D-T}{2} + 1) & n = \frac{D-T}{2}, ..., \frac{D+T}{2} - 1 \\ -1 & n = \frac{D+T}{2}, ..., D-1 \end{cases} \quad (1)$$

where D represents the total length of the observation window, being D an even-valued integer.

The angle series, represented as $\varphi_l[n]$, and computed for each lead l ($l = 1, \ldots, L$), were considered for determining whether an acute ischemic episode occurred (hypothesis $\mathcal{H}_1$) or only noise was present (hypothesis $\mathcal{H}_0$):

$$\begin{aligned} \mathcal{H}_0 : & \quad \varphi_l[n] = w_l[n], \\ \mathcal{H}_1 : & \quad \varphi_l[n] = a_l[n_0] \cdot h[n - n_0] + w_l[n] \end{aligned} \quad (2)$$

with $n = n_0, ..., n_0 + D - 1$. The additive noise $w_l[n]$ was assumed to have a Laplacian probability density function:

$$p(w_l[n]) = \frac{1}{\sqrt{2}\sigma_l} \exp\left[-\frac{\sqrt{2}}{\sigma_l} |w_l[n] - m_l[n_0]|\right] \quad (3)$$

with mean $m_l[n_0]$ and variance σ_l^2. All variables were assumed to be mutually independent and uncorrelated to the observation angle series $\varphi_l[n]$.

The generalized likelihood detector was used to select between hypotheses $\mathcal{H}_1$ and $\mathcal{H}_0$ according to:

$$\Lambda_G(\boldsymbol{\varphi}) = \frac{p(\boldsymbol{\varphi}; \hat{a}_{l,\mathcal{H}_1}, \hat{m}_{l,\mathcal{H}_1}, \mathcal{H}_1)}{p(\boldsymbol{\varphi}; \hat{m}_{l,\mathcal{H}_0}, \mathcal{H}_0)}$$

$$= \frac{\exp\left[-\frac{\sqrt{2}}{\sigma_l} \sum_{n=n_0}^{n_0+D-1} |\varphi_l[n] - \hat{m}_{l,\mathcal{H}_1} - \hat{a}_{l,\mathcal{H}_1} \cdot h[n - n_0]|\right]}{\exp\left[-\frac{\sqrt{2}}{\sigma_l} \sum_{n=n_0}^{n_0+D-1} |\varphi_l[n] - \hat{m}_{l,\mathcal{H}_0}|\right]} \gtrless_{\mathcal{H}_0}^{\mathcal{H}_1} \gamma \quad (4)$$

where $\hat{a}_{l,\mathcal{H}_i}$ and $\hat{m}_{l,\mathcal{H}_i}$ denote the maximum likelihood estimators (MLEs) under $\mathcal{H}_i$, i={0,1}. The unknown parameter $\hat{m}_{l,\mathcal{H}_i}$ is regarded as a nuisance parameter.

2.4.1. Estimation of $\hat{m}_{l,\mathcal{H}_1}$, $\hat{m}_{l,\mathcal{H}_0}$ and $\hat{a}_{l,\mathcal{H}_1}$

Under hypothesis $\mathcal{H}_0$, the MLE of $m_{l,\mathcal{H}_0}$ was determined by minimizing the cost function:

$$J(m_{l,\mathcal{H}_0}) = \sum_{n=n_0}^{n_0+D-1} |\varphi_l[n] - m_l| \quad (5)$$

leading to:

$$\hat{m}_{l,\mathcal{H}_0} = \text{med}(\varphi_l[n]) \quad (6)$$

Under $\mathcal{H}_1$, the MLEs of $m_{l,\mathcal{H}_1}$ and $a_{l,\mathcal{H}_1}$ were determined by minimizing the cost function:

$$J(m_{l,\mathcal{H}_1}, a_{l,\mathcal{H}_1}) = \sum_{n=n_0}^{n_0+D-1} |\varphi_l[n] - m_{l,\mathcal{H}_1} - a_{l,\mathcal{H}_1} \cdot h[n-n_0]| \quad (7)$$

with respect to $m_{l,\mathcal{H}_1}$ and $a_{l,\mathcal{H}_1}$, respectively. The partial derivative of $J(m_{l,\mathcal{H}_1}, a_{l,\mathcal{H}_1})$ with respect to $m_{l,\mathcal{H}_1}$ led to:

$$\hat{m}_{l,\mathcal{H}_1} = \text{med}(\varphi_l[n] - \hat{a}_{l,\mathcal{H}_1} h[n-n_0]) \quad (8)$$

with $n = n_0, \cdots, n_0 + D - 1$. With respect to $a_{l,\mathcal{H}_1}$, the partial derivative of $J(m_{l,\mathcal{H}_1}, a_{l,\mathcal{H}_1})$ led to:

$$\hat{a}_{l,1} = \text{med}\left(|h[n-n_0]| \diamond \frac{\varphi_l[n] - \hat{m}_{l,1}}{h[n-n_0]} \right) \quad (9)$$

where $\diamond$ denotes the weighted median operation [9].

Note that $\hat{m}_{l,\mathcal{H}_1}$ and $\hat{a}_{l,\mathcal{H}_1}$ are dependent on each other, thus an iterative optimization algorithm was applied. An initial estimate $\hat{m}_{l,\mathcal{H}_1}$, taken as the median of $\varphi_l[n]$, as included then in (2.4.1) to calculate $\hat{a}_{l,\mathcal{H}_1}$. The obtained value was then included in equation (8) and so forth until convergence, which was typically achieved in less than 10 iterations.

2.4.2. Detector design

Considering the MLEs for the unknown parameters ($\hat{m}_{l,\mathcal{H}_0}$, $\hat{m}_{l,\mathcal{H}_1}$ and $\hat{a}_{l,\mathcal{H}_1}$) and applying the logarithm to both sides of equation (4):

$$T[n_0] = \ln \Lambda_G[n_0] = \frac{\sqrt{2}}{\sigma_l} \sum_{n=n_0}^{n_0+D-1} (|\varphi_l[n] - \hat{m}_{l,\mathcal{H}_0}| - |\varphi_l[n] - \hat{m}_{l,\mathcal{H}_1} - \hat{a}_{l,\mathcal{H}_1} \cdot h[n-n_0]|) \gtrless_{\mathcal{H}_0}^{\mathcal{H}_1} \gamma' \quad (10)$$

being $\gamma' = \ln\gamma$. The SD of the Laplacian noise, σ_l, was determined from the entire control recording $\varphi_l^c[n]$:

$$\hat{\sigma}_l = \frac{\sqrt{2}}{N} \sum_{n=1}^{N_{\sigma_l}} |\varphi_l^c[n] - \hat{m}_l^c| \quad (11)$$

Under $\mathcal{H}_1$, the detector output $T[n_0]$ in (10) can be interpreted as a difference between the area $A_l = a_l \cdot (D - T/2)$ and D times the standard deviation of the noise, $D \cdot \sigma_l$, giving so an estimated value of $A_l - D \cdot \sigma_l$.

2.4.3. Design parameters

The total length of the step-like change D was set to 70 s. For the duration T of the transition, different values were tested every 4 s, starting from 2 s and up to 60 s. The angles ϕ_{U} and ϕ_{D} were then independently used in the detection procedure using Eq. (10).

Each individual detector output corresponding to the angle series of each lead was independently used to apply the final decision. To do this, a lead-dependent threshold γ_l' was set as a function of the standard deviation σ_l according to the expression $\gamma_l' = \delta\sigma_l D$, where δ varies from 0.01 to 40. This range of values is selected because of the different ranges of changes observed in the different artery groups and leads. Finally, to consider the detection of an ischemic event, the detector output $T_l[n]$ must exceed the fixed threshold γ_l'.

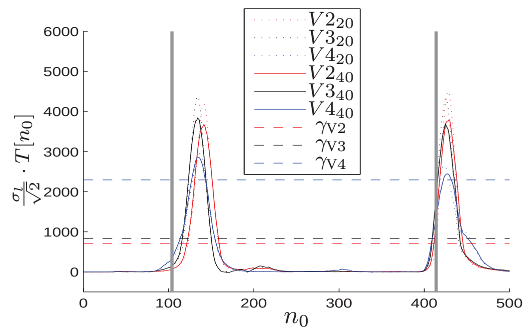

Figure 2. Example of six detector outputs (T= 20 and 40 s, leads V2-V4) for a patient with LAD occlusion. Dashed lines correspond to the thresholds obtained by using δ=8 . Vertical gray lines indicate the occlusion period.

Sensitivity Se and specificity Sp values were assessed by testing the ischemia detector at different thresholds γ' and transition duration T in each lead as explained before. Afterward, the optimum combination of γ' and T (design parameters) were selected from the receiver operating characteristic (ROC) curves obtained for each artery group to build the final ischemia detector.

3. Results

Figure 2 displays an example with the outputs of the ischemia detector applied over angle ϕ_{U} in the precordial leads V2-V4 for a particular recording corresponding to a LAD occlusion. The threshold γ' was set using δ= 8 whereas the transition T was set to 20 and 40 sec.

Results of the ischemia detector performance are summarized in Table 1. The two most sensitive leads for each artery group (LAD, LCX and RCA) are shown. Optimal δ and T values are also shown for such leads as well as the best global performance, assessed by the area under the curve (AUC). It can be observed that Se values in these leads are mostly over 70% for the three artery groups whereas the Sp values achieved up to 100% in the LAD and LCX groups. Optimal transition duration values T found to be different between ϕ_{U} and ϕ_{D} evaluated in the same lead and between the same angle (ϕ_{U} or ϕ_{D}) evaluated in different leads. Optimal threshold values as a function of δ were, however, much more similar between ϕ_{U} and ϕ_{D} evaluated in the same lead, but slightly different between the three artery groups. The LAD group needed the largest

δ values (ϕ_U: 1.75, ϕ_D: 1.85 in the lead V2) for the optimal ischemia detection performance, followed by RCA (ϕ_U: 0.35, ϕ_D: 0.30 in the lead II) and LCX (ϕ_U: 0.17, ϕ_D: 0.14 in the lead aVL).

Table 1. Se and Sp values obtained for the three artery groups. Optimal T and δ values and AUC are also shown.

Group	Param.	Se/Sp (%)	T (sec)/ δ	AUC (%)
R	ϕ_U (II)	75.2/97.2	54/0.35	92.4
C	ϕ_U (aVF)	72.2/94.4	10/0.30	87.2
A	ϕ_D (II)	72.2/94.4	6/0.30	87.7
	ϕ_D (aVF)	75.0/86.1	10/0.25	83.1
L	ϕ_U(V2)	68.2/100	58/1.85	73.9
A	ϕ_U(V3)	72.7/95.5	42/0.20	84.9
D	ϕ_D(V2)	68.2/95.5	22/1.75	77.2
	ϕ_D(V3)	68.1/100	10/0.45	76.8
L	ϕ_U(V5)	72.2/88.9	58/0.12	79.5
C	ϕ_U(aVL)	77.8/72.2	2/0.17	80.4
X	ϕ_D(V5)	72.7/100	26/0.15	79.9
	ϕ_D(aVL)	72.2/72.2	38/0.14	71.1

4. Discussion and conclusions

In this paper an acute ischemia detector based on the analysis of QRS angles, denoted as ϕ_U and ϕ_D, has been developed and tested. The ischemia detector was implemented based on signal model, in which the ischemic changes were modeled as a step-like change with a gradually linear transition, modelling so the ischemic changes observed in this particular dataset. The angles ϕ_U and ϕ_D were previously characterized and reported in [5], where it was found that they present a nonlinear behavior in response to induced ischemia, which is used as a potential trigger for detecting acute ischemic episodes in this study .

From all the standard ECG leads tested into the GLRT detector, the most sensitive in terms of detection performance were: for the LAD group, the leads V2 and V3; for the RCA group, the leads II and aVF and for the LCX group, the leads V5 and aVL. As expected, the leads best suited for ischemia detection in the three artery groups are justly those leads close to the area irrigated by the occluded artery . Regardless the artery group, both the angle ϕ_U and ϕ_D presented similar outcomes in terms of detection as one can see in Table 1, which is in line with the complementary behavior observed when we look to their time course evolution during ischemia [5].

Regarding the design parameters T and δ used to set the ischemia detector, the most important was δ, which is directly related to the threshold γ' fixed to detect the ischemia episodes. Different values of δ were obtained for the different artery groups, as a result of the amplitude changes developed in the angle series during occlusion and their normal variations at baseline. Therefore, smaller values of δ were associated with smaller amplitude changes occurring during occlusion. This led to obtained three different ischemia detectors tailored to each coronary artery. Results obtained after testing all the transition duration values suggested that, using smaller values of T do not significantly change the detector performance when comparing to those obtained with larger values of T.

As a final conclusion, we can say that the QRS angles can be used as a trigger for detecting acute myocardial ischemia. However, this must be further validated in other contexts where ischemic events occur in a progressive way.

Acknowledgements

This work was supported by projects TEC2010-21703-C03-02 and TEC2010-19410 from MINECO, Spain, by Aragón government and European Social Fund under Grupo Consolidado BSICoS. EP acknowledges the financial support of Ramón y Cajal program from MINECO.

References

[1] Stadler R W, Lu S N, Nelson S D *et al*. A real-time ST-segment monitoring algorithm for implantable devices. J Electrocardiol 2001; 34(4): 119-126.

[2] Smrdel, A, Jager, F. Automated detection of transient ST-segment episodes in 24h electrocardiograms. Med Biol Eng Comp 2004; 42(3): 303-311.

[3] García J, Sornmo L, Olmos S, Laguna P. Automatic detection of ST-T complex changes on the ECG using filtered RMS difference series: application to ambulatory ischemia monitoring. IEEE Trans Biomed Eng, 47(9), 1195-1201, (2000).

[4] Laguna P, Moody G B, G arcía J et al. Analysis of the ST-T complex of the electrocardiogram using the Karhunen Loève transform: adaptive monitoring and alternans detection. Med Biol Eng Comput, 1999; 37(2), 175-189.

[5] Romero D, Ringborn M, Laguna P *et al*. Detection and quantification of acute myocardial ischemia by morphologic evaluation of QRS changes by an angle-based method. J Electrocardiol 2013; 46(3): 204-214.

[6] García J *et al*. Temporal evolution of traditional versus transformed ECG-based indexes in patients with induced myocardial ischemia. J Electrocardiol 2000; 33(1): 37-47.

[7] Martínez J P, Almeida R, Olmos S *et al*. A wavelet-based ECG delineator: evaluation on standard databases. IEEE Trans Bio-Med Eng 2004; 51(4), 570-581.

[8] Mincholé A, Sörnmo L, Laguna P. Detection of body position changes from the ECG using a Laplacian noise model. Biomed Signal Process Control 2014; 14, 189-196.

[9] Yin L, Yan R, Gabbouj M *et al*. Weighted median filters: a tutorial. Circuits and Systems II: IEEE Trans Circuits Syst II 1996; 43(3): 157–192.

Address for correspondence:

Daniel Romero Pérez

I3A, Mariano Esquillor s/n / 50018 / Zaragoza / Spain

e-mail: daromero@unizar.es