High-Frequency Signature of the QRS Complex across Ischemia Quantified by QRS Slopes

E Pueyo, A Arciniega, P Laguna

Comm Techn Group, Aragon Institute of Eng Research, University of Zaragoza, Spain

Abstract

In this study two new indexes that measure the upward and downward slopes of the QRS complex are proposed to quantify variations in the depolarization period due to induced ischemia during Percutaneous Transluminal Coronary Angioplasty. Our results show that QRS slopes turn out to be substantially less steep during artery occlusion, being this effect more manifested for the downward slope than for the upward one. Comparing the proposed indexes with a previously reported index that quantifies the energy of the high-frequency QRS signal (150-250 Hz), it is shown that the ability of the slope indexes for ischemia detection is clearly superior. When comparing with the conventional ST level, enhanced performance of the proposed indexes is only found in some leads. It can be concluded that diminution of QRS slopes can be used as an additional tool, alternative to HF-QRS content, to ST deviation when diagnosing ischemia.

1. Introduction

The diagnosis of myocardial ischemia is usually performed by assessing the repolarization period (ST segment and T wave) of the standard electrocardiogram (ECG). In clinical practice, evaluation of ST-segment deviation is the most commonly used marker of ischemia, despite its limitations in terms of sensitivity and specificity. Other ECG indexes, like T wave amplitude, QRS duration or indexes derived from the Karhunen-Loeve transform [1], have been proposed as additional tools for ischemia detection, but they have not been incorporated into clinical routine.

Recent studies have suggested that the decrease of the high-frequency content of the QRS complex (HF-QRS), in the band from 150 to 250 Hz, can be a better marker of ischemia than the traditional ST index [2],[3] and, since the information provided by HF-QRS is complementary to that of ST [2], they can be used in conjunction to provide a robust unique tool for ischemia detection. Nevertheless, the decrease in the amplitude of the high-frequency QRS components has shown only moderate sensitivity and specificity values. The reason for this could be in the hypothesis itself or in the way the high-frequency components are usually quantified by high-pass filtering of the narrow transient QRS signal. The filtering introduces leakage in frequency and smearing in time that can mask the very nature of the localized HF-QRS features. To further investigate on this we hypothesize that if the decrease in the HF-QRS components is due to a reduction of the conduction velocity in the region of ischemia [4], such a phenomenon could be also quantified by measuring the upward and downward slopes of the QRS complex.

To test our hypothesis, we analyze recordings of patients before and during prolonged Percutaneous Transluminal Coronary Angioplasty (PTCA), for which we measure HF-QRS and the proposed slope indexes. The purpose of this study is to assess the temporal evolution of the ischemic changes shown by the different examined indexes and compare their abilities, together with that of other traditional indexes, for diagnosis of ischemia.

2. Methods

2.1. Study population

The study evaluates ECG recordings obtained from 83 patients (55 males, 28 females) of the Staff III database [1, 2]. For each patient, two electrocardiograms are analyzed: the *occlusion ECG*, recorded while the patient was receiving elective PTCA in one of the major coronary arteries, and the *control ECG*, recorded immediately prior to the angioplasty procedure. The average duration of the occlusion period was 4’26”, considerably longer than that of usual PTCA procedures, and the control interval was around 5 minutes long. The study of this type of recordings allows us to investigate ischemic changes that occur during the first minutes of occlusion and compare them with normal variations recorded in control conditions.

2.2. Analyzed indexes

A pre-processing step is applied to each of the ECG signals prior to measure. Such a pre-processing includes QRS detection, baseline drift attenuation via cubic spline interpolation and ECG wave delineation by means of a validated wavelet transform-based system [5].

2.2.1. QRS slope indexes

In this study two new indexes are proposed to quantify high-frequency variations in the QRS signal due to the induced ischemia. These two indexes are:

- US-QRS, measuring the upward slope of the QRS complex between the peak of the Q wave and the peak of the R wave.
- DS-QRS, measuring the downward slope of the QRS complex between the peaks of R and S waves.

To evaluate US-QRS and DS-QRS on each beat, the time locations of Q, R and S waves obtained from the delineation, denoted by Q_p, R_p and S_p, respectively, are considered. In all beats, R_p could be determined successfully. For those beats where the delineator was not able to supply Q_p or S_p, a second search is performed. In the case of the Q wave, the interval covering from 2 ms after the QRS onset up to 2 ms before R_p is examined and the point associated with lowest signal amplitude is identified as Q_p. Analogously, S_p is searched in the interval from 2 ms after R_p to 2 ms prior to the end of the QRS complex.

The next step in the evaluation of US-QRS and DS-QRS is the determination of the time instant n_U associated with maximum slope of the ECG signal between Q_p and R_p (i.e. global maxima of the derivative between Q_p and R_p) and, analogously, of the point n_D leading to minimum slope between R_p and S_p positions.

Finally, a pair of lines are optimally fitted, in a least squares sense, to the ECG signal in a window of 15 ms around the points n_U and n_D, respectively. The slopes of each of these two lines are denoted by US-QRS and DS-QRS.

2.2.2. HF-QRS index

Assessment of the high-frequency content (150-250 Hz) of the QRS complex requires low noise conditions and, consequently, signal averaging is needed. Since the final purpose of this study is to investigate the temporal evolution of changes during the inflation time, the generation of only two averaged beats, one representative of the control and the other one representative of the occlusion period, as developed in [2], is not satisfactory. To comply with the requisite of averaging and, at the same time, be able to follow the evolution of changes, the next method is proposed:

- for the occlusion recording, running averaged beats are obtained from the beginning of the occlusion, retaining one averaged beat every 10 s for subsequent analysis. To monitor morphological ECG changes during the occlusion time and concurrently reduce the noise level, exponential averaging is applied with updating weights inversely proportional to the noise level of each beat:

$$\overline{x}_l^i(n) = (1 - \alpha_l^i)\, \overline{x}_l^{i-1}(n) + \alpha_l^i\, x_l^i(n)$$

where $x_l^i(n)$, $n = 0, ..., N-1$, is the segmented i-th beat of lead l, α_l^i is inversely proportional to its noise level and $\overline{x}_l^i(n)$ is the correspondingly generated averaged beat. Prior to averaging, alignment of beats is performed by cross-correlating each beat to a template [2]. Beats presenting a correlation value inferior to 0.97 are not included in the averaging and the last averaged beat obtained within the analyzed segment (10 s, 20 s, etc) is considered for HF-QRS measuring. Those ECG leads for which an averaged beat cannot be obtained during the final 30 s of inflation are discarded for subsequent analysis.

- for the control recording, conventional averaging is applied over non-overlapping blocks of 10 s.

A noise level value is calculated for each averaged beat of the control and PTCA recordings. ECG leads presenting excessive noise level during the occlusion period or large noise differences between control and occlusion are rejected [2].

On each averaged beat of the accepted ECG leads, HF-QRS is evaluated by filtering the signal with a Butterworth filter of passband between 150 and 250 Hz. The RMS value of the filtered signal within the duration of the QRS complex is defined as the HF-QRS index.

2.2.3. Other ECG indexes

For comparison purposes, traditional ECG indexes such as ST level, T wave amplitude or QRS duration (evaluated in [1]) and S wave amplitude (evaluated in [6]) are also considered in this study. Such indexes are measured on each beat of the standard ECG both for the control and the PTCA recordings.

2.3. Quantification of ischemic changes

To assess changes occurred in the electrocardiogram as a consequence of the induced ischemia, variations of the examined indexes, in absolute terms, are computed. For each analyzed index, $\Delta_{index}(t_i)$ is evaluated by fitting a linear polynomial to the index values measured from $t = 0$ (beginning of occlusion) to $t = t_i$, with $\{t_i\}$ taken every 10 s from the start of inflation.

To compare the ability of the different indexes for tracking ischemic changes, a parameter termed Ischemic Changes Sensor (ICS), originally proposed in [1], is evaluated for each index. The ICS parameter is the factor expressing the amount of change in Δ_{index} during the occlusion period as compared to normal variations during the

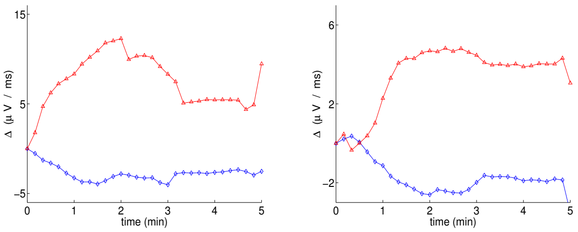

Figure 1. Time course of averaged variations shown by upward (◇) and downward (△) QRS slopes during five minutes of occlusion (left panel for lead V3 and right panel for -aVR).

control recording:

$$ICS_{index}(t_i) = \frac{\Delta_{index}(t_i)}{\sigma_{index}}$$

where $\Delta_{index}(t_i)$ is computed as explained above and σ_{index} represents the standard deviation of the index during the control period.

3. Results

3.1. Alterations in the QRS slopes during PTCA

Figure 1 presents absolute variations of the upward and downward QRS slopes averaged over patients along five minutes of occlusion, for two different leads (V3 in the left panel and -aVR in the right panel). The number of patients included in the average varies across time, since only those that are still in occlusion are included at each time instant. It can be observed from figure 1 that both the upward and downward slopes become less steep as the inflation progresses, which is manifested as decreasing negative values of Δ_{US-QRS} and increasing positive values of Δ_{DS-QRS}.

An example of the above remark is presented in figure 2 for a particular patient of the study group. Figure 2 shows values of US-QRS and DS-QRS during the control and the PTCA periods for one of the analyzed recordings in lead V6. The induced alteration in the QRS slopes is clearly noticeable.

3.2. Comparison between QRS slopes, HF-QRS and other local ECG indexes

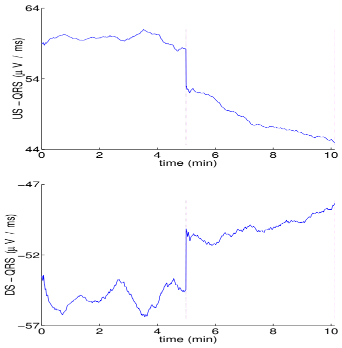

Figure 2. Example of evolution of QRS slopes during control and PTCA.

The performance of the proposed US-QRS and DS-QRS indexes is compared with that of HF-QRS and also with that of other indexes of the standard electrocardiogram, namely ST (level of ST segment measured at 60 ms after J point), T_a (maximum amplitude of the T wave), QRS_d (duration of the QRS complex) and S_a (amplitude of the S wave).

In figures 3 and 4, the time course of changes (averaged absolute values of ICS during five minutes of occlusion) shown by the different examined indexes is presented for leads V3 and -aVR, respectively. Analyzing the relative variations of the three indexes that measure high-frequency QRS variations, it is observed that DS-QRS is the one that better reflects the induced ischemic changes, for all leads.

Contrasting the performances of the proposed slope indexes with that of other ECG indexes, it can be concluded that results are highly dependent on the lead under consideration. In leads with higher projection of the ST-T complex, e.g. V2-V4, the ability of the repolarization indexes (ST, T_a) for ischemia detection is clearly superior to that of the depolarization indexes. Quite the reverse, in leads with usual low amplitude ST-T complexes, such as V1, V6, aVF or -aVR, repolarization indexes show substantially lower ICS values as compared to those found in other leads and, in such cases, depolarization indexes (mainly S_a and DS-QRS), exhibit relative variations of higher magnitude than those of ST or T_a. For depolarization indexes S_a and DS-QRS, it is clear from figures 3 and 4 that their response to the induced ischemia is not as fast as for ST, but, on the contrary, their ICS values become more significant from the second minute of occlusion. This contrasts with the behaviour of repolarization indexes, which are activated much faster, supporting the principle that ischemic perturbations in the QRS complex are always preceded by alterations in the ST segment and the T wave.

4. Discussion and conclusions

In this study the incidence of myocardial ischemia on the ventricular depolarization period has been analyzed from the examination of two indexes, US-QRS and DS-QRS, that measure the upward and downward slopes of the QRS complex, respectively. Examination of changes as the occlusion time increases reveals that QRS slopes become

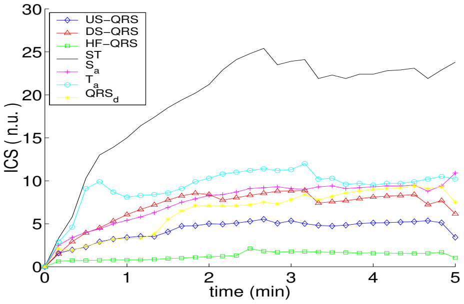

Figure 3. Temporal evolution of averaged ICS absolute values in lead V3.

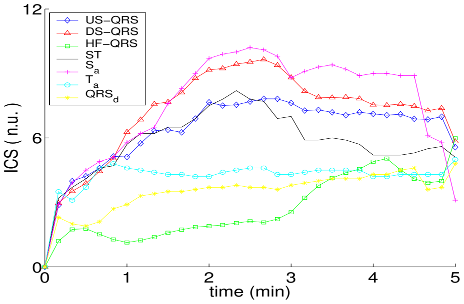

Figure 4. Temporal evolution of averaged ICS absolute values in lead -aVR.

less steep, being this phenomenon more noticeable for the downward slope than for the upward one, possibly due to the fact that the final part of the QRS complex is more susceptible to conduction disturbances.

Comparing the ability of the slope indexes for ischemia detection with that of the previously reported HF-QRS index, which measures the high-frequency content (150-250 Hz) of the QRS signal, an enhanced performance of the slope indexes is observed. Under the hypothesis that both the decrease in the QRS high-frequency content and the reduction in the absolute value of the QRS slopes are related to the conduction velocity of the myocardial cells and the conduction fibers, the results pointed out in this study suggest the consideration of the indexes US-QRS and DS-QRS in lieu of HF-QRS. The slope indexes have the advantage that they are easier to be measured than the high-frequency index (since they do not require signal averaging) and, moreover, they have a direct reading on the ECG.

Additionally, the ability of the slope indexes for reflecting ischemic changes has been compared with that of other ECG indexes, such as the ST level, which is usually the only indicator of myocardial ischemia on which clinical decisions are based. According to the results obtained in our study, indexes from the depolarization period (US-QRS, DS-QRS and HF-QRS) have a stronger capacity to reveal ischemic alterations than the traditional ST in some of the analyzed leads, while in other leads, the effect is the reverse. These results contrast with those found by Pettersson et al [2], who showed that acute coronary artery occlusion is detected with higher sensitivity using high-frequency QRS analysis than with conventional ST segment evaluation in all leads. Nevertheless, it should be noticed that the approaches used in the two studies for assessment of indexes' performances is clearly different, since in the work of Pettersson evaluation of ST segment is performed on two averaged beats representative of the control and the occlusion periods, while in this study ST is measured on each single beat of the recordings. This same consideration is made for assessment of QRS slopes, which are evaluated on individual beats rather than on averaged beats, since averaging can substantially affect their measurement. Also, the study population used in this work is different from the one used in [2] because in that work patients for which QRS duration in the control recording exceeded 120 ms were excluded from the analysis, while in our study the 83 patients of the database are included.

Acknowledgements

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References

[1] Garcia J, Wagner G, Sornmo L, Olmos S, Lander P, Laguna P. Temporal evolution of traditional versus transformed ECG-based indexes in patients with induced myocardial ischemia. J Electrocardiol 2000;33:37–47.
[2] Pettersson J, Pahlm O, Carro E, Edenbrandt L, Ringborn M, Sornmo L, Warren SG, Wagner GS. Changes in high-frequency QRS components are more sensitive than ST-segment deviation for detecting acute coronary artery occlusion. J Am Coll Cardiol 2000;36:1827–34.
[3] Abboud S, Cohen RJ, Selwyn A, Ganz P, Sadeh D, Friedman PL. Detection of transient myocardial ischemia by computer analysis of standard and signal-averaged high-frequency electrocardiograms in patients undergoing percutaneous transluminal coronary angioplasty.Circulation 1987;76:585–96.
[4] Tragardh E, Pahlm O, Wagner GS, Pettersson J. Reduced high-frequency QRS components in patients with ischemic heart disease compared to normal subjects. J Electrocardiol 2004;37:157–62.
[5] Martinez JP, Almeida R, Olmos S, Rocha AP, Laguna P. Non-invasive detection of coronary artery disease by a newly developed high-frequency QRS electrocardiogram. IEEE Trans Biomed Eng 2004;51:570–81.
[6] Pueyo E, Garcia J, Wagner G, Bailon R, Sornmo L, Laguna P. Time course of ECG depolarization and repolarization changes during ischemia in PTCA recordings. Methods Inf Med 2004;43:43–6.

Address for correspondence:

Esther Pueyo
Dpto Ingenieria Electronica y Comunicaciones
Maria de Luna, 1. 50018 Zaragoza (Spain)
epueyo@unizar.es