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Effect of acute myocardial ischemia on different high-frequency bandwidths and temporal regions of the QRS

Rudys Magrans, Pedro Gomis, *Member, IEEE*, Andreas Voss, and Pere Caminal, *Member, IEEE*

Abstract—**The purpose of this study was to describe the changes in high-frequency QRS (HF-QRS) components due to myocardial ischemia provoked by prolonged artery occlusion during percutaneous coronary interventions (PCI). Signal-averaged ECGs from 69 patients were obtained during PCI procedures and comparison of high-frequency components of the QRS at different temporal regions and frequency bandwidth were performed. Continuous wavelet transform was applied to estimate the energy contents over the studied time-frequency regions. Seven frequency bands from 50 to 300 Hz, with bandwidth = 100 Hz were considered. The sum of all 12 leads energy decreased significantly ($p < 0.001$) from pre-PCI to PCI during both second half and total QRS complex in all frequency bands, but the main effect was found in the 200-300 Hz band. The energy changes were more marked toward higher frequency bands. The second half of QRS complex was more sensitive to changes due to myocardial ischemia.**

I. Introduction

EARLY non-invasive detection of myocardial ischemia remains an important challenge. Percutaneous coronary interventions (PCI) provide an excellent model in which to investigate transmural ischemia in a controlled setting and could mimic the spontaneous thrombotic occlusion responsible for acute myocardial infarction.

The study of abnormal signals during and outlast the high-resolution QRS complex, usually referred as abnormal intra-QRS potentials (AIQP) and late potentials (LP) respectively, provide additional and relevant information to the ST segment deviation and T waves changes in the standard 12-lead electrocardiogram (ECG). The origin of these abnormal signals have been related to disruptions in ventricular activation due to both conduction system disorders and diseased regions within or surrounding ischemic or infarct areas [1],[2]. Furthermore, several clinical studies have documented changes in HF-QRS components and have been used as novel tool to detect [3]-[5] and, recently, to quantify myocardial ischemic areas with 12-lead ECG [6]. Most studies [3]-[6] have focused on 150-250 Hz frequency band showing that myocardial ischemia affects HF-QRS components. But, these changes have also been observed in other frequency ranges as 40-80 Hz or 80-300 Hz [7]-[9].

Using time-frequency techniques, an increased HF-QRS energy has been found on the terminal portion of the QRS in post-myocardial infarction groups [10]. However, depressed energy was also observed in the first 50 ms of the QRS complex.

The aim of this work was to characterize changes in HF-QRS contents due to myocardial ischemia induced by long PCI procedures and to analyze several temporal regions and frequency bandwidths.

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R. Magrans, P. Gomis, and P. Caminal are with the Department ESAII, EUETIB, Universitat Politècnica de Catalunya (UPC), and CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), c/ Pau Gargallo 5, 08028, Barcelona, Spain (e-mail: {rudys.magrans, pedro.gomis, pere.caminal}@upc.edu).

A. Voss is with the Department of Medical Engineering and Biotechnology, University of Applied Sciences, Carl-Zeiss-Promenade 2, 07745, Jena, Germany (e-mail: voss@fh-jena.de).

II. Materials and Methods

A. Database

This study was based on 69 patients undergoing elective PCI on the main coronary arteries in the catheterization laboratory at the Charleston Area Medical Center, West Virginia, USA (STAFF III database). Patients selected met the following criteria: (a) no symptoms of ischemia during the ECG recording, (b) QRS duration below 120 ms measured on a previous control ECG and (c) artery occlusion duration of at least 3 minutes. Strict criteria concerning to noise level in each 12 leads of the ECG signal were also imposed as describe in subsection C. In patients with multiple occlusions only the first one was considered.

HR-ECGs were acquired with equipment provided by Siemens-Elena AB (Solna, Sweden) at 1 kHz sample frequency, with 0.6 μV amplitude resolution in standard I, II and III, and precordial V1–V6 leads. Additionally, the augmented aVR, -aVL and aVF leads were generated from the limb leads to obtain the conventional 12-lead ECG.

For each patient, a pre-inflation ECG (pre-PCI) was acquired over 5 minutes, with the patient in a supine position immediately before any catheter insertion in the catheterization lab. During PCI, ECG recording started 1 min before balloon inflation, and was then continuously acquired throughout the inflation period, ending at least 4 min after deflation. Note that occlusion periods were considerably longer than those in usual coronary angioplasty procedures due to the treatment protocol included a single prolonged occlusion instead of a series of brief occlusions in each artery.

B. Signal Averaging ECG (SAECG)

ECG recordings were signal averaged to ensure low noise level when analyzing the micro-potential signals. SAECG procedure was done using a ECG analysis software developed by Department of Applied Electronics, Lund University, Sweden [6],[7],[11],[12]. For pre-PCI records, averaging was performed using conventional ensemble averaging, whereas for PCI recording a exponential averaging recursive technique was employed to track dynamics changes while ensuring a better noise level reduction. In both cases, averaging was applied to segments of 15 s. A detailed description of the procedure is presented in [13].

C. Noise estimation and SAECG analysis

Due to conditions of the catheterization lab each patient has specific noise and signal level characteristics. Noise level in each lead was estimated as the root-mean-square (RMS) value from the averaged beat bandpass filtered in the range of 150 - 250 Hz, in an isoelectric portion of 100 ms, starting 100 ms after QRS end in order to avoid possible LPs [6],[7],[13],

An ischemic beat was analyzed at 3 min after PCI procedure started, taken from the SAECG inflation record. However, if the noise level in any lead was higher than 0.75 μV, then this beat was discarded and the latest beat (within the interval of 15 s; i.e. the preceding beat) was chosen, if it had an acceptable noise level, otherwise the patient was discarded [6]. Next, a beat from pre-inflation SAECG with acceptable noise level similar to the noise level of ischemic beat (within 0.35 μV) was chosen for further analysis. This procedure minimizes the influence of different noise levels when comparing both recordings [6].

Leads from selected beats were passed through a Butterworth bidirectional filter within the frequency interval of f_L = 50 to f_H = 300 Hz. Later, time-frequency representation of each lead was computed as described next, and the energy for different time and frequency regions was estimated. Seven frequency bands (*FB1, FB,…, FB7*) were defined for this study, from f_L to f_H in steps of 25 Hz each with bandwidth of 100 Hz. Three temporal regions were defined, the first half of QRS complex (*QRS1*), the second one (*QRS2*) and the entire QRS complex (*QRS*).

D. Time-frequency analysis

Time-frequency analysis as the continuous wavelet transform (CWT) offers information of the signal about both time and frequency domains. CWT is defined as:

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^{*}_{a,b}(t)dt \qquad (1)$$

where *T(a,b)* are the CWT coefficients resulting from the convolution of signal *x(t)* with shifted and dilated versions of a wavelet function *ψ(t)*. Parameters *a* and *b* are the parameters of dilation (or scale) and location of *ψ(t)* respectively. The normalizing factor $1/\sqrt{a}$ ensures the same energy for all wavelets at each scale. We used a noncomplex Mexican hat wavelet, i.e. the second derivative of a Gaussian function, given by:

$$\psi(t) = \frac{2}{\sqrt{3\sqrt[4]{\pi}}}(1-t^2)e^{-t^2/2} . \qquad (2)$$

Factor $2/(\sqrt{3\sqrt[4]{\pi}})$ ensures that wavelet has unit energy. The admissibility constant C_g is introduced so that *ψ(t)* has zero mean. For *ψ(t)* in (2), $C_g = 4\sqrt{\pi}/3$.

The total energy can be obtained by integration of scalogram $|T(a, b)|^2$ as:

$$E = \frac{1}{C_g} \int_{-\infty}^{\infty} \int_{0}^{\infty} |T(a,b)|^2 \frac{da}{a^2} db . \qquad (3)$$

Energy in terms of frequency is:

$$E = \frac{1}{C_g f_c} \int_{-\infty}^{\infty} \int_{0}^{\infty} |T(f,b)|^2 dfdb , \qquad (4)$$

where *T(f,b)* = *T(a,b)* for $f = f_c/a$; *f* is the characteristic frequency associated with a wavelet of arbitrary scale *a* and f_c is the central frequency of mother wavelet (defined for *a* = 1 and *b* = 0). For Mexican hat wavelet f_c = 0.251.

E. Changes in HF-QRS components due to ischemia

A spatial characterization was done throughout PCI procedure [4]. Additionally, the maximum intra-lead variation ($1 - E_{min}/E_{max}$) in each period was obtained. Similar to previous works [4], [12] the sum of energy *E* of all 12-leads was also used for assessment changes produced by ischemia. Finally, an index named *IC* (*ischemic changes*), was used to identify both the frequency band and temporal region where ischemic episodes are more evident,

$$IC = abs(I_0 - I)/I_0 . \qquad (5)$$

Here, *I* is any of the two indices during pre-inflation (I_0) and inflation.

F. Statistical analysis

A Wilcoxon nonparametric rank-based test was used to assess the statistical significance when comparing values of the indexes between different periods, temporal regions and frequency bands. Bonferroni correction was employed in comparisons among temporal regions to maintain the global probability ($p < 0.05$). Analyses were performed with the SPSS for Windows release 15.0 (SPSS Inc., Chicago, Ill).

III. Results

A. Spatial distribution and maximum intra-lead variation

Figure 1 shows the spatial distribution of QRS energy. Energy values were higher in the precordials leads V2 − V4 and in II, aVF and III leads for both periods. Furthermore, the energy decreased from pre-PCI to PCI in each lead being more notable in the second half of QRS than in the first one.

We found a significant increase in the maximum intra-lead variation during the inflation period for all frequency bands and temporal regions, as seen in Fig. 2. Temporal region corresponding to the whole QRS complex (bottom graph in Fig. 2) showed the most important augment ($p < 0.001$) in all frequency bands.

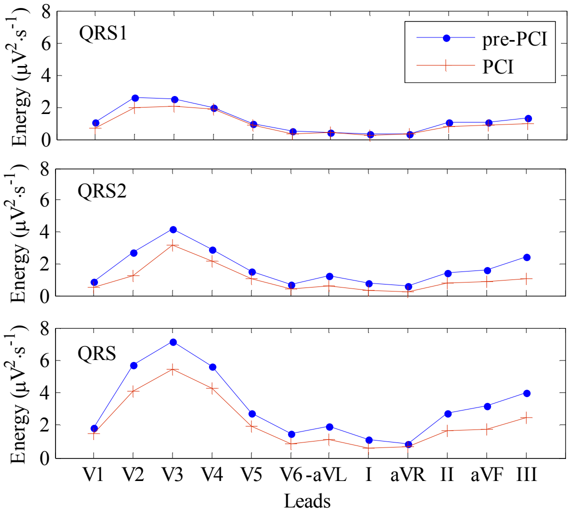

Fig. 1. Spatial distribution of the energy of QRS complex throughout PCI procedure in the frequency band of 200−300 Hz for all time regions.

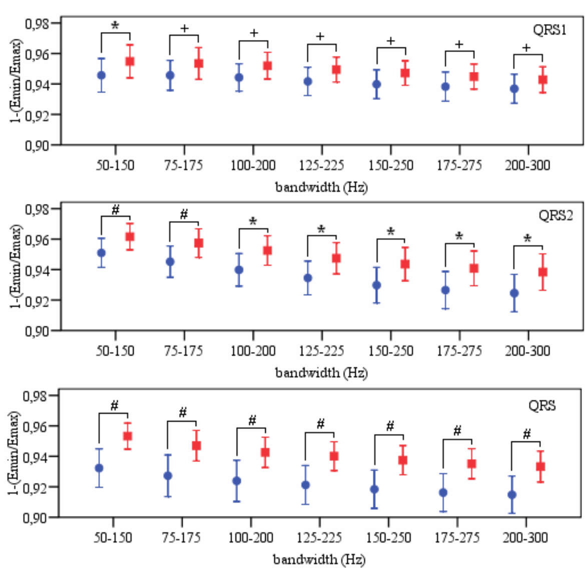

Fig. 2. Maximum intra-lead variation during pre-PCI (circles) and PCI (squares) periods in each frequency band for each time region. Significant differences between periods have been indicated as: (+) p

B. Sum of all 12-leads energy

The sum of all 12 leads energy decreased significantly ($p < 0.001$) from pre-PCI to PCI during both second half and total QRS complex in all frequency bands (Fig. 3). During the first half of QRS complex no important difference were found between energy in frequency bands below 125 Hz. Higher energy values were found in QRS2 temporal region than in QRS1 for all frequency bands.

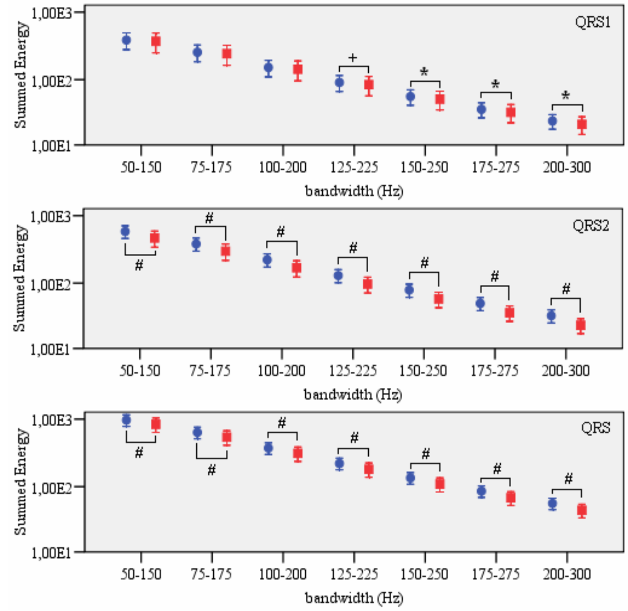

Fig. 3. Sum of all 12 leads energy in ($\mu V^2 \cdot s^{-1}$) during pre-PCI (circles) and PCI (squares) periods in each frequency band for each temporal region. Significant differences between periods have been indicated as: (+) $p < 0.05$, (*) $p < 0.01$, and (#) $p < 0.001$.

C. Quantification changes due to ischemia

Figure 4 shows the variation from pre-PCI to PCI accounted by both the maximum intra-lead variation index (IC_1) and by the sum of all 12-leads energy (IC_2).

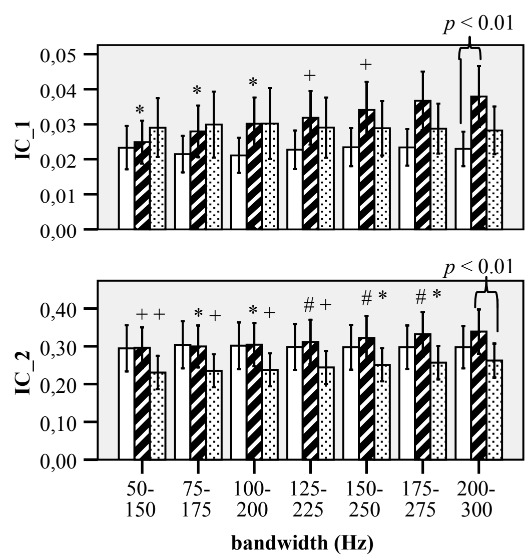

Fig. 4. Ischemic changes for both the maximum intra-lead variation (top panel) and the summed energy (bottom panel) by frequency bands and temporal regions (QRS1, white bars; QRS2, cross lines bars and QRS, dotted bars). Significant differences (+ $p < 0.05$, * $p < 0.01$ and # $p < 0.001$) between temporal regions at different bands respect to the band with the highest index values are shown.

IC_1 index in both first half and total QRS complex was practically constant from one frequency band to other and no significant differences were observed. In contrast, QRS2 region showed the maximum variation (0.038±0.036) in the frequency interval of 200–300 Hz and such variation was statistically significant respect to the variation observed for other frequency bands.

By the way, IC_2 index showed a maximum value in the frequency interval of 200−300 Hz for all temporal regions (*0.297±0.231* in QRS1, *0.339±0.242* in QRS2, and *0.262±0.186* in all QRS). The changes observed in this band during both second half and total QRS complex were statistically significant in comparison to changes in other frequency bands; whereas no statistical differences were found in the first half of QRS complex.

Furthermore, the IC_1 and IC_2 values during the second half of QRS complex were higher than those during both the first half and total QRS in the majority of frequency bands studied. Comparisons among temporal regions were only realized into the frequency band of 200−300 Hz, showing differences statistically significant between QRS1 and QRS2 for IC_1 and between QRS2 and total QRS for IC_2.

IV. Discussion and Conclusions

This study has found significant changes in several temporal and frequency regions of the QRS provoked by acute myocardial ischemia in a controlled setting. Most of previous studies of HF-QRS changes during ischemia [3]-[6],[12] have focused on the band of 150−250 Hz.

Previous works [10] have shown reduced high-frequency QRS components in patients with ischemic heart disease compared to normal subjects, regardless the presence or not of old myocardial infarction. These changes have been associated to abnormal impulse propagation in the ischemic heart due to structural changes [12]. Whereas, an alternative analysis postulates that ischemia causes a slowing of conduction which will decrease high frequency energy [5]. Our results showed a decrease of the sum of all 12-lead energy during transient ischemia in all high-frequency bands and temporal regions. This decrease has been more evident during the second half of QRS complex. Abnormal signals, consequence of disruption in ventricular activation, as shown in [1], could explain the observed changes in the second part of the QRS.

Spatial distribution was similar in both pre-inflation and inflation periods for all temporal and frequency regions. However, there is a higher variation during occlusion despite the energy is lower. The reason of this finding is unclear and future studies should be performed for a better understanding.

The changes were more marked toward higher frequency bands and the second half of QRS complex was more sensitive to changes due to myocardial ischemia. Frequency interval of 200-300 Hz showed the most prominent changes. This suggests that other frequency bands and temporal regions should be explored and not only the usual frequency interval of 150-250 Hz on the entire QRS complex.

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