Changes In Time-Frequency Phase Spectra Vs. ST-Segment Deviation For Detecting Acute Coronary Artery Occlusion

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Abstract

The paper deals with a new method for detection of myocardial ischemia caused by acute coronary artery occlusion in early phases. The method is based on analysis of intra-QRS changes in time-frequency phase spectra generated by wavelet transform. To verify the method, 11 Langendorff-perfused rabbit hearts have been used. The presented results show that models can detect early ischemia in one of three orthogonal leads as early as one minute after coronary artery occlusion. Further, the method is compared to the traditional ST-segment analysis.

1. Introduction

In the Western world, sudden cardiac death remains a leading cause of death [1]. In the majority of the cases, sudden death is caused by lethal arrhythmias preceded by acute myocardial ischemia. The study of ischemic heart disease can reveal mechanisms of its genesis and its influence in the electrophysiology of the heart. Results of the study could then contribute to a better understanding and both pre-infarction and post-infarction treatment of the disease. Further, the results could help to develop a new noninvasive method needed in cardiology diagnostics [2].

For more than half a century, analysis of the ST segment has been the most commonly used diagnostic test for the detection and evaluation of coronary artery disease in asymptomatic subjects and in patients with chest pain syndrome [3]. However, myocardial ischemia can also affect components of the surface ECG other than the ST segment [4]. Separate findings include the occasional increase in QRS amplitude, subtle prolongation of QRS duration, QRS axis shifts, T-wave morphology changes [13].

Since ischemia causes conduction changes, irregular depolarization (activation) of the myocardium may occur. This would be manifested as intra-QRS changes. There is much evidence that ischemia changes in the heart muscle may cause alterations in the QRS spectrum, as an expression of the fragmentation of ventricular depolarization. Abboud [5] detected high-frequency changes (150–250 Hz) in signal-averaged QRS complexes of dogs and human patients caused by ischemia. Okajima et al. [5] studied the frequency components between the onset and offset of the QRS complex, which were different for normal subjects and patients with coronary artery disease. Latter had prominent mid-QRS peaks in the frequency range 40-100 Hz. Further, focal reduction of high-frequency components of the QRS complex (150–250 Hz) under myocardial ischemia induced by percutaneous transluminal coronary angioplasty have been showed [7]. Therefore, a technique similar to the spectrotemporal analysis of late potentials [8] might prove useful in early detection of ischemic changes. This idea is further promoted by Petterson [9], where ST-segment analysis criteria are combined with root-mean-square (RMS) values of QRS high-frequency components criteria (in time-domain).

The fundamental hypothesis used here follows the idea of intra-QRS changes during myocardial ischemia [14]. These changes could reveal local ischemia-induced propagation changes earlier than traditional ECG-based indexes [15]. Most of published works, e.g. [14], deal only with low-level changes in time domain and confirm their presence during acute ischemia and/or reperfusion. According to the preliminary study [10], these changes should appear in relatively wide frequency range of 20-200 Hz and in short time window of ventricular depolarization. The actual frequency localization of the changes depends on the heart status.

2. Methods

The methods used in the project are based on animal experiments when electrograms are recorded from a Langendorff-perfused rabbit heart during various phases of acute myocardial ischemia. Recorded data are processed by a wavelet transform in order to obtain complex-valued time-frequency patterns.

2.1. Experimental setup

Experiments on isolated mammalian hearts were first reported by Langendorff in 1895 [16]. The underlying

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principle is the retrograde perfusion of the coronary bed with oxygenated solution via of a cannula inserted into the ascending aorta. Retrograde flow of the solution closes the aortic valves and the perfusate is displaced into the coronary arteries. After passing through the coronary system the perfusate leaves the heart through the coronary sinus and open right atrium, respectively. The cardiac cavities remain basically empty during the experiment. Various solutions can be used for perfusion. According to our experience, Krebs-Henseleit solution is most suitable for the experiments described in this paper.

11 New Zealand rabbit hearts were examined in this study. The animal was deeply anesthetized, its chest opened and the heart quickly removed. It was mounted on the Langendorff apparatus and placed in a thermostatically controlled bath filled with the solution.

The experimental setup can be used for the electrogram recording by a touch-free method [11]. Six silver-silver chloride disc electrodes (4 mm in diameter) for electrogram recording were positioned in the inner surface of the bath. The hearts were perfused with Krebs-Henseleit solution (37°C, 1.25 mM Ca^{2+}).

The experiment was carried out in two steps. First, each heart was allowed to stabilize for 15 minutes. Then, hearts underwent a 20 min episode of left anterior descending (LAD) coronary artery occlusion. ECG signals were recorded from three orthogonal bipolar leads positioned around the heart. Signals were amplified and digitized at sampling rate 500 Hz by three-channel 16-bit AD converter. Maximum amplitude of recorded signals varied between 100 μV-500 μV depending on subject and extent of ischemia.

60-second recordings of heart activity (electrograms) were taken at baseline (control recording), and 1, 3, 5, 10, 15, and 20 minutes after artery occlusion.

2.2 Analysis tools

Wavelets are an efficient tool for analysis of short-time changes in signal morphology. As pointed out by Unser and Aldroubi in [12], the preferred type of wavelet transform for signal analysis is the redundant one that is the continuous wavelet transform (CWT) in opposition to the non-redundant type corresponding to the expansion on orthogonal bases (multiresolution analysis). The reason is that the CWT allows decomposition on an arbitrary scale. Thus, frequency bands of interest can be studied properly at chosen resolution.

CWT uses shifts and scales (dilation and contraction) of the prototype function $\psi(t)$ instead of its shifts and modulations as for Fourier transform. It is defined as

$$CWT(a,b) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{a}} \psi^* \left(\frac{t-b}{a} \right) \cdot f(t) \cdot dt$$

where $a>0$. CWT gives characteristic pattern (depended on wavelet function ψ) showing good frequency resolution for high scales corresponding to low frequencies and poor frequency resolution for low scales corresponding to high frequencies. It can be shown that CWT also possesses poor time resolution for high scales and good time resolution for low scales.

As a generating "mother" wavelet, complex Gaussian wavelet No.3 has been chosen. It is defined as

$$\psi(t) = \left(\exp(-it)\exp\left(-t^2\right)\right)^{(3)},$$

where $^{(3)}$ denotes 3-rd derivative. Complex Gaussian wavelet No.3 possesses relatively good time and frequency ration as compared to other common wavelets such as complex Morlet wavelet and complex Shannon wavelet.

2.3 Example of CWT analysis

An example of recorded electrograms is shown in Figure 1. QRS complexes extracted from seven recordings from X-lead are shown from baseline (0 min) to 20 minute after occlusion of LAD coronary artery occlusion. In this example, one can easily find significant ST-segment elevation from 3rd minute and subtle shape distortions including QRS complex prolongation from 15th minute of the experiment.

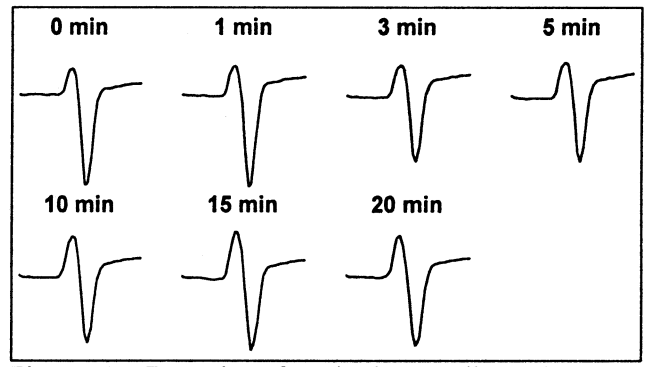

Figure 1. Example of X-lead recordings (80 msec segments, 0.5 mV amplitude window). 0 min: baseline, 1-20 min: LAD occlusion.

The recordings from Figure 1 have been analysed by complex-valued CWT using complex Gaussian wavelet No.3. Resulting magnitude time-frequency spectra are shown in Figure 2. The used time-axes corresponds to those used in Figure 1. Frequency axes are nonlinear as they corresponds to inverted scale axes that are linear here. Resulting phase time-frequency spectra are shown in Figure 3.

In both the spectra, one can find changes over time. While magnitude time-frequency spectra include many components and the relevant information seems to be hidden, phase time-frequency spectra contains phase steps across almost all frequencies. The hypothesis used in the study is based on detection of these steps and tracking their shift in time.

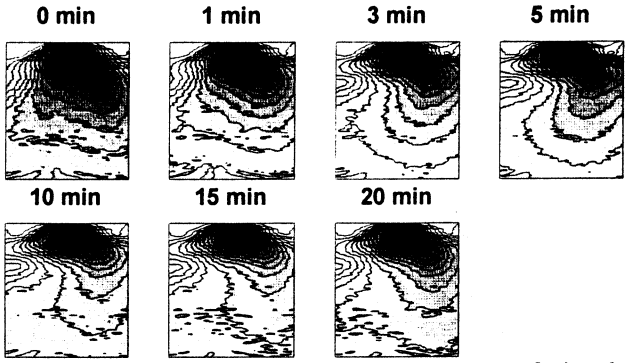

Figure 2. Magnitude time-frequency spectra of signals from Figure 1 by complex CWT using Gaussian wavelet No.3.

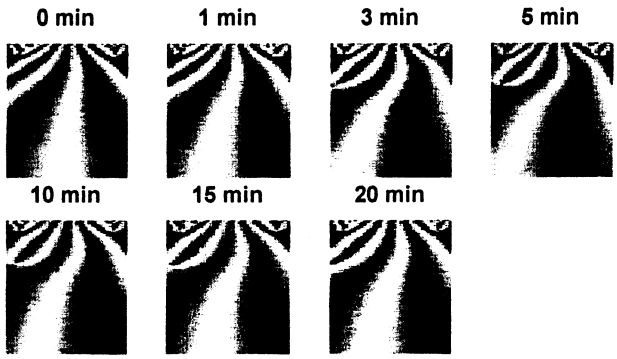

Figure 3. Phase time-frequency spectra of signals from Figure 1 by complex CWT using Gaussian wavelet No.3.

2.4 Phase shift detection

For analysis purposes, the phase can be thresholded to obtain a less complex output image. Thresholded phase is defined as

$$P_{th}(a,b) = \begin{cases} 1 & for \quad |\arg[CWT(a,b)]| \in \langle th-\varepsilon,\ th+\varepsilon \rangle \\ 0 & for \quad |\arg[CWT(a,b)]| \notin \langle th-\varepsilon,\ th+\varepsilon \rangle \end{cases}$$

where $th=\{0, \pi\}$ or $\{-\pi/2, \pi/2\}$ is threshold, ε is a small real number. The phase thresholding at $\{-\pi/2, 0, \pi/2, \pi\}$ results in binary image with vertically oriented lines located at positions of phase steps.

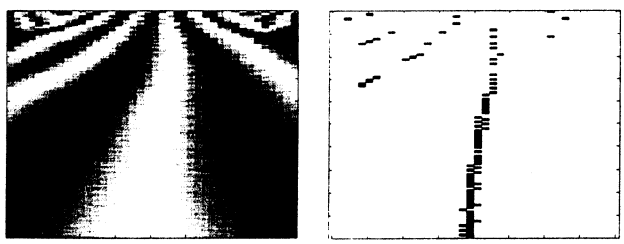
Figure 4. Thresholding phase time-frequency spectra at thresholds $\{0, \pi\}$.

It is well visible in Figure 3 that phase lines detected by thresholding shifts to left – i.e. its time delay decreases – as ischemia progresses. This fact can be exploited to detect the ischemia. Simply, phase lines are constructed and phase shift of central line at a chosen frequency (scale) is measured.

3. Results

11 experiments have been run in the study. For each experiment, seven three-channel recordings of 60-second length have been taken. Only two recordings (baseline and 1 minute after coronary artery occlusion) have been analysed to confirm or reject hypothesis on phase shift in time-frequency spectra. To suppress possible disturbing noise and avoid abrupt phase steps in the spectra, 10 consequent QRS complexes have been averaged. Each averaged QRS complex underwent CWT analysis and phase time-frequency spectra have been generated. Then, phase shift of central lines $\{0, \pi\}$ and $\{-\pi/2, \pi/2\}$ at frequency of 5 Hz has been measured. The frequency have been chosen experimentally. The results are shown in Figure 5 and quantified in Table 1 and Table 2.

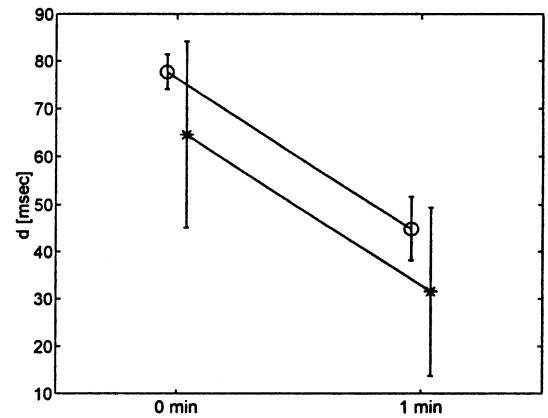

Figure 5. Comparison of central phase line shift d for phase 0 and π (marked by circle), and for phase $\pi/2$ and $-\pi/2$ (marked by star).

lead	0 min	1 min
X	77.8 ± 4.2	45.1 ± 6.3
Y	61.4 ± 28.6	47.9 ± 8.1
Z	24.1 ± 29.3	46.3 ± 11.1

Table 1. Comparison of central phase line shift d for phase 0 and π (all values in msec).

lead	0 min	1 min
X	64.3 ± 20.1	32.1 ± 17.1
Y	60.4 ± 28.7	47.6 ± 8.3
Z	22.8 ± 27.6	40.8 ± 11.3

Table 2. Comparison of central phase line shift d for phase $\pi/2$ and $-\pi/2$ (all values in msec).

Further, ST-segment deviation at 1 minute after coronary artery occlusion have been measured. The results are in Table 3.

lead	1 min
X	-0.071 ± 0.033
Y	0.047 ± 0.006
Z	0.018 ± 0.001

Table 3. ST-segment deviation (all values in mV).

5. Conclusions

The results show that the technique of measurement of phase shift is most sensitive in X-lead. There, the central line $\{0, \pi\}$ has shifted from 77.8 ± 4.2 msec to 45.1 ± 6.3 msec (and from 64.3 ± 20.1 msec to 32.1 ± 17.1 msec for $\{-\pi/2, \pi/2\}$). At the same time, ST-segment deviation has not indicated any significant change in any lead. Maximum elevation among all experiments has been detected in X-lead as 0.169 mV but remained sporadic (compare to mean and standard deviation in Table 3). The reason why ST-segment analysis has failed is most likely caused by too low extent of ischemia in its early phase (only 1 minute after coronary artery occlusion). Thus, phase spectra analysis using complex-valued wavelet transform is obviously more sensitive technique in early phases of myocardial ischemia.

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References

[1] Alpert A, Thygesen T. Myocardial infarction redefined. J Am Coll Cardiol 2000; 36(3):959-969.

[2] de Luna AB, Stern S. Future of noninvasive electrocardiology. In: Zareba W, Maison-Blanche P, Locati EH. Noninvasive electrocardiology in clinical practice. Futura Publishing Co., 2001:475-478.

[3] Drew BJ, Krucoff MW. Multilead ST-segment monitoring in patients with acute coronary syndromes: a consensus statement for healthcare professionals. Am J Critical Care 2000; 8(6):372-386.

[4] Kligfield P. ST segment analysis in exercise stress testing. In: Zareba W, Maison-Blanche P, Locati EH. Noninvasive electrocardiology in clinical practice. Futura Publishing Co., 2001:227-256.

[5] Okajima M, Kawaguchi T, Suzuki S. Detection of higher frequency components at mid-QRS stage of electrocardiogram. IEEE Comp Soc Press. 1990:343-346.

[6] Abboud S. High frequency ECG - a new method to examine depolarization changes mediated by transient myocardial ischemia. Computers in Cardiology 1989; 105-108.

[7] Gramatikov B, Brinker J, Yi-chun S, Thakor NV. Wavelet analysis and time-frequency distributions of the body surface ECG before and after angioplasty. Comp Meth Prog Biomed 2000; 62:87-98.

[8] Lander P, Gomis P. Analysis of High-Resolution ECG changes during percutaneous transluminal coronary angioplasty. J Electrocardiol 1995; 28(Suppl):39-40.

[9] Pettersson J, Pahlm O, Carro E, Edenbrandt L, Ringborn M, Sörnmo 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(6):1827-1834.

[10] Bardonova J, Provaznik I, Novakova M, Novakova Z. Hidden markov model in wavelet analysis of myocardial ischemia in rabbit. Computers in Cardiology 2000; 419-422.

[11] Franz MR. Method and theory of monophasic action potential recording. Prog Cardiovasc Dis 1991; 33:347-368.

[12] Unser M. A Practical guide to the implementation of the wavelet transform. In: Aldroubi A, Unser M. Wavelets in Medicine and Biology. CRC Press, New York 1996:37-76.

[13] Lemire D, Pharand C, Rajaonah J-C, Dube B, LeBlanc AR. Wavelet time entropy, T wave morphology and myocardial ischemia. IEEE Trans Biomed Eng 2000; 47(7):967-970.

[14] Gomis P, Jones DL. Analysis of abnormal signals within the QRS complex of the high-resolution electrocardiogram. IEEE Trans Biomed Eng 1997; 44:681-93.

[15] Garcia J, Wagner G, Sornmo L, Lander P, Laguna P. Identification of the occluded artery in patients with myocardial ischemia induced by prolonged percutaneous transluminal coronary angioplasty using traditional vs transformed ECG-based indexes. Comp Biomed Res 1998; 32:470-482.

[16] Langendorff O. Untersuchugen am überlebenden Säugethierherzen. Pflügers Archiv für die gesamte Physiologie des Menschen und der Tiere 1895; 65(1): 291-332.

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