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HIGH RESOLUTION METHODS FOR DETECTION OF ELECTROPHYSIOLOGICAL CHANGES IN THE ISCHAEMIC HEART

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Abstract

In search for instruments of early diagnosis of myocardial ischaemia, the latest high-resolution methods have been adopted. These methods are based on time-frequency wavelet analysis of intra-QRS changes. In this study, the sensitivity of the wavelet transform was further improved by using phase spectra analysis and hidden Markov model recognition. Ischaemic changes in ECG signals, recorded by orthogonal leads, were studied in 11 isolated rabbit hearts. The most reliable results, in terms of early diagnosis of myoardial ischaemia, were obtained in lead X on the basis of phase-shift detection and by hidden Markov model recognition.

Key words

Myocardial ischaemia, Intra-QRS changes, Wavelet analysis, Hidden Markov model recognition

INTRODUCTION

Sudden cardiac death remains a leading cause of death in highly developed countries. In the majority of cases, sudden death is caused by lethal arrhythmias preceded by acute myocardial ischaemia. For a better understanding of the disease and, consequently, better pre- and post- infarction treatment, it is necessary to study mechanisms of disease genesis and its influence on heart electrophysiology. The results of these studies may also be useful in the development of new, non-invasive diagnostic methods in cardiology (*4*).

For more than half a century, analysis of the ST segment of the surface ECG has been the most commonly used diagnostic test in the detection and evaluation of coronary artery disease in asymptomatic subjects and in patients with chest pain syndrome (*5*). However, myocardial ischaemia can also affect components of the surface ECG other than the ST segment (*10*). Other findings include an occasional increase in the QRS amplitude, subtle prolongation of QRS duration, QRS axis shifts and/or T-wave morphology changes *(12*). Since ischaemia causes changes in conduction, an irregular depolarisation (activation) of the myocardium may occur (*9*). This would be manifested as intra-QRS changes. There is much evidence that ischaemic changes in the heart muscle may cause alterations in the

QRS spectrum, as an expression of fragmentation of ventricular depolarisation. For example, *Okajima et al.* studied frequency components between the onset and offset of the QRS complex and found them to be different for normal subjects and patients with coronary artery disease (*13*). The latter had prominent mid-QRS peaks in the frequency range of 40–100 Hz. In addition, under myocardial ischaemia induced by percutaneous transluminal coronary angioplasty, a focal reduction in high-frequency components of the QRS complex (150–250 Hz) has been shown (*8*). Therefore, a technique similar to the spectrotemporal analysis of late potentials (*11*) might prove useful in early detection of ischaemic changes (*14*).

Our assumption was that intra-QRS changes, which are caused by impaired action potential propagation due to coronary occlusion, may detect the subsequent myocardial ischemia earlier than conventional ECG-based indices (*6, 7).* Because these changes are very subtle, they can only be detected by sofisticated, high-resolution methods. The aim of this work was to assess one of these methods, using two different approaches to the analysis of results.

MATERIALS AND METHODS

To detect electrophysiological changes in the ischeamic heart, we recorded signals from rabbit hearts in which acute myocardial ischeamia was induced by coronary artery occlusion. The data recorded were processed by the wavelet transform approach in order to obtain time-frequency patterns for further analysis.

Experimental setup and protocol

Eleven New Zealand rabbit hearts were used. The animals were deeply anaesthetised by urethan, their chests were opened and the hearts were quickly removed. Each was mounted on a Langendorff apparatus, perfused with Krebs-Henseleit solution (1.25 mM Ca^{2+}) and placed in a thermostat-controlled bath (37°C) filled with the Krebs-Henseleit solution.

The recording of electrograms was carried out by the touch-free method. Six silver-silver chloride disc electrodes (4 mm in diameter) were positioned on the inner surface of the bath.

ECG signals were recorded from three orthogonal bipolar leads (X, Y, Z). The signals were amplified and digitised at a sampling rate of 500 Hz by a three-channel, 16-bit AD converter. The maximum amplitude of recorded signals varied between 100 μV and 500 μV, depending on the subject and the extent of ischaemia.

Two ECG records were obtained from each heart. The first 60-second record was taken after the heart was allowed to stabilise for 15 min in the bath. The heart then underwent a 1-minute episode of occlusion of the left anterior descending (LAD) coronary artery. The second 60-second record was taken 1 min after the artery occlusion.

The eleven experimental animals provided a total of 22 three-lead records. From each record, ten ECG cycles were chosen (total, 660 QRS complexes) and subsequently analysed by the methods described below.

Wavelet analysis

The continuous-time wavelet transform (CWT) is an efficient tool for the analysis of short-time changes in signal morphology (*1*). CWT allows the decomposition of a signal on an arbitrary scale and a study of the selected frequency bands at a chosen resolution. The CWT gives a characteristic pattern (dependent on wavelet function) showing the distribution of signal energy in the time-frequency plane. CWT uses the shifts and scales (dilation and contraction) of wavelet function $\psi(t)$ and is defined as follows:

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

where scale a>0, b is time shift, $f(t)$ is the ECG signal analysed. CWT shows a good frequency resolution for high scales that correspond to low frequencies, and a poor frequency resolution for low scales that correspond to high frequencies (*16*). Gaussian wavelet no.3 was chosen as the prototype function. The wavelet possesses a relatively good time and frequency ratio, as compared to other common wavelets *(9).*

To suppress a possible disturbing noise and to avoid abrupt changes in the spectra, 10 consequent QRS complexes were averaged. Each averaged QRS complex was analysed by CWT. The results of the wavelet analysis were processed by two mathematical approaches described below.

1. Phase shift detection. The phase spectra of wavelet transform were thresholded to obtain a less complex output pattern (). A thresholded phase is defined as follows:

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

where th={0 or p} is a threshold, ε is a small real number. This phase thresholding resulted in a binary pattern with vertically oriented curves located at positions of phase steps.

The phase curves detected by thresholding shifted to the left, i.e., their time delay decreased as ischaemia progressed. This fact was used to detect the ischaemia induced by coronary occlusion.

2. Hidden Markov model recognition. The hidden Markov modelling technique allowed us to infer the state sequence S of a hidden random process from the values of a related process, i.e., the observation sequence O. The sequence S represents desired information, O is a measured ECG signal and the hidden process is a process of ECG signal generation.

For the application of this modelling technique, we regarded the data sequence to be analysed as the observation sequence of a hidden Markov process *(3)* that was composed of vertically oriented frequency components of the magnitude CWT spectra (*2).* The widely used, iterative MacQueen algorithm was used for self-teaching of the model (*3).* To detect myocardial ischaemia on the basis of time-frequency pattern analysis, two models had to be built for each lead, one for ischaemic and the other for non-ischaemic data. The recognition was achieved by processing the analysed signals by the appropriate pair of models.

The „winning“ model, which was the one with a higher probability at the output, showed what is the most probable state of the heart.

To assess the validity of these methods and to compare them to the standart method, ST-segment deviations at 1 min after coronary artery occlusion were measured.

RESULTS

Of the results of analysis of 660 QRS complexes, one is shown as an example in *Fig. 1.* This shows QRS complexes extracted from lead X signals (control and 1 min after LAD coronary artery occlusion). This standart record did not allow us to detect the small extent of ischaemia resulting from 1-minute LAD occlusion.

The results of analyses of ST-segment deviations are given in *Table 1*. The maximum elevation reached 0.169 mV and was detected only in lead X on a few occasions (as seen from the relevant SD).

The recorded data were further analysed by the wavelet transform. The result of this analysis (carried out on the record presented in *Fig. 1*), showing the magnitude and phase time-frequency spectra, is in *Fig. 2*. By comparing the magnitude spectra patterns (upper part) no obvious differences were seen between the non-ischaemic and the ischaemic state of the myocardium. On the contrary, the phase spectra (expressed as multiple curves along the vertical frequency axis in the lower part) showed distinct differences.

The phase-shift detection method was applied to the time-frequency spectra obtained from all experiments. The phase shifts of central lines for thresholds 0 and π, at a frequency of 5 Hz chosen arbitrarily, were measured. The results are summarized in *Table 2*.

The magnitude frequency spectra were examined by hidden Markov models. A model was built up for each non-ischaemic and ischaemic situation and for each of the three ECG leads. In addition, the state of either truth or untruth was considered for each model. The total number of states was 12. The results of this analysis are summarized in *Table 3*.

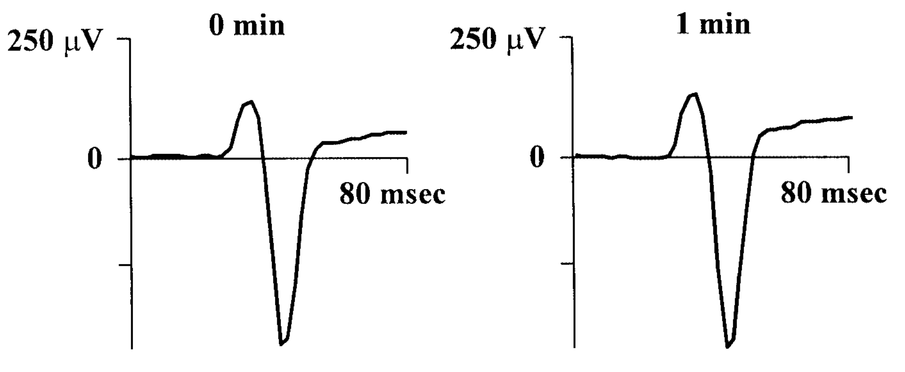

Fig. 1
Example of the QRS complex on ECG records of non-ischaemic (0 min) and ischaemic (1 min after LAD occlusion) signals from lead X.

Table 1

ST segment deviations after 1 min of LAD occlusion, as detected in three-lead ECG records.

Lead	**ST deviation [mV]** (amplitude±SD)
X	- 0.071 ± 0.033
Y	0.047 ± 0.006
Z	0.018 ± 0.001

Table 2

Comparison of phase shifts at 0 and at 1 min following LAD occlusion, as detected in three-lead ECG records

Lead	**Phase shift at 0 min** (non-ischaemic) [msec]	**Phase shift at 1 min** (ischaemic) [msec]
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

All values are expressed as mean±SD

Table 3

Detection scores for the best fitting hidden Markov recognition model in ischaemic and non-ischaemic states of the myocardium

Signal tested / best fitting model	**Score [%]**
X (non-ischaemic) / X (non-ischaemic)	81.8
X (ischaemic) / X (ischaemic)	90.9
Y (non-ischaemic) / Y (non-ischaemic)	18.2
Y (ischaemic) / Y (ischaemic)	90.9
Z (non-ischaemic) / Z (non-ischaemic)	63.6
Z (ischaemic) / Z (ischaemic)	63.6

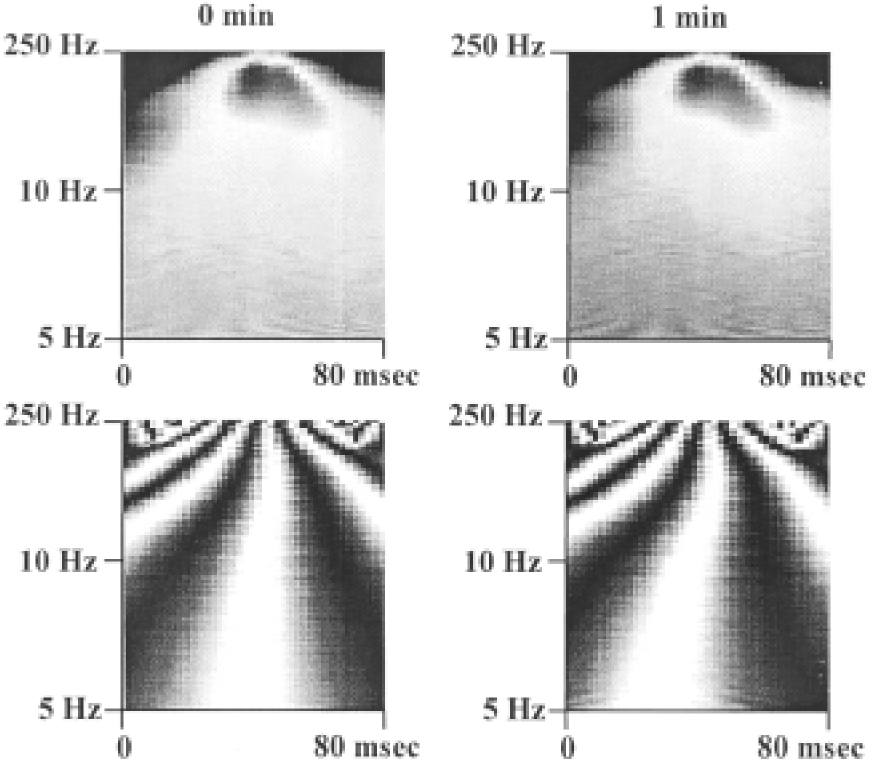

Fig. 2
Magnitude time-frequency (upper) and phase time-frequency (lower) spectra of signals presented in Fig. 1, as computed by the wavelet transform using the Gaussian wavelet no.3.

DISCUSSION

The analysis of our experimental data by ST-segment deviation measurement did not reveal any significant change in signals from the three ECG leads on recording both the ischaemic and the non-ischaemic heart. The ST deviations did not exceed 0.1 mV. The reason for which ST-segment analysis failed to show the difference was most likely a low extent of ischaemia at its early stage (1 min after coronary artery occlusion).

When the data were analysed by magnitude time-frequency spectra, no distinct difference was found between the spectra of non-ischaemic and ischaemic hearts. On the contrary, it was obvious that the curves of phase time-frequency spectra shifted in the ischaemic heart, as compared with the non-ischaemic one. In addition, it was shown that this analysis gave the best results in lead X. The statistical evaluation of the results confirmed that the phase spectra obtained on the basis of complex-valued wavelet transform provide a sensitive tool for the diagnosis of myocardial ischaemia at its very early stage, i.e., at 1 min after coronary artery occlusion.

A direct comparison between the results of phase shift measurement and those of the hidden Markov model recognition technique was not possible because the latter method gave binary outputs. Even these results, however, showed that myocardial ischaemia was best detected in lead X, for which the relevant models for ischaemia and non-ischaemia were sensitive and robust enough and for which good scores for the detection of ischaemia were obtained.

The hidden Markov models showed only low scores for the detection of non-ischaemic signals in lead Y. We therefore conclude that, in this lead, this analysis is not reliable enough to discriminate between ischaemic and non-ischaemic myocardium.

The scores obtained in lead Z were not sufficiently high for this analysis to be used at all.

In conclusion, when ECG signals processed by wavelet transform analysis were further evaluated on the basis of phase spectra analysis and hidden Markov model recognition, the most reliable outcomes in terms of early diagnosis of myoardial ischaemia were obtained in lead X by phase-shift detection and hidden Markov model recognition.

A c k n o w l e d g e m e n t s

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SENZITIVNÍ METODY DETEKCE ELEKTROFYZIOLOGICKÝCH ZMĚN V ISCHEMICKÉM SRDCI

S o u h r n

Článek pojednává o nových senzitivních metodách pro včasnou detekci ischemie myokardu. Popisované metody jsou založené na časově-frekvenční vlnkové analýze intra-QRS změn. Senzitivita metody vlnkové analýzy byla v této studii dále zvýšena použitím analýzy fázového spektra a použitím skrytých Markovových modelů. Ischemické změny v signálech EKG byly studovány na 11 izolovaných králičích srdcích. Prezentované výsledky ukazují, že metody založené na detekci fázového posuvu a na rozpoznávání skrytými Markovovými modely jsou nejcitlivější v ortogonálním svodu X.

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