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MATCHING PURSUIT DECOMPOSITION FOR DETECTION OF FREQUENCY CHANGES IN EXPERIMENTAL DATA – APPLICATION TO HEART SIGNAL RECORDING ANALYSIS

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A b s t r a c t

The time-frequency analysis is a powerful tool to describe the nature of non-stationary biological signals. Short Time Fourier Transform and Wavelet Transform are well-known analysis tools used in the experimental field. This paper deals with another method, Matching Pursuit (MP) decomposition. This method decomposes a signal into an optimal linear expansion of waveforms, which are functions previously defined in a dictionary, and thus extends capability of traditional tools.

The MP method is applied to study changes of energy of ECG signal frequency components during three experimental phases. The experiments include application of voltage-sensitive dye (VSD) needed for non-invasive optical mapping from heart surface. Our previous Langendorff perfused heart experiments suggested shape changes in ECG signals in time-frequency domain caused by application of VSD di-4-ANEPPS. In this study, the heart cycles were decomposed by MP in all phases (control, loading and washout period). The histograms of the relative frequency of waveforms resulting from MP were computed to show frequency details for each experimental phase. The study shows significant shifts of majority energy frequency components during loading and their recovery after washout. Further, MP confirmed subtle frequency changes within QSR complexes during the experiment.

K e y w o r d s

Voltage-sensitive dye di-4-ANEPPS, ECG signal, Wavelet analysis, Matching Pursuit decomposition

INTRODUCTION

Various heart diseases can be studied from the recordings of a range of signals reflecting heart function or anatomy. Action potentials, electrocardiograms, ultrasound images, intracardial pressure are examples of the most often used recordings. Their analysis significantly contributes to clinical diagnostics and to basic cardiology research. Today's methods of biological signal analysis involve a number of sophisticated and complex mathematical approaches allowed by the use of high-performance computers. However, the choice of the appropriate method is difficult as the electrophysiological phenomena to be detected are usually expressed by subtle changes in the recordings.

Optical mapping of action potentials is a valuable technique which has been developed in late 1960's (*1*) as a new high-resolution tool breaking the limits of the traditional microelectrode ECG mapping (*2*). At present, this approach is widely used in cardiac electrophysiology research (*3, 4, 5*). Optical mapping is also widely employed in cardiac electrophysiology animal experiments (*1, 2*). The principle of optical mapping is the application of voltage-sensitive dye (VSD) to the examined tissue (*6*) where it binds to a membrane of cardiac cells. The dye undergoes changes in its fluorescence spectra, in response to changes in the surrounding electrical field. The absorption and fluorescence spectra of the dye are highly dependent on its environment. In general, the dyes are essentially non-fluorescent in water and become quite strongly fluorescent upon binding to membranes. The tissue is illuminated by light with relatively limited narrow spectra. Then, the dye emits fluorescent light of higher wavelength and amplitude proportional to the potential at heart surface. The emitted light can be easily detected and recorded.

The application of VSDs may negatively affect the electrophysiology of the examined heart. The study of these effects is essential in order to support scientific importance and plausibility of the experimental protocol used. In this paper, VSD effects were examined in the first part of our experiments focused on myocardial ischemia: control period, loading with dye, and wash-out. Previous studies revealed certain changes in the heart electrophysiology. However, such changes were not detectable in the time domain by the analysis of signal shape. Therefore, a time-frequency domain analysis is proposed.

The need of a combined time-frequency representation resulted from the inadequacy of either the time domain or the frequency domain analysis to describe the nature of non-stationary (e.g. biological) signals. The time frequency distribution of a signal provides information about how the spectral content of the signal evolves with time, thus providing a tool to dissect and analyse non-stationary signals. This is performed by mapping a one-dimensional signal in the time domain, into a two-dimensional time-frequency representation of this signal. A variety of methods for obtaining the energy density of a signal, simultaneously in time and frequency, have been devised, most notably the short time Fourier transform, the wavelet transform, Wigner-Ville distribution, and Matching Pursuit decomposition. These methods should be used for data analysis in the experimental biomedical area.

MATERIALS AND METHODS

The signals processed in this study were obtained in experiments on isolated rabbit hearts perfused according to Langendorff. Three-dimensional electrograms were recorded during three experimental phases (control, loading, and washout). These signals were then analysed by Matching Pursuit decomposition in order to obtain time-frequency changes during the experiment. The frequency changes were then studied by relative frequency decomposition.

Experimental setup and protocol

All experiments were approved by the institutional Laboratory Animal Care and Use Committee of the Faculty of Medicine, Masaryk University in Brno. Each animal was introduced into deep anaesthesia by ketamine (60 mg/kg of body mass) and xylazine (2 mg/kg of b.m.) after pre-treatment with diazepam (2 mg). The chest was opened, the heart with a sufficiently long piece of aorta cut-off and placed in a preparation bowl with a cold (5 °C) Krebs-Henseleit (K-H) solution of the following composition: NaCl, 118mM; NaHCO3, 24mM; KCl, 4.2mM; KH2PO4, 1.2mM; $MgCl_2$, 1.2mM; $CaCl_2$, 1.2mM; glucose, 5.5mM, and taurine, 10mM. The aorta was cannulated and the heart perfused at a constant perfusion pressure (80 mmHg) with K-H solution. All experiments were performed at a temperature of 37 °C. During the control period (20–30 minutes) all hearts exhibiting any reperfusion arrhythmias were excluded from the experiment. Then, the heart was loaded with a voltage-sensitive dye di-4-ANEPPS diluted in K-H solution (22–27 minutes – depending on real coronary flow). Then a period of wash-out with K-H solution followed (of the same length as the loading period). The preparation was then ready for measurements of monophasic action potentials. During all experiments, simultaneous touch-free recordings of the electrogram were performed.

The employed optical recording system is based on the application of a voltage sensitive dye di-4-ANEPPS (Molecular Probes, USA) into the examined tissue (*7*). The dye undergoes changes in its fluorescence spectra, in response to changes in the surrounding electrical field.

The ECG signals from orthogonal leads were recorded from Ag-AgCl electrodes positioned on the inner surface of the bath. The signals were digitised by a 12-bit AD converter at 4 kHz sampling rate using a data acquisition multifunction card PCI-6111E (National Instruments, USA). The digital signal was stored on a hard disk for further off-line processing. The recorded data were down-sampled from 4000 Hz to 500 Hz.

Wavelet analysis

Continuous wavelet transform (CWT) is a mathematical tool for time-frequency analysis. WT uses a basis of functions of two parameters: time shift and time dilation. To decompose the analysed signal, projection to each dilated basis function (wavelet) must be computed. WT is then defined as a correlation of signal $x(t)$ with wavelets $g^*[(t-\tau)/\lambda]$, where τ is time shift, λ is time dilation, and * represents complex conjugate:

$$CWT(\lambda,\tau)=\int_{-\infty}^{\infty}\frac{1}{\sqrt{\lambda}}g^*\left(\frac{t-\tau}{\lambda}\right)x(t)dt \qquad (1)$$

For the time-frequency analysis, the Morlet wavelet has been used due to its relatively smooth shape (*1*). The analysis resulted in a sequence of columns representing frequency components between 0 to half the sampling frequency (0.01–250 Hz) at each time instant. Previous Langendorff perfused heart experiments suggested that shape changes in ECG signals were recognisable in the time-frequency domain computed with CWT (*8*).

Matching Pursuit In ECG signal processing

Matching pursuit (MP) is an iterative procedure of finding a suboptimal signal representation in a highly redundant dictionary of functions. Used with a time-frequency dictionary of Gabor functions it provides a high-resolution adaptive parameterisation of the structures of the signal. From this parameterisation, time-frequency maps of the energy density of the signal can be constructed by adding Wigner distributions of structures selected for the signal representation.

The Gabor functions used are called time-frequency atoms. Depending upon the choice of these atoms, the decomposition might have very different properties. These waveforms are automatically chosen in order to best match the signal structures.

Given a set of functions (dictionary) $D=[g_1, g_2, ..., g_n]$ such that $||g_i||=1$, we can define an optimal M approximation as an expansion, minimising the error ε of an approximation of the signal $f(t)$ by M

waveforms $g_\gamma(t)$ multiplied by w_i:

$$\varepsilon = \left\| f(t) - \sum_{i=1}^{M} w_i g_{\gamma_i}(t) \right\| \tag{2}$$

The discrete Gabor dictionary is used as a waveform dictionary:

$$g_\gamma(t) = K(\gamma) e^{-\pi((t-u)/s)^2} \sin\left(2\pi \frac{\omega}{N}(t-u) + \phi \right) \tag{3}$$

where N is the length of the signal for which the dictionary is constructed, $K(\gamma)$ is such that $||g_\gamma||=1$. $\gamma=[u,\omega,s,\phi]$ denotes parameters of the dictionary's functions (time-frequency atoms), as time and frequency position, scale, and phase.

MP is an iterative algorithm. The final condition of the iteration is set either as a defined number of atoms used or energy conservation represented by the detection of crossing threshold of the relative energy (*9, 10*).

Fig. 2 presents examples of time-frequency maps for three heart cycles recorded during the experimental phases (left panels). The cycles slightly vary in their shape, which is well visible in the corresponding maps (right panels). The resulting maps are too complex to be analysed even by simple comparison with a reference. Therefore, histograms of the relative frequency of atoms across all frequencies are used. The histograms well describe the frequency components used to construct time-frequency maps. In the histograms, the number of atoms for each frequency was counted and normalised.

RESULTS

The Matching Pursuit decomposition has been introduced in the study of voltage-sensitive dye effects on the isolated rabbit heart electrogram. The recorded heart cycles were decomposed by the MP method in each experimental phase (control, dye loading, and washout). Then, the histogram was computed as a relative occurrence of the waveforms that contributed to the MP result. The histogram was further analysed to study the frequency details of signals in each experimental phase.

Loading the heart muscle with the voltage-sensitive dye and its washout causes energy translations in the frequency spectra of recorded signals. This is demonstrated by changes in the histogram of the relative occurrence of atoms, as shown in *Fig. 3* (left panels). The histograms were computed in a frequency range of 0–40Hz divided into 2Hz intervals. Blue arrows in *Fig. 3* show the direction of frequency changes of atoms with majority energy. The majority energy is shifted from the stable low frequency range corresponding to the control phase of the experiment to higher frequencies during loading. In the washout, the majority of energy components shifts back to low frequencies.

The loading phase and washout were also compared with the control to find frequency changes within QRS complexes. Thus, differences in histograms in a frequency range of 7–15Hz were computed which represent changes in the number of

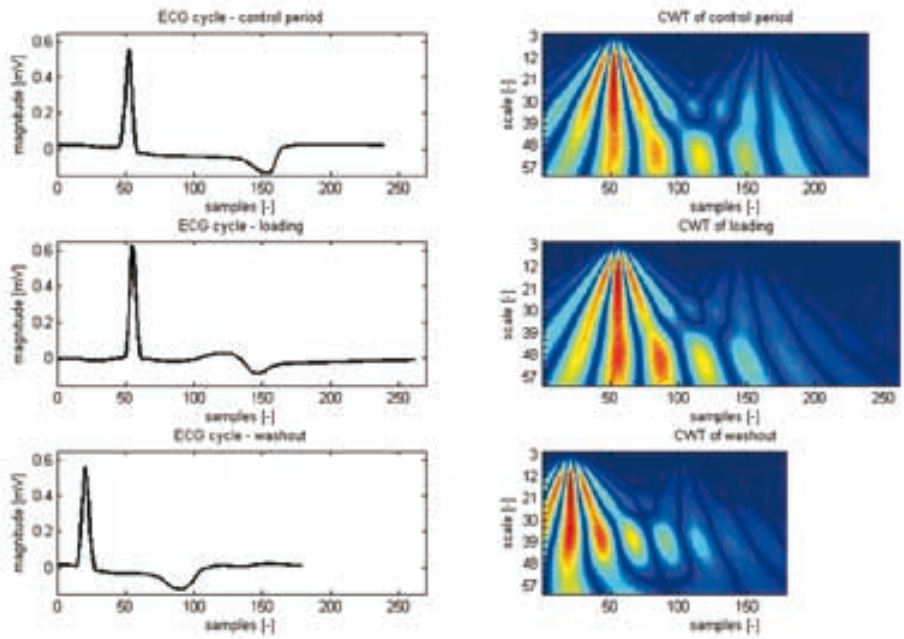

Fig. 1

Continuous time wavelet transform of ECG signals. Left column: ECG cycles recorded during control period, dye loading, and washout. Right column: Corresponding time-frequency spectra of ECG cycles in frequency range of 5Hz to 150Hz, scaled from 3 to 60. Colour legend: from blue to red – low to high energy areas.

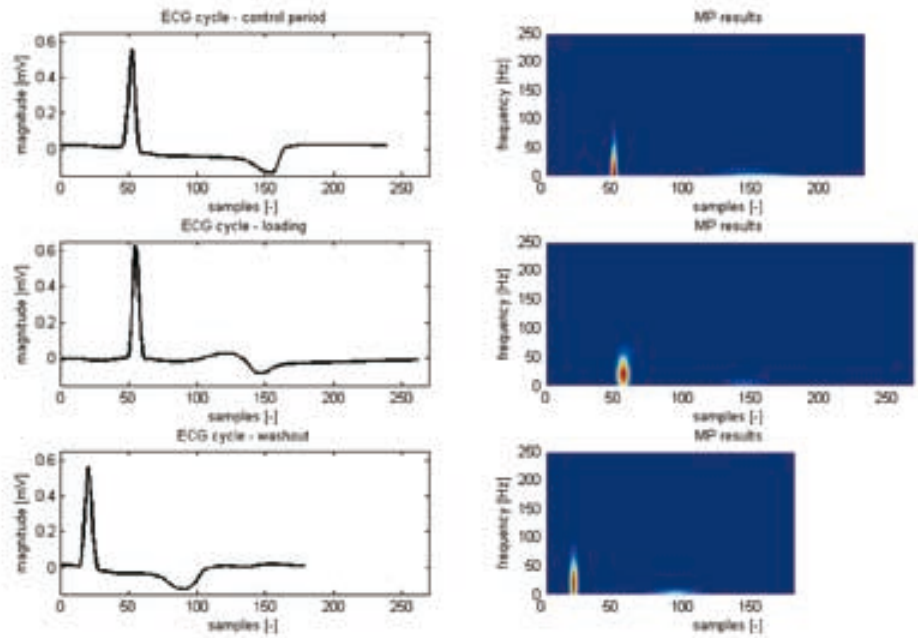

Fig. 2

Matching Pursuit decomposition of ECG signals. Left column: ECG cycles recorded during control period, dye loading, and washout. Right column: Corresponding time-frequency MP maps in frequency range of 0Hz-250Hz. Colour legend: from blue to red – low to high energy areas.

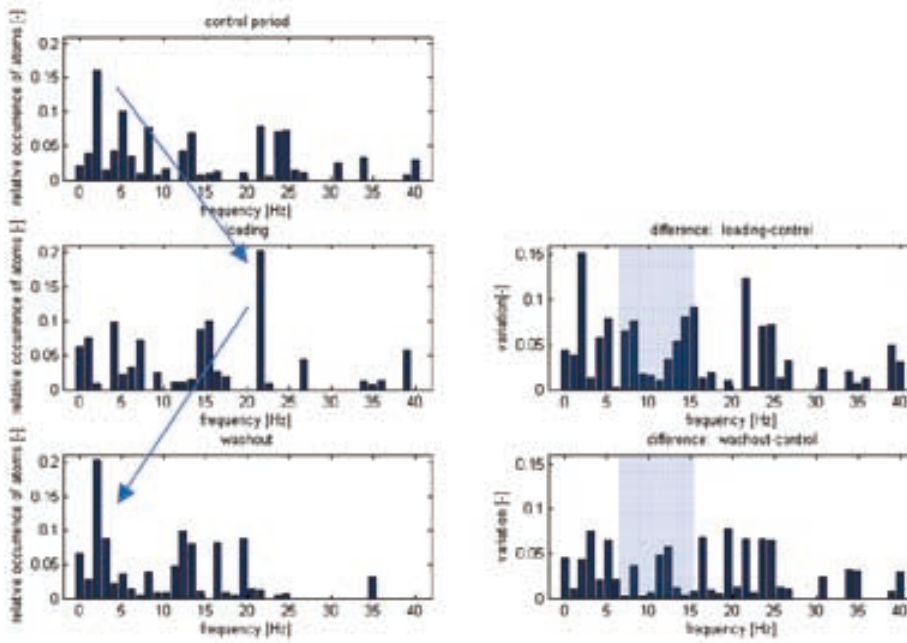

Fig. 3

Histograms of atoms in Matching Pursuit decomposition of ECG signals. Left column: Relative frequency of MP atoms for all experimental phases. Blue arrows represent frequency changes of components with majority energy. Right column: Difference histograms between loading and control period (upper graph) and washout and control period (lower graph). Shaded areas correspond to QRS frequency range.

atoms in each frequency subinterval as shown in *Fig. 3* (right column). The shaded areas mark the analysed frequency range corresponding to the QRS complex content. There are remarkable changes between both analysed cases. When the control and loading are compared, the histograms significantly differ. The differences tend to decrease during the washout period.

DISCUSSION

Voltage-sensitive dyes have been extensively employed by numerous research groups to record optical action potentials (APs) in a wide variety of tissues, mainly in neurology and cardiology research. This method represents a very sophisticated, up-to-date approach to the measurement of fine voltage changes on the membrane of the excitable cell. It also enables researchers to measure spatial and temporal variations in the membrane potential along the surface of a single cell. This approach is often applied in cases where microelectrode measurements are unsuitable or inadequate (e.g. in the presence of external electric fields during stimulation or defibrillation). It is especially powerful and suitable in complex multicellular preparations – in heart preparations it is used not only in isolated cardiomyocytes, but with success also in the papillary muscle or the isolated heart (*11, 12*).

Although some studies have been done to elucidate the effects of various voltage-sensitive dyes on loaded tissue, not very much is known about the direct effects on the membranes of excitable cells, especially cardiomyocytes. It is known that the VSD binds (during the loading phase in our experiments) to the membrane by its carbon chains and the ability of a dye to anchor is directly proportional to the length of these carbon chains. During the washout phase the excess of the dye is removed from the tissue and from the coronary system. This helps to get a better signal: signal-to-noise ratio, with low fluorescence of the background.

In our experiments we have observed prominent changes of electrograms recorded during loading and washout from VSD, namely heart rate decrease and changes of the shape of the QRS complex and the T wave. Some of these changes are clearly visible or detectable by classical methods, some of them are quite subtle (intra-QRS changes). Thus, subtle methods for the analysis of these signals are necessary to work them up. For this reason, Match Pursuit decomposition has been chosen to complete the results obtained from the analyses done by the wavelet transform. Combined results from the wavelet transform and from MP decomposition facilitate our interpretation of electrogram changes in various situations. Moreover, MP offers information about frequency details which is not so perceptible in the results from the wavelet transform.

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

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MATCHING PURSUIT DEKOMPOZICE PRO DETEKCI FREKVENČNÍCH ZMĚN V EXPERIMENTÁLNÍCH DATECH – APLIKACE V ANALÝZE ZÁZNAMŮ SRDEČNÍCH SIGNÁLŮ

S o u h r n

Časově-frekvenční analýza je velice účinným nástrojem pro analýzu experimentálních dat. Nejznámějšími používanými metodami jsou krátkodobá Fourierova transformace a vlnková (Wavelet) transformace. Další používanou metodou pro analýzu signálu je metoda Matching Pursuit (MP). Tuto metodu je možno charakterizovat jako výběrový rozklad signálů pomocí bázových funkcí předem definovaných ve slovníku.

Metoda MP dekompozice je použita pro sledování energie frekvenčních složek zaznamenaného signálu během jednotlivých fází experimentu. Experiment zahrnuje aplikaci napěťově citlivého barviva di-4-ANEPPS, která je nezbytná pro realizaci optického snímání akčních potenciálů z povrchu srdce. Pomocí MP dekompozice zaznamenaných signálů byly vyjádřeny časově-frekvenční mapy a zobrazeny odpovídající histogramy bázových funkcí, které byly využity při dekompozici. Sledovaným parametrem bázových funkcí je jejich základní frekvence. Z histogramů relativních četností bázových funkcí je pak patrné, že největší podíl energie je soustředěn v intervalu nižších frekvencí v průběhu kontrolní fáze experimentu. V následující etapě se pak rozložení energií mění a energie je soustředěna u složek s vyšší frekvencí. Ve fázi vymývání barviva se rozložení energií jednotlivých frekvenčních složek vrací do původního rozložení sledovaného na začátku experimentu. Metoda MP dekompozice udává detailní rozložení bázových funkcí, tedy přesné informace o zastoupení jednotlivých frekvenčních složek v signálu.

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